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ENERGY EFFICIENCY IMPROVEMENTS IN TRADITIONAL BUILDINGS

Exploring the Role of User Behaviour in the Hygrothermal Performance of Solid Walls

Daniel Herrera Gutierrez-Avellanosa

A thesis submitted in partial fulfilment of the
requirements of the
Robert Gordon University
for the degree of Doctor of Philosophy

This research programme was carried out
in collaboration with the
Institute for Innovation, Design and Sustainability (IDEAS)

August 2016

A Paco y Yolanda.

"Si te dan papel rayado, escribe de través;
si atravesado, del derecho"

Juan Ramón Jiménez

("If they give you ruled paper,
write the other way"
As quoted in the epigraph of Fahrenheit 451
(1953) by Ray Bradbury)

CERTIFICATE OF ORIGINALITY

This is to certify that I am solely responsible for the work, which has been submitted within this thesis. Apart from where identified, by means of referencing, I confirm that the contents of the thesis are original and my own. I confirm also, that no part of the thesis has been submitted to any other institution or body in consideration for any other degree or qualification.

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Daniel Herrera Gutierrez-Avellanosa

ABSTRACT

Thermal improvement of traditional and historic buildings is going to play a crucial role in the achievement of established carbon emission targets. The suitable retrofit options for traditional buildings are, however, very limited and their long term performance is still uncertain. Evaluation of risks, prior to any alteration of building physics, is critical to avoid future damage to the fabric or occupants' health. Moisture dynamics in building envelopes are affected by the enclosure's geometry, materials properties and external and internal boundary conditions. Since the internal boundary is heavily influenced by users, understanding their behaviour is essential to predict the outcome of energy retrofit measures more accurately.

The effect of user behaviour on energy demand has been extensively investigated; however, its impact on the hygrothermal performance of the envelopes has barely been explored. This research approached the connection between users and buildings from a new angle looking at the effect that user behaviour has on moisture dynamics of buildings' envelopes after the retrofit. Qualitative and quantitative research methods were used to develop a holistic evaluation of the question. Firstly, factors influencing the adoption of energy efficiency measures in traditional buildings were explored by means of semi-structured interviews with private owners and project managers. Subsequently, a multi-case study including interviews with occupants and monitoring of environmental conditions was conducted. Data collected at this stage was used to explore users' daily practices of comfort and to characterise the internal climate of traditional dwellings. Lastly, users' impact was quantified using Heat, Air and Moisture (HAM) numerical simulation. This allowed for the evaluation of the hygrothermal performance of walls under different internal climate scenarios.

Combined results of interviews, environmental monitoring and simulation showed that internal climate can compromise envelope performance after the retrofit and highlighted the need to consider users in the decision making process. Ultimately, the results of this research will help to increase awareness about the potential impact of user behaviour and provide recommendations to decision makers involved in the energy retrofit of traditional structures.

Keywords: traditional buildings, solid wall insulation, energy retrofit, user behaviour, hygrothermal performance, numerical simulation

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LIST OF ABBREVIATIONS AND ACRONYMS

BRE	Building Research Establishment
BS	British Standard
CEN	Comité Européen de Normalisation
CWI	Cavity Wall Insulation
DECC	Department for Energy & Climate Change
DM	Decision maker
EMC	Equilibrium Moisture Content
EPS	Expanded Polystyrene
ESRC	Economic and Social Research Council
EST	Energy Saving Trust
EWI	External Wall Insulation
GHG	Greenhouse Gas
HAM	Heat, Air and Moisture
HES	Historic Environment Scotland
HVAC	Heating, ventilation, and air conditioning
IAQ/IEQ	Indoor Air (Environmental) Quality
ICOMOS	International Council on Monuments and Sites
ISO	International Organization for Standardization
IWI	Internal Wall Insulation
MC	Moisture Content
MI	Mould Index
MVHR	Mechanical Ventilation with Heat Recovery
PIR	Polyisocyanurate
PUR	Polyurethane
SHCS	Scottish House Condition Survey
SPAB	Society for the Protection of Ancient Buildings
STBA	Sustainable Traditional Buildings Alliance
TOW	Time Of Wetness
TRV	Thermostatic Radiator Valves
VCL	Vapour Control Layer
VIP	Vacuum Insulation Panel
WDR	Wind Driven Rain
XPS	Extruded Polystyrene

NOMENCLATURE

A	Area	m^2
j_{disp}	Dispersive flux	-
j_{diff}	Diffusive flux	-
M	Molal mass of water	g/mol
n	Total air change rate	h^{-1}
N	Sample size	-
R	Universal gas constant	$m^3/(mol \cdot K)$
SD	Standard Deviation	-
T	Temperature	°C
V	Volume	m^3
δ	Daily variation	-
θ_l	Volumetric content of the liquid phase	m^3/m^3
θ_g	Volumetric content of the gaseous phase	m^3/m^3
λ	Thermal conductivity	W/mK
ν	Moisture content	g/m^3
ϱ	Density of air at room temperature	kg/m^3
ϱ_w	Liquid moisture partial density	kg/m^3
ϱ_v	Mass density of water vapour	kg/m^3
ϱ_a	Air partial density	kg/m^3
x	Mixing ratio	kg vapour/kg dry air

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1 INTRODUCTION

1.1 Research context

Since 1960 global CO_2 emissions have increased continuously and CO_2 concentrations have risen to 387 ppm, while the threshold to *"preserve a planet similar to that on which civilization developed and to which life on Earth is adapted"* was established in 350 ppm (Hansen et al. 2008). To tackle this situation, the Scottish government is aiming to reduce 80 % of total CO_2 emissions, in respect to 1990 levels, before 2050 (Scottish Parliament 2009). In order to achieve this ambitious goal it will be essential to reduce CO_2 emissions of traditionally constructed buildings, since 45 % of total CO_2 emissions in the UK are linked to the built environment (RAENG 2010) and 19 % of this built stock can be considered *"traditional"* (Curtis 2010). Furthermore, existing buildings are going to play a crucial role in the achievement of the future CO_2 emissions target considering that, according to recent publications, existing buildings will represent around 80-85 % of the total stock in 2050 (RAENG 2010; Palmer et al. 2006). Research in this field is needed to improve the low rate of renovation in European countries (between 1.2 % and 1.4 % per year according to Dyrbøl et al. (2010).

Most of the energy used in buildings is expended during 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 total energy consumption (DECC 2012). Improving the efficiency of existing buildings will directly reduce the energy demand and with that the risk of fuel poverty. In the current context of fuel price unpredictability (Mari 2014), reducing energy demand is crucial to minimise the risk of unaffordable bills in the future. According to the report elaborated by House Condition Surveys Team in 2004, every 5 % increase in average annual fuel prices would result in 30,000 more households in risk of fuel poverty (Cormack et al. 2002).

Beyond the CO_2 reduction targets or fuel price affordability, built heritage and vernacular architecture need to be preserved for other 'non-tangible' reasons. As recognized in 1975 in the Declaration of Amsterdam, *"Europe's architectural heritage gives to her peoples the consciousness of their common history and common future. Its preservation is, therefore, a matter of vital importance."* In addition to that, the historic environment sector is estimated to contribute to Scotland's national gross value added (GVA) with more than £ 2.3 billion, and it has been estimated that the Scottish historic environment sector accounts for 2.5 % of Scotland's total employment (HEACS 2009). However, as stated by the International Council On Monuments & Sites (ICOMOS 1999), *"due to homogenisation of culture and of global socio-economic transformation, vernacular structures all around the world are extremely vulnerable, facing serious problems of obsolescence, internal equilibrium and integration".*

Although the benefits of improving built environment efficiency and especially of the heritage built stock are undeniable, exclusively technical solutions will not be able to solve the problem since final energy consumption is heavily affected by users' behaviour. As Janda (2011) illustrated, *"buildings don't use energy: people do"* and therefore the actual energy consumption reduction depends on the user's interaction with the building and its services (Hong et al. 2006). A major concern in energy retrofits is the so-called 'rebound effect' (Hertwich 2005), that is, an increase in demand after renovation due to user behaviour. In complex structures like traditional buildings, user behaviour may have an important impact not only on the final consumption but also on the indoor environmental quality and long term performance of the building (J Garratt & F Nowak 1991).

1.2 Rationale for research

Any retrofit project is per se *"a challenge in terms of conservation of historical buildings"* (Cantin et al. 2010) and the long term effect on the conservation of the fabric remains unclear (May & Rye 2012). The rationale for this research is presented below. Further clarification of these concepts is provided throughout the next two chapters of the thesis.

i. There is an urgent need to improve the thermal performance of the traditional built stock in the UK in order to reduce our energy consumption and CO_2 emissions.

ii. Solid masonry walls are considered 'hard to treat' and insulation of the narrow cavity between masonry and lath and plaster may offer a compromise solution between efficiency, conservation and effectiveness.
iii. There is a high level of uncertainty regarding the long term effect of internal insulation on the conservation of the fabric because of the changes caused to the moisture dynamics in the wall.
iv. Moisture dynamics in building envelopes, as well as final energy consumption, are determined by the enclosure properties and the boundary conditions.
v. Internal boundary conditions are difficult to predict because of the strong dependence on occupants' behaviour.
vi. Internal climate and occupants' behaviour is often neglected during the feasibility assessment of retrofit options, and therefore the actual outcome of the intervention remains unclear.

1.3 Research framework

Based on the above rationale, the research question was stated as follows:

In the context of Scottish traditionally constructed buildings,

> *What role does user behaviour play in the hygrothermal performance of internally insulated solid granite walls?*

In order to understand the influence of user behaviour on the hygrothermal performance of insulated solid walls, as well as the role of user behaviour in the decision making process for the implementation of energy efficient measures, the main research question was developed further into three objectives (Figure 1-1). The objectives, in turn, are broken down in several sub-questions. These questions, although numbered sequentially, do not necessarily feed into each other, but rather help to build up an answer to the main research question. The methodological approach chosen to tackle these objectives and questions is presented in Chapter 3.

Objective I. To investigate the relationship between the adoption of retrofit measures in traditional buildings and the energy related patterns of their users.

- Sub-Question 1. What are the driving factors for decision makers when adopting energy efficient technologies in traditional buildings?

- Sub-Question 2. How are user behaviour and comfort needs considered when adopting energy efficient technologies in traditional buildings?

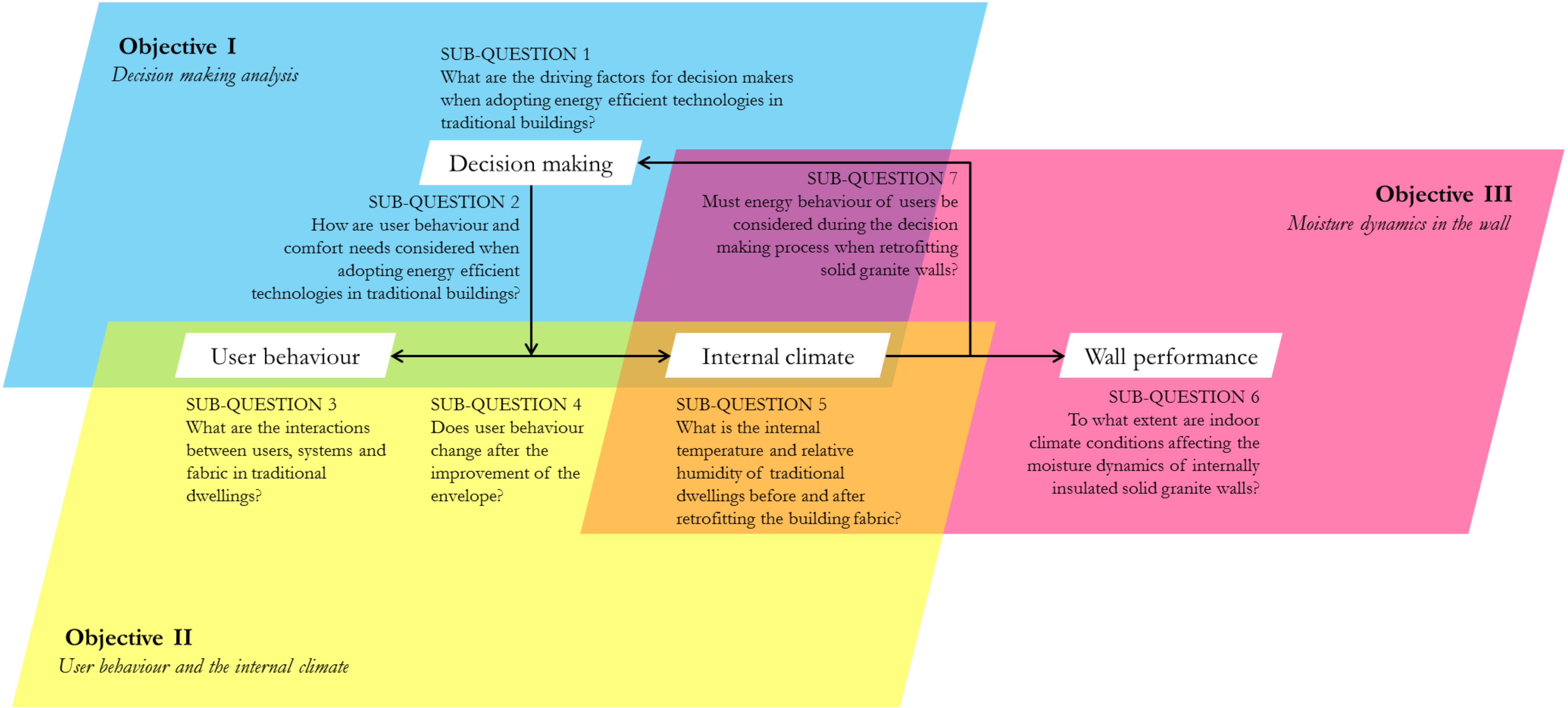
Objective II. To study the influence of user behaviour on the internal climate of traditional dwellings.

- Sub-Question 3. What are the interactions between users, systems and fabric in traditional dwellings?
- Sub-Question 4. Does user behaviour change after the improvement of the envelope?
- Sub-Question 5. What is the internal temperature and relative humidity of traditional dwellings before and after retrofitting the building fabric?

Objective III. To explore the effect of the internal boundary conditions on the performance of internally insulated solid granite walls.

- Sub-Question 6. To what extent are indoor climate conditions affecting the moisture dynamics of internally insulated solid granite walls?
- Sub-Question 7. Must energy behaviour of users be considered during the decision making process when retrofitting solid granite walls?

What role does user behaviour play in the hygrothermal performance of internally insulated solid granite walls?



SUB-QUESTION 1
What are the driving factors for decision makers when adopting energy efficient technologies in traditional buildings?

SUB-QUESTION 2
How are user behaviour and comfort needs considered when adopting energy efficient technologies in traditional buildings?

SUB-QUESTION 7
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What are the interactions between users, systems and fabric in traditional dwellings?

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SUB-QUESTION 5
What is the internal temperature and relative humidity of traditional dwellings before and after retrofitting the building fabric?

SUB-QUESTION 6
To what extent are indoor climate conditions affecting the moisture dynamics of internally insulated solid granite walls?

Figure 1-1 Research framework. The interconnection between research objectives and sub-questions.

1.4 Scope of the research

The focus of this research is on the interaction between user behaviour and moisture dynamics in internally insulated solid granite walls of residential traditional buildings in the North-East of Scotland. The final scope, however, was narrowed as the research was developed.

Thus, the exploration of the decision making process developed in the first stage of the research was approached from a general perspective and included any energy retrofit of traditional buildings independent of their use. In the next stage, the project moved into the investigation of the relationship between the energy behaviour of users and the internal climate. The scope was then limited to residential buildings in order to control the range of behavioural patterns studied and to have a comparable sample. The last stage of the research also restricted the type of construction and materials studied. The investigation was finally limited to solid granite walls with internal insulation applied in the cavity existing between the masonry and the internal lining. Granite was chosen as it is the most common construction stone found in the area of Aberdeen (Urquhart & Young 1998) whereas cavity insulation is a recommended option by Historic Environment Scotland for non-rendered walls where the original lath and plaster is still in situ (Curtis 2010).

1.5 Overview of the thesis

Chapter 1 introduces the background and rationale of the research, formulates the research question and discusses the scope of the thesis. The main research question is divided into three objectives and seven sub-questions.

Chapter 2 presents a detailed review of the existing literature in the fields of traditional construction, energy efficient measures, user behaviour and moisture physics in building envelopes.

Chapter 3 describes the research framework, methodological approach and research design. The methods used in each of the research stages are described and the limitations are justified. Ethical considerations of the research are also discussed.

Chapter 4 focuses on the exploration of the decision making process. The interviews held with owners and managers of traditional buildings are examined and the conclusions regarding the role of the user are presented. The results of this chapter answered both sub-questions (1 and 2) of Objective I.

Chapter 5 analyses the energy related behaviour of occupants. The results of the qualitative studies carried out as part of a multi-case study are discussed in order to understand the elements that structure users' daily practices of comfort. Qualitative data helped answering sub-questions 3 and 4 of Objective II.

Chapter 6 presents the analysis of the quantitative data gathered during the same multi-case study. Monitoring campaigns results are studied to characterize the internal climate of the traditionally constructed dwellings. This answered the last question of Objective II (sub-question 5).

Chapter 7 makes use of numerical simulation to quantify the effect of different internal climates scenarios resulted from the previous chapter. The outputs of the simulation are used to assess the performance of the wall. Simulations results answered the questions (sub-questions 6 and 7) of Objective III.

Chapter 8 connects and discusses the results of previous chapters. The research sub-questions are revisited in the light of the findings and the thesis concludes with some recommendations for the assessment of traditional buildings retrofit and suggests lines for future research.

The thesis also includes a complete list of references and a number of Appendices. These include copies of the consent forms and scripts of interviews and questionnaires. One interview is transcribed in full and all the results from the simulations are summarised. A list of selected publications is also included.

2 LITERATURE REVIEW

Since this research was focused on the hygrothermal performance of traditional buildings of the North-East of Scotland it was important to define the term 'traditional' or 'traditionally constructed' building, as used in this thesis.

The Venice charter, adopted by ICOMOS in 1965, already acknowledged the importance not only of historic buildings but also the *"more modest works of the past which have acquired cultural significance with the passing of time"* (ICOMOS 1964). According to the first section of the Charter on the Built Vernacular Heritage, 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"* (ICOMOS 1999, p.1).

The definition and characteristics of traditional architecture are therefore intimately bounded to its place of creation. In the Scottish context the definition of terms like 'historic', 'listed' or 'traditional', as part of the Building Standards, is the responsibility of Historic Environment Scotland and they have been described as follows (The Scottish Government 2016):

> *"Historic building means a building of architectural or historic interest. An historic building does not have to be listed by Scottish Ministers or lie within a conservation area to be deemed to have special interest or significance;*
>
> *Listed building means a historic building, which has been included in a statutory list because of its special architectural or historic interest; and*

Traditional building means a building or part of a building of a type constructed before or around 1919;

- *using construction techniques that were commonly in use before 1919; and*
- *with permeable components, in a way that promotes dissipation of moisture from the building fabric"*

According to Curtis (2010), Historic Environment Scotland used 1919 as a threshold following the convention adopted by the Scottish House Condition Survey (SHCS) in their first assessment in 1991. After World War I, the use of cavity wall construction became increasingly common due to the economic advantages that this system offered over solid wall construction (English Heritage 2010a). The rest of the definition proposed for traditional buildings, however, is vague and the limits ambiguous. In order to reduce this ambiguity, this thesis used a more detailed definition based on the descriptions found in the literature (The Scottish Lime Centre 2001; Newsom 2002; Simpson & Brown Architects & The Scottish Lime Centre 2002; Urquhart 2007; Curtis 2010; Rye & Hubbard 2011; Buda et al. 2012; Historic Scotland 2010; English Heritage 2012). Thus, the denominations 'traditional' or 'traditionally constructed' were used in this research to refer to:

- buildings built before or around 1919,
- using load bearing masonry walls,
- pitched roofs covered with slates,
- internal finishes made out of vapour permeable materials that both absorb and release moisture and
- timber sash and case windows with single glazed panes.

2.1 Traditional buildings

2.1.1 The evolution of residential construction in the North-East of Scotland

The local environment and history plays a central role in the development of North-East of Scotland vernacular architecture, as shown by Stones (1987) in the book *"A tale of two burghs"*. Stones describes the evolution of typologies and materials used in Aberdeen from the medieval town to 19th century, when the construction of Union Street, King Street and George Street shaped the city present layout (Figure 2-1).

Figure 2-1 A detail from John Wood's Aberdeen map of 1828 (National Library of Scotland. Available from http://maps.nls.uk/view/74400001)

In the medieval town, dwellings formed part of buildings situated at the front of long narrow plots called 'rigs'. These buildings often included a shop on the ground level leaving the floors above it for the accommodation (Figure 2-2 left). As time went by people changed this pattern of use and houses were built at right angles to the frontages or in the 'backlands' in order to satisfy the increasing demand for housing (Figure 2-2 right). Only wealthier people occupied the entire building and most of the houses were split into flats with separate entrances from the street. Although not too many of these buildings have been found, it is assumed that the use of stone was the exception and the majority of the houses were built using either timber frame or wattle-and-dub systems. Similarly, the use of slates for the roof was reserved for the most important buildings while the rest were thatched with heather, rushes or straw.

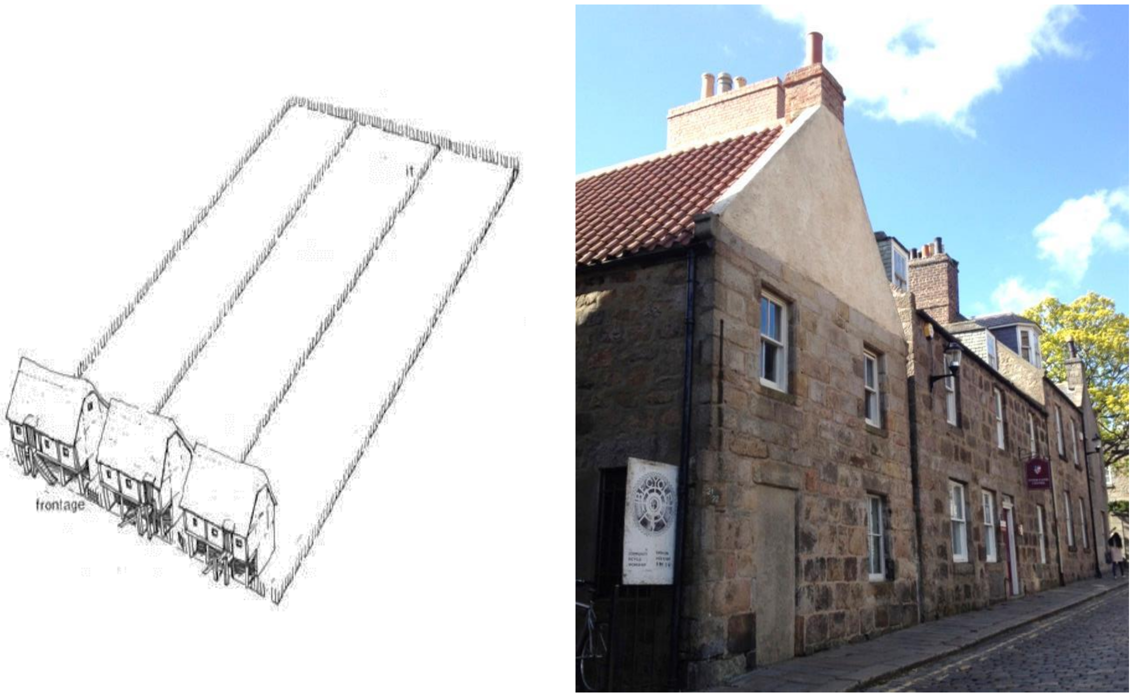


Figure 2-2 (left) The layout of typical medieval tenement (Stones 1987) and (right) a building with its gable facing on to the High Street of Old Aberdeen.

Between 1500 and 1800, Aberdeen experienced a series of major transformations. Size and appearance of buildings changed due to an increasing demand and the introduction of new construction materials. With a growing population (from 3,000 in 1400 to 6,000 in 1700 and over 12,000 in 1800) more houses were built at right-angles to the street, buildings grew in height and they were split into more flats. Parson Gordon - in Stones (1987) - described the town in 1661 as follows:

> *"The houses are built of stone and lime, and have sloping roofs covered with slates. Most of them are three-storied, and not a few rise to a height of four flats. (...) The dwellings are very beautiful outside and inside, and where they look out on the street, they are adorned with wooden porches"*

However, according to Stones, Gordon's description seems to focus on the more exciting modern constructions disregarding the extensive use of timber and thatch until the beginning of the 18th century (Urquhart & Young 1998). The use of stone and slates was still minimal at that time and only the regulations of 1716 and 1741, both following big fires in the city of Aberdeen, which banned construction with thatch and timber caused a change in traditional construction technologies (Coyle 2010).

> *"1741. On the 4th of August, this year, a terrible fire broke out in a house on the west side of the Broadgate, which, at first, threatened destruction of part of the town. The houses being constructed of wood, with stake and rice chimnies, the fire rapidly spread itself on each side, and no efforts of the people could extinguish it until several adjoining houses were completely consumed. Although this was a severe calamity for both the owners and the inhabitants of these buildings, yet it ultimately proved beneficial to the town. After this accident, an act of council was passed, ordaining the outside walls of houses to be constructed wholly of stone or brick, and the roofs to be covered with slate or tyle; and prohibiting every person from building outside walls with wood, chimnies with lath and plaister, or covering houses with turf, heath, or straw. In consequence of this salutary regulation, the citizens began to rebuild their tenements in a more regular manner, with more durable and substantial materials than formerly, and to embellish the front walls of their houses with dressed and regular coursed granite, on which method of building improvements have continued to made" (Kennedy 1818, p.294)*

As Coyle (2010) described, a new phase in large-scale mining began and the industry developed greatly after the act was passed. The early quarries and extraction techniques were gradually replaced by modern methods mainly developed by Gibb in 1819. Transport improvements around 1830 with a new turnpike road, a canal and railways boosted the development of the industry with new quarries opened in Peterhead and Rubislaw. Besides, Aberdeenshire granite was largely exported to other parts of the UK and abroad during the 19th century (Mcmillan et al. 2006).

Stonemasons played a crucial role in the rise of granite as a construction material. Making the rough granite into building stones was done using a hand pick until the introduction of pneumatic tools in the 1890's. Due to the difficulty in shaping the stones, local builders developed techniques to fill or 'pin' the areas between the vertical joists with squares of small stones. This practice, common throughout the North-East of Scotland, is now known as *"Aberdeen bonding"* (Beaton 1997) (Figure 2-3).

After the peak production in the 1890's, with quarries employing 2,000 men, there was a decline in the use of local granite as people demanded greater variety of colours and stone was imported from Norway or Czechoslovakia.

Figure 2-3 Different traditional finishes of granite walls: rubble (top left), cherry caulking (top right and bottom left) and Aberdeen bonding (bottom right).

2.1.2 Characteristics and performance

There is not enough data to determine the exact number of existing traditionally constructed buildings (Ingram 2013). Nowadays we count around 450,000 pre-1919 buildings in Scotland, 47,000 of which are listed. That represents almost 20 % of total building stock (Historic Scotland 2010).

Table 2-1 Age profile of built stock (The Scottish Government 2013)

Local Authority	000s	%
Aberdeen City	17	16%
Aberdeenshire	29	28%
Scotland	473	20%

As shown in Table 2-1, pre-1919 buildings are not evenly spread throughout Scotland. Thus, while in Aberdeen city traditional buildings represent 16 % of the built stock, in Aberdeenshire the percentage rises to 28 %, considerably higher than the national average (20 %). Besides the differences in age profiles, the distribution of dwellings types also changes across the country. No data of pre-1919 dwellings is available; however, looking at residential buildings built before 1945 obvious differences between Aberdeen City and Aberdeenshire can be observed (Table 2-2). While the distribution in Aberdeen City is fairly homogenous, with 41.4 % of houses and 58.6 % of flats, in Aberdeenshire the old dwellings are predominantly houses (91.2 % / 8.8 %).

Table 2-2 Age of dwelling (banded) by type (The Scottish Government 2013)

Local Authority	House				Flat			
	Pre-1945		Post-1945		Pre-1945		Post-1945	
	000's	%	000's	%	000's	%	000's	%
Aberdeen City	12	12%	46	44%	18	17%	28	27%
Aberdeenshire	32	31%	60	58%	3	3%	9	9%
Scotland	398	17%	1118	47%	370	16%	485	20%

Due to the materials and systems used in their construction, traditional buildings have a poor thermal performance compared to modern construction and are responsible for the largest ratio of CO_2 emissions per square metre (Table 2-3). However, prior to the implementation of any retrofit measure it is necessary to understand the hygrothermal behaviour of these buildings and the differences between traditional and modern construction. Otherwise, the misinterpretation of how traditional buildings perform might result in unintended consequences after the thermal retrofit (May 2014).

Table 2-3 Annual modelled emissions (T/a) and modelled emissions per square metre (kg/m^2) by age and type of dwelling, 2014. Adapted from (The Scottish Government 2014)

House Type		Pre-1919		1919-1982		post-1982		All Ages	
		T/a	kg/m^2	T/a	kg/m^2	T/a	kg/m^2	T/a	kg/m^2
Type	Detached	19.8	120	10.8	88	8.5	63	11.4	82
	Semi	13.9	104	7.4	82	5.8	68	7.9	82
	Terraced	10.1	101	6.7	80	5.4	68	6.8	81
	Tenement	6.2	94	4.6	74	3.5	54	4.9	77
	Other flats	8.8	97	4.8	72	3.6	64	5.4	76
All types		10.7	102	6.7	79	6.2	63	7.4	80

As the proposed definition of the term ‘traditional’ stated, Scottish buildings are traditionally built using solid masonry walls, pitched slate roofs and timber sash and case windows. It is commonly accepted that these traditional materials have a poor thermal performance compared to modern materials. However, Baker (2011) measured the U-value of 67 different assemblies in situ and concluded that traditional walls perform better than expected from the calculations or the literature. Thus, for 600 mm thick stone walls with lath and plaster the Energy Saving Trust proposes a value of 1.7 W/m^{2}K and the CIBSE Guide suggest a value of 1.38 W/m^{2}K. The results of Baker's study obtained a U-value of 1.1 ± 0.2 W/m^{2}K. The U-value decreased to 0.9 ± 0.2 W/m^{2}K in walls finished with plasterboard. In a different study, Currie et al. (2013) monitored the thermal performance of ten buildings and obtained an average value of 1.4 W/m^{2}K. The same result was obtained by Rye (2011) after monitoring 21 different stone walls. In this case the U-values were also calculated using BuildDesk, a calculating software package based on the standard BR 443 (Anderson 2006) and commonly used throughout the UK. The average calculated U-value was 1 W/m^{2}K higher than the in situ measurements. Baker argued that the discrepancies are partially due to the underestimation of lime mortar influence on the thermal transmission. Walls are often perceived as a homogenous layer while in reality these constructions are formed by two leafs of larger stones with rough internal finishes and a core filled with smaller stones and mortar (Figure 2-4).

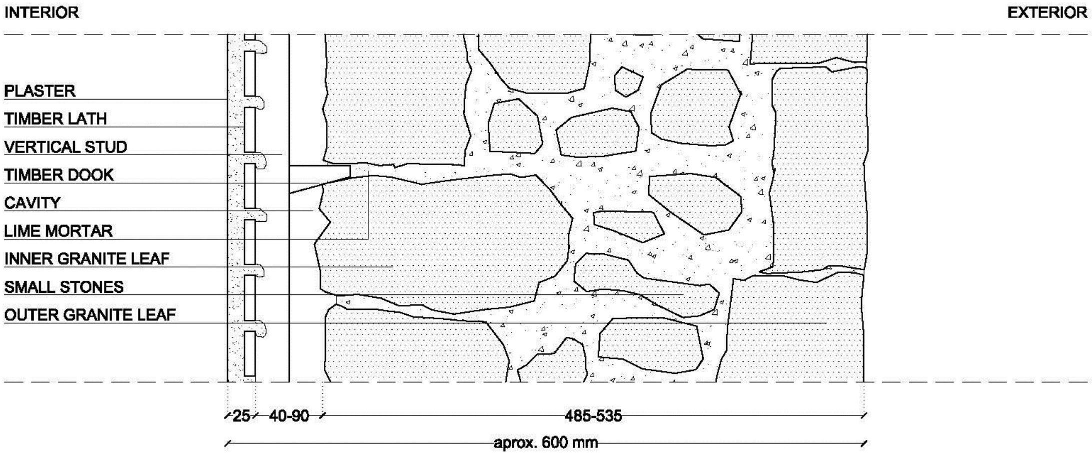


Figure 2-4 Solid wall section

Similar discrepancies have also been found in other European countries. In Italy for instance, a study on the thermal transmittance of walls in historical buildings (Adhikari et al. 2012) found a difference between measured and calculated U-values that varied from 13 to 58 %. As pointed by Rye et al. (2012), the overestimation of U-values leads to inaccuracies in the final calculations of energy and cost savings and encourages the implementation of highly invasive measures.

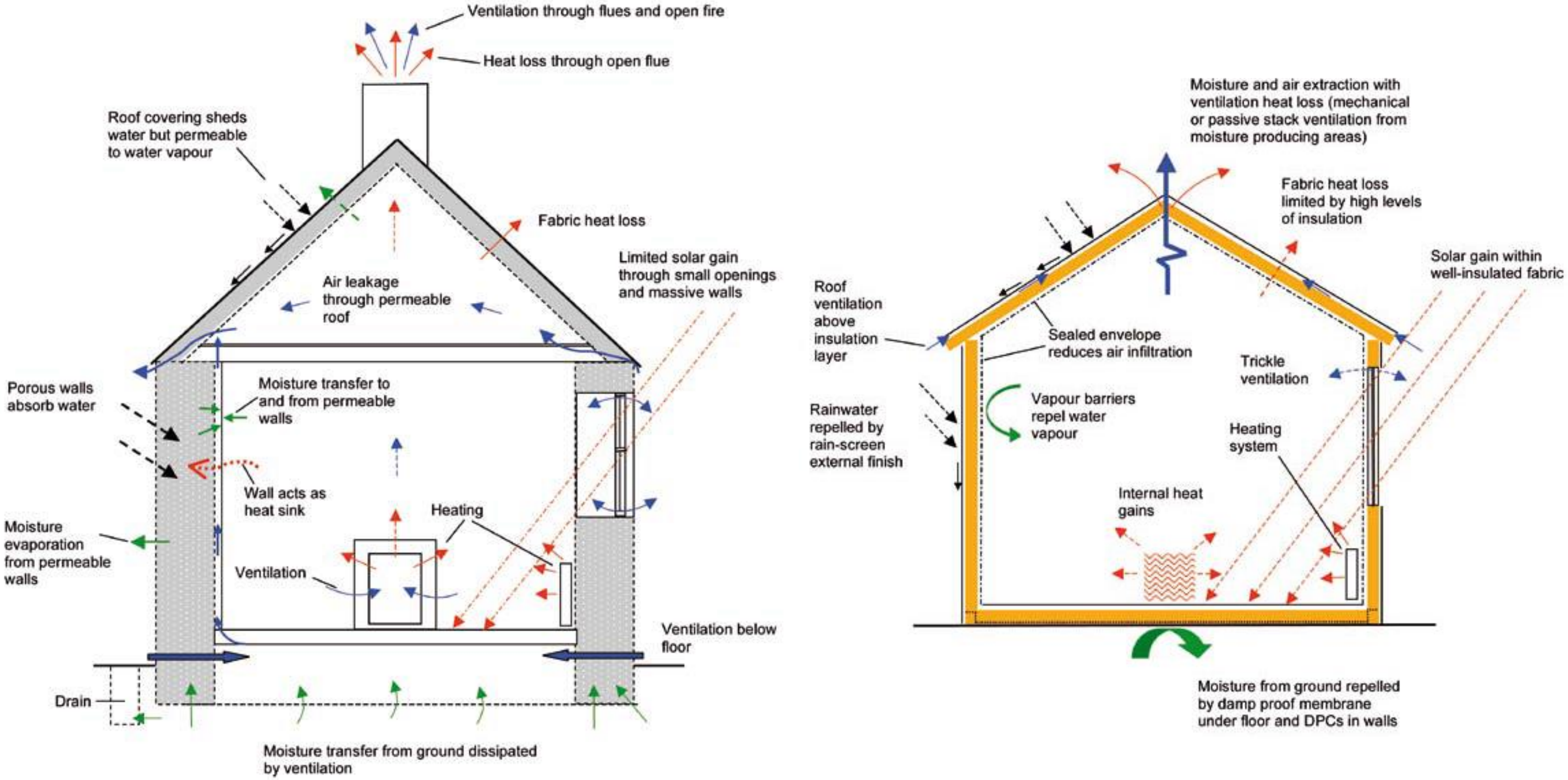


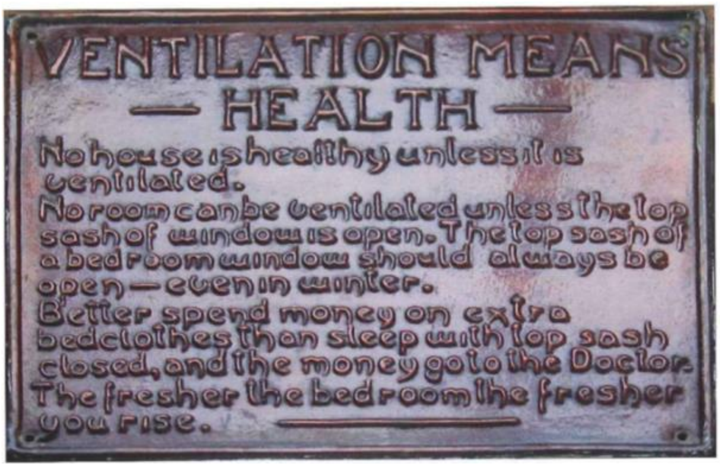
Figure 2-5 Traditional versus modern construction. Source: Urquhart (2007)

Traditional buildings are affected by moisture in a completely different way to that of modern construction (Figure 2-5). While impermeable barriers are used to keep humidity out of the envelope of modern buildings, traditional construction makes use of the porosity and permeability of natural materials to buffer and slowly evaporate water vapour (Hughes 1986; Urquhart 2007). Besides, traditional construction relies on high rates of ventilation in unheated cavities (crawl space, loft or wall cavity) to avoid condensation and mould growth (Halliday 2009) (Figure 2-6). Modern construction, on the other hand, makes use of mechanical ventilation for the removal of any moisture excess. Changes on the hygrothermal characteristics of the envelope, such as internal insulation or inappropriate repointing, could lead to interstitial condensation and thus deterioration of the internal lath and plaster, fabric decay or even structural failure due to the degradation of timber joists ends (May 2005).

Figure 2-6 Original lath, suspended timber floor, loft insulation and coombes between roof and lath & plaster

Besides the effect on moisture control, the permeability of the envelope also plays an important role in the final heat loss of buildings. It is generally assumed that the envelope of traditional buildings is more permeable than those of modern construction (Johnston et al. 2011). The 'rule of thumb' of ventilation used to say that traditional buildings needed twice the normal levels of ventilation and assumed that the infiltration rates already exceeded this value and so draught-proofing was generally beneficial (Figure 2-7). However, the study carried out by (Hubbard 2011) measuring the air permeability of 12 traditional British dwellings challenged that idea. The values measured ranged from 7.2 to 20.1 ach. In some cases, the results would even comply with current regulations of air tightness for new buildings.

The analysis carried out by Stephen (1998) using the results gathered by BRE after 15 years of measurements did not find any clear relationship between the buildings age and the air leakage rate. The common belief that older buildings are more permeable than modern ones is not supported by the BRE database. The study showed that buildings with suspended timber floors (as in traditional construction) are more permeable than those with solid floors, but buildings with solid masonry walls are more airtight than cavity wall constructions.



VENTILATION MEANS
— HEALTH —
No house is healthy unless it is ventilated.
No room can be ventilated unless the top sash of window is open. The top sash of a bedroom window should always be open—even in winter.
Better spend money on extra bedclothes than sleep with top sash closed, and the money go to the Doctor.
The fresher the bedroom the fresher you rise.

Figure 2-7 Embossed tinplate notice with ventilation instructions for tenants. Gannochy Trust on a traditional cottage from the interwar period built by AK Bell (Historic Scotland 2015)

The results of the work carried out by the Sustainable Traditional Building Alliance (STBA) reviewing the existing research and guidance (May & Rye 2012) concluded that there is a lack of reliable data to characterise traditional buildings in terms of air permeability and ventilation rates. In addition to the effect that air permeability might have on the conservation of the fabric and total heat loss, dampness and inadequate ventilation are the main factors for the presence of biological agents associated to occupants' health problems (Afshari et al. 2009). Any alteration of the envelope aiming to change the ventilation rates should be therefore carefully studied.

2.1.3 Energy & built heritage

The language of the Intergovernmental Panel on Climate Change (IPCC) reports have suffered a great change over time (Roaf et al. n.d.) and now current research shows no doubt regarding the role of human activities in the alteration of the atmospheric composition:

> *"Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history" (Pachauri et al. 2014, p.2)*

As a result of that, and led by United Nations, countries all over the world have agreed to move towards a decarbonised society. Regarding the built environment, the efforts on the reduction of energy consumption have been mainly focused on new housing. However, since 2009 attention shifted towards the existing built stock and its potential for improvement. The Directive 2010/31/EU on the Energy Performance of Buildings (Dyrbøl et al. 2010) concentrated the efforts to reduce carbon emissions from existing buildings on the reduction of heat loss, the conservation of energy and the use of renewable sources of energy.

As presented by Ingram (2013), two opposed argumentation trends can be found in the literature when considering the retrofit of old buildings. On one hand, some scholars defend the idea *"that old, energy-inefficient dwellings should be demolished and replaced with modern constructed, more efficient dwellings"* (p. 38). Dubois & Allacker (2015), for instance, argue that from an economic point of view substitution is more effective than renovation. They are in favour of eliminating the support schemes for retrofits and incentivizing only deep renovations or the demolition and reconstruction of inefficient buildings. In addition to that, Matsumoto (1999) claims that the impact associated to the demolition and construction of new buildings is quickly offset by the lower energy demand of the new buildings.

However, the majority of the literature aligns with the idea "that inefficient dwellings should be upgraded, whether through building fabric improvements, upgraded building services such as lighting and heating, or retrofitting renewable energy technology to reduce CO_2 emissions" (Ingram 2013, p.38). For instance, Plimmer et al. (2008), Sanfilippo & Ngan (2008), Patrice Frey et al. (2011) and the guide to "The principles of the conservation of historic buildings" (British Standard Institution 1998) defend the environmental benefits of renovating the existing stock against its demolition and substitution with new structures.

Furthermore, the results of a separate study carried out along with this thesis (Herrera-Gutierrez-Avellanosa & Bennadji 2014) showed that the 'environmental payback' of energy efficient measures like internal insulation of solid walls is fairly short. That is, the embodied impacts associated with the fabrication and installation of such measures are compensated in less than five years in most of the cases.

From an economic point of view, Plimmer et al. (2008) defended the relevance of retrofit highlighting the shorter timescale required when compared to demolition and reconstruction. A shorter duration is translated into shorter contracts and therefore the effect of inflation on the building costs is limited. Moreover, shorter development periods reduce the cost of financing the schemes and allow clients to start recovering their investment earlier. Beyond economic or environmental issues, Power (2008) pointed out that accelerated demolition and substitution of the built stock could help us meeting our energy and climate change targets but it would not respond to our social needs. Demolition of the existing buildings has a negative effect on the value of the neighbouring properties and the state of schools, shops, health facilities and other local services driving to more demand for housing in new areas and urban sprawl.

> *"It is for all these buildings, therefore, of all times and styles, that we plead, and call upon those who have to deal with them, to put Protection in the place of Restoration, to stave off decay by daily care, to prop a perilous wall or mend a leaky roof by such means as are obviously meant for support or covering, and show no pretence of other art, and otherwise to resist all tampering with either the fabric or ornament of the building as it stands" (Morris 1877)*

This corresponds to the manifesto of The Society for the Protection of Ancient Buildings (SPAB) written by W. Morris in 1877. This vision regarding the major losses that highly invasive restorations were producing in the most important medieval buildings was shared with John Ruskin, author of the *"The seven lamps of architecture"* (1849). Both authors fought against those who pursued the *"beauty of appearance at expense of historic authenticity"* (Fawcett 2001) laying the foundations of future conservation principles. The 1999 ICOMOS charter established the principles for modern conservation of vernacular architecture and guidelines for practice. According to this charter:

> *"Adaptation and reuse of vernacular structures should be carried out in a manner which will respect the integrity of the structure, its character and form while being compatible with acceptable standards of living"* (ICOMOS 1999)

The built heritage represents cultural and historical values that need to be preserved. At the same time, our standards of living have suffered a great change since the construction of these structures (Martins & Carlos 2014) (Figure 2-8). Therefore, to ensure their conservation, traditional buildings need to be adapted to cope with the current expectations of users while contributing to the established carbon reduction targets (Nielsen et al. 2012).

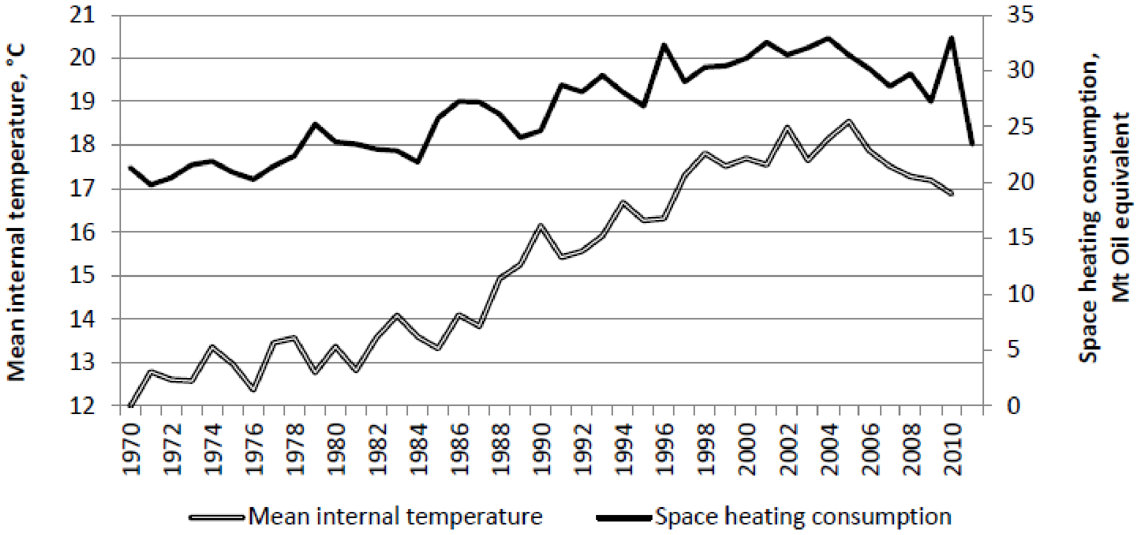


Figure 2-8 Relationship between increase in internal temperature, alongside increased energy consumption for space heating (DECC 2012)

The various Charters, Conventions and Recommendations developed by the ICOMOS have worked to create definitions that make it possible to communicate conservation work criteria "*simply, clearly and with the least opportunity of misunderstanding*" (Bell 1997).

- Adaptation means "*modifying a place to suit proposed compatible uses*" (Burra Charter 1.9, 1.10; New Zealand Charter 22)
- Compatible use means "a use which involves no change to the culturally significant fabric, changes which are substantially reversible, or changes which require a minimal impact" (Burra Charter 1.10)
- Preservation is the action taken to maintain "*the fabric of a place in its existing state*" and to retard deterioration (Burra Charter 1.6; New Zealand Charter 22)
- Rehabilitation is the "modification of a resource to contemporary functional standards which may involve adaption for new use" (Appleton Charter, B)

- Restoration means "returning the existing fabric of a place to a known earlier state by removing accretions or by reassembling existing components without the introduction of new material" (Burra Charter 1.7; New Zealand Charter 22)

The energy retrofit of traditional buildings would therefore be considered a rehabilitation since its purpose is to bring the performance of the buildings to contemporary standards. The particularities of this type of energy-led rehabilitation, however, have not been well-defined by ICOMOS yet. More importantly, up to now no international act has been proposed to address energy and energy retrofit in the field of Architectural Heritage conservation (Mazzarella 2014).

Historic Environment Scotland, as an executive agency of the Government, introduces and implements policy to safeguard and promote the historic environment (Ingram 2013). The 2011 revised version of the Scottish Historic Environment Policy (SHEP) is the most recent document summarising their position in regards to the management of the historic built stock (Historic Scotland 2011). Unlike the ICOMOS Charters, centred almost exclusively in the conservation of the heritage, the SHEP states that *"the protection of the historic environment is not about preventing change. Ministers believe that change in this dynamic environment should be managed intelligently and with understanding, to achieve the best outcome for the historic environment and for the people of Scotland."* As Roger Curtis stated, the position of Historic Environment Scotland regarding the built heritage has changed *"from one of preservation through cultural necessity, to one of accepting that they are good things to live in and with appropriate improvements have a significant role to play in a lower carbon future"* (Curtis 2010, p.26).

2.2 Improving traditional buildings energy efficiency

Energy consumption could be expressed as the result of the following equation (Hernández-Sánchez 2011) [1]:

$$Energy\ consumption = \frac{Energy\ demand}{System\ performance}$$

Equation 2.1 Energy consumption as a function of demand and performance

Consequently, a reduction in the energy consumption in buildings can be achieved by upgrading the systems that consume energy or modifying the factors that affect demand. The implementation of modern building services into historic structures was studied in great detail by Hillier (2004). In her research, different aspects of integrating new services (such as influence of the tenant, restriction on working hours or materials availability) were rated according to the frequency of occurrence and degree of difficulty. Moreover, the problems of integrating modern services in listed buildings were assessed based on the experiences of practitioners and three case studies. The thesis concludes by outlining a model that could be developed as a project framework for the implementation of modern services in historic buildings.

The use of electric radiant heating has been studied by Hubbard (2014) and Hobday (2011) as an alternative source of heat that can provide comfort while minimising the disruption caused to the original fabric and ensuring adequate rates of ventilation. However, the results showed that the running costs of such system could be prohibitive depending on the heating pattern of the occupants. In addition to that, this type of heating system has been found to produce important differences in the local skin temperature and that is a known cause of thermal discomfort (Arslanoglu & Yigit 2016).

The energy saving potential of zonal space heating controls was explored by Beizaee et al. (2015) in a non-retrofitted 1930s dwelling. The results of their work showed that the use of control systems like programmable room thermostat (PRT) or thermostatic radiator valves (TRV) could achieve a 2 % reduction in gas consumption for space heating in most regions of the UK. The use of zonal controls, however, reduced boiler efficiency by 2.4 points and required active engagement from the occupants.

In terms of mechanical ventilation with heat recovery (MVHR), a recent study (Banfill et al. 2012) determined that the air tightness of the envelope should achieve a permeability below 5 m^3/m^2 (@50Pa) to ensure a positive balance of energy consumption and CO_2 emissions. As noted by the authors, that level of air tightness can only be reached in traditional buildings with deep renovations of the envelope that would cause great disruption and are unlikely to be accepted by the occupants. Furthermore, STBA (May & Rye 2012) expressed their concern regarding the compatibility of MVHR equipment with traditional structures and the effect of users' understanding, in terms of the influence of ventilation on energy consumption and indoor air quality.

Both Changeworks (2009) and English Heritage (2008) published guidelines and recommendations for the implementation of renewable energy systems in traditional buildings. Depending on the availability of natural resources, these systems could provide space heating and domestic hot water (DHW) by means of solar thermal panels, heat pumps or biomass and generate electricity using solar photovoltaic panels, wind power, hydropower or combined heat and power. However, access to most of these resources within the urban environment might be difficult.

An alternative approach to the improvement of buildings' efficiency is to reduce heat losses in order to reduce the final energy demand of the building. This approach, often referred to as 'fabric-first' (Abdel-Wahab & Bennadji 2013), has also been extensively researched.

One of the main factors affecting heat loss in buildings is the envelope's air tightness. The high rate of uncontrolled air leakage makes traditional buildings more difficult to heat than modern buildings where the optimal levels of ventilation are adjusted with both passive and mechanical systems. Air tightness can be improved by draught proofing doors and windows, sealing chimney flues or insulating walls and roof with air-tight materials (English Heritage 2010b). Draught-proofing an original timber sash and case can achieve an 85 % reduction in the permeability of the window, achieving results that are comparable to current standards (Wood et al. 2009). The insulation of walls has shown very different results. Snow (2012) reported a 37 % reduction in the permeability of a traditional stone cottage after the retrofit whereas Rye & Hubbard (2011) monitored a reduction of 23 % in a retrofitted end-terrace brick house and only 4 % reduction in a renovated semi-detached cob cottage.

The performance of windows and doors can also be improved by replacing them (with the inherent change to the building's character) or by adding secondary glazing, shutters, blinds or insulating panels. The improvement of these features has already been explored by Baker (2010b), Wood et al. (2009), Currie et al. (2014) and Baker (2010a). Studies conducted on behalf of English Heritage (Wood et al. 2009) and Historic Environment Scotland (Baker 2010b) found that shutters are the most effective traditional method of improving timber sash windows. Shutters achieved results that are comparable to the use of insulating blinds or low emissivity secondary glazing with a U-value reduction of around 55 %. Heavy curtains and roller blinds would achieve a U-value reduction of 40 %. Replacement of the original single glazed panes with slim double glaze has been successfully tested by (Baker 2010a) and (Heath et al. 2010). The measured U-value of the improved panes ranged from 1.0 to 2.8 W/m^{2}K, a considerable reduction when compared with the 5.4 W/m^{2}K of the original single panes. The windows fitted with vacuum double glazing obtained the best results. Durability of slim-profile panes was also investigated

(Heath & Baker 2013). The re-measurements of double glazed panes two years after their installation showed some deterioration in the performance of units filled with gas (especially in the case filled with xenon-krypton) whereas the cases filled with air, or the vacuum units did not show any clear sign of deterioration.

Insulation in ground floors or roofs depends on the construction typology. In houses with a ventilated roof space, insulation can be placed at ceiling level (Changeworks 2008). In buildings where rooms are provided within the roof space, insulation should be placed between the rafters (Baker 2011; Currie et al. 2013). Suspended timber floors allow for the installation of insulation between the timber joists, while solid slab floors require lifting the original finishes and excavating to a new level (Currie et al. 2013). However, the performance of traditional floors and roofs is not fully understood yet and therefore the effect of insulating them cannot be truly predicted (May & Rye 2012). A doctoral research project is currently looking at the thermal performance of pre-1919 suspended timber ground floors, the opportunities for insulation and the potential consequences (Pelsmakers 2015).

Building efficiency can also be improved by minimising heat lost through external walls. Walls are the main source of heat loss in traditional buildings (Energy Saving Trust 2016) as they usually are the larger area in contact with the external environment. However, inspired by Edinburgh's New Town from the 1760s, street facades of Scottish towns were usually built using ashlar masonry (Mcmillan et al. 2006) and therefore external insulation would be inappropriate (Urquhart 2007). Internal wall insulation (IWI) is therefore the only feasible option for the insulation of solid walls in most cases. The feasibility of its implementation would depend on existing finishes and available floor space (Currie et al. 2013). The opportunities of internal insulation, as well as the existing research on the subject, are discussed in more detail in the next section.

2.2.1 Internal Wall Insulation

The type of insulation and the final assembly of the wall have an important impact on the final performance of internally insulated walls. Accordingly, Hendrickx et al. (2013) (based on the work of Roels and Vereecken *"Innovatieve materialen en technieken in de monumentenzorg"*) classified the available systems for internal insulation in two groups:

- Systems using vapour-tight materials or a vapour control layer (VCL) on the inside and finished with a gypsum board.

- Systems with porous materials that allow buffer and transport of water vapour and are either glued to the wall or fixed with screws or staples.

The Historic Environment Scotland Technical Paper 19 reports the application of different permeable insulation materials in 10 traditional buildings (Currie et al. 2013). A wall insulated with an aerogel blanket applied directly to the internal lining achieved a reduction in the U-value of 0.7 W/m^{2}K, similar to the results obtained with blown cellulose applied directly to the wall after removing the original lining. The walls treated with calcium-silicate boards 'on the hard' achieved an average reduction of 1 W/m^{2}K and those walls insulated with wood-fibre boards improved by 1.7 W/m^{2}K.

Walker & Pavía (2015) undertook a thermal performance assessment of several insulation materials on a historic brick wall with a measured U-value of 1.3 w/m^{2}K. Of the permeable materials tested, aerogel had the best thermal performance with a U-value reduction of 0.8 W/m^{2}K. Timber board, cork lime, hemp lime and calcium silicate boards reduced the wall U-values by 0.72, 0.59, 0.49, 0.45 W/m^{2}K respectively. The only material that did not produce any improvement on the wall was the thermal paint. It should be noted, however, that all the materials, with the exception of the cork lime, achieved worse in-situ results than those specified by the manufacturers.

Bianco et al. (2014) investigated the feasibility of using a thermal, "vegetal based", insulating plaster as a solution for the thermal retrofit of historic buildings. The solution offered a good compromise between energy savings and conservation of the original fabric as it was easy to install and reversible, it presented good hygrothermal behaviour and very low embodied energy. The application of a 60 mm thick layer led to a reduction in the heat loss of around 30% (from 0.8 to 0.56 W/m^{2}K). A different insulating plaster based on the use of aerogel was investigated by Buratti et al. (2016). Their research aimed to overcome the mechanical and economic limitations associated with the conventional use of aerogel. The application of a 15 mm thick layer on a stone wall achieved a reduction in the U-value of 19 % (from 2.14 to 1.73 W/m^{2}K)

Despite being a common form of internal insulation (Little et al. 2015), not many examples of vapour tight materials application on traditional buildings have been found in the literature. The application of phenolic rigid boards on a sandstone wall in North Lancashire reduced the measured U-value of the wall from 1.27 to 0.48 W/m^{2}K (Bros-Williamson 2013). Rye et al. (2012) applied 100 mm of polyisocyanurate (PIR) on a granite barn built in the nineteenth century and measured a reduction of the fabric's U-value of 87 %, from 1.24 to 0.16 W/m^{2}K.

The use of vacuum insulation panels (VIPs) for the internal insulation of historical brick walls was investigated by Johansson et al. (2014). VIPs require less thickness than most of the other insulating materials to achieve the same U-value and therefore would be appropriate for internal retrofits, as they would minimise the loss of floor space. However, the simulation results showed that despite a reduction in the U-value of the wall (20 mm VIPs reduced the U-value by 84-92 % compared to the wall without VIPs), thermal bridges created by the wooden joist ends increased the overall U-value of the wall.

An intermediate solution between vapour-tight and permeable materials was investigated by Klõšeiko et al. (2014). As part of their field experimentation, they monitored the performance of a polyurethane board with capillary-active channels (IT-t) that combined low thermal conductivity and certain capillary activity. The results of this solution were comparable to those obtained with a PIR board despite the different thickness applied (50 mm versus 30 mm).

Figure 2-9 PUR foam application, (left) cavity injection (Historic Scotland 2015) and (right) foam at the eave level (courtesy of Dr Bennadji)

The implementation of internal insulation has some evident weaknesses including difficulty of installation, disruption for the occupants, upfront costs and loss of floor space and original features (Gilbertson et al. 2006; Abdel-Wahab & Bennadji 2013; Mallaband et al. 2012; Achtnicht & Madlener 2014). Insulation materials pumped into the cavity formed between the solid wall and the lath and plaster offers a compromise solution. 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 disruption caused to the occupants.

Several experiments carried out in 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:

- polyurethane (PUR) foam (Abdel-Wahab & Bennadji 2013; Historic Scotland 2015) (Figure 2-9),
- polystyrene (EPS) beads (Jack & Dudley 2012; Jenkins 2012a; Jenkins 2012b; Jenkins 2012c; Changeworks 2012),
- cellulose (Curtis 2012; Jenkins 2012c),
- aerogel (Curtis 2012),
- perlite (Snow 2012) or
- mineral wool (Changeworks 2013).

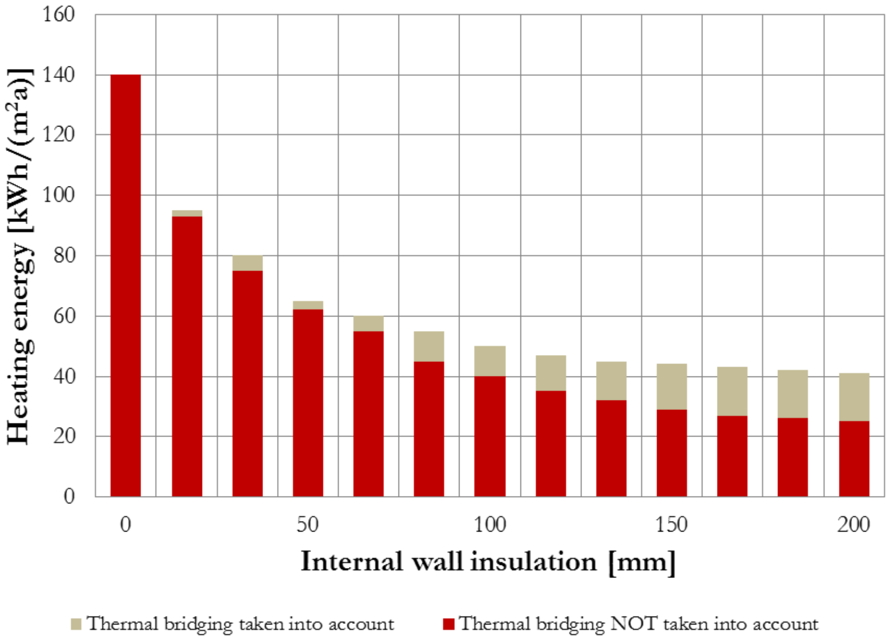


Figure 2-10 Insulation optimal thickness. Adapted from Little (2011)

Although it is difficult to make an estimation of energy savings, previous investigations have shown that it is feasible to reduce heat loss by more than half, depending on the material and thickness of the cavity (Abdel-Wahab & Bennadji 2013; Currie et al. 2013; Historic Scotland 2015). However, the level of uncertainty regarding the consequences of blocking air circulation within the cavity is still fairly high (May & Rye 2012). The pitfalls of internal insulation of solid walls were summarised by Hendrickx et al. (2013) as part of an assessment of the retrofit options for a former veterinary school in Belgium. According to Hendrickx et al., from a hygrothermal point of view the main drawbacks are:

- creation of thermal bridges in the connections of structural elements (Figure 2-10),
- risk of interstitial condensation due to vapour diffusion,
- risk of frost damage in the masonry due to a reduction in its temperature and
- risk of overheating due to the loss of thermal mass.

2.2.2 The unintended consequences of unsuitable retrofits

As stated by Shrubsole et al. (2014), mass implementation of energy efficiency measures *"will likely lead to a wide range of unintended consequences"* (p.340). Due to the complex nature of refurbishment projects, the effect of retrofit measures on building physics requires the evaluation of numerous factors (Hashemi et al. 2014). As acknowledged by the Scottish Government in its Technical Handbook, when applying measures like thermal insulation it is also necessary to consider heating and ventilation conditions as neglecting one of these factors may lead to undesired scenarios with greater energy use, higher risk of condensation and poorer indoor environments. This is a cause of concern in any retrofit project, but it is especially important in traditional stock due to potential disastrous consequences (May & Rye 2012).

Throughout the literature, continuous references to possible undesired consequences have been found. Agbota (2014), for instance, reviewed the unintended consequences that the policies of decarbonisation might have on the historic built environment of the UK. In his conclusions, Agbota pointed out that there is almost no anticipation of the consequences of policies on built heritage and stressed the need of interdisciplinary research to minimise negative impacts and optimise the potential of the renovations.

Figure 2-11 (left) Discarded original timber sash and case windows (Source: Historic Environment Scotland); (right) Condensation as a result of poor insulation and inadequate heating (Brosnan 2012)

The risks identified in the literature referred mainly to two categories: the conservation of the heritage and the health and well-being of the occupants. Since traditional buildings form a valuable asset for the Scottish culture and economy (HEACS 2009), it is crucial that thermal retrofits ensure the preservation of the built heritage. The most common risks for the preservation of traditional buildings are:

- changes in the external appearance, because of the poor selection of insulation, windows, etc. (Rodwell 2016);
- loss of original features due to the application of internal insulation or the substitution of original windows, doors, etc. (Figure 2-11 left);
- fabric decay due to interstitial condensation in walls, floor or roof (Godwin 2011) (Figure 2-11 right) or
- damage to original materials and features due to changes in the indoor temperature and humidity (Figure 2-12)

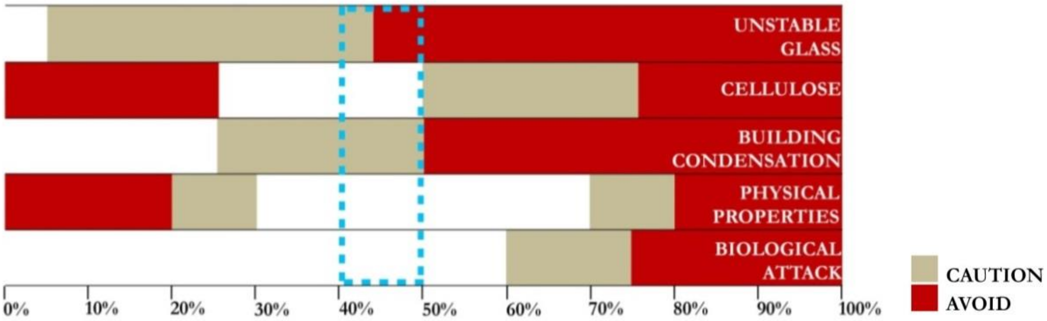


Figure 2-12 Relative humidity stability zones. Adapted from: Erhardt & Mecklenburg (2013)

Energy efficient interventions can lead to significant improvements in the health of the residents (Maidment et al. 2014), however, the existing research on the actual indoor environmental quality in highly energy-efficient buildings is still very limited (Hobday 2011). The World Health Organisation links the presence of many biological agents in the indoor environment with the presence of dampness and inadequate ventilation (Afshari et al. 2009). Risks for the health of the occupants can be classified in two different groups according to their cause:

- Relative humidity. Very high (or low) levels of internal humidity could lead to increased risk of respiratory diseases and asthma (Figure 2-13).

- Allergens and pollutants. Proliferation of dust mite allergens, other known allergens like formaldehyde or pollutants such as radon, lead, CO or NOx might endanger occupants' wellbeing (Halliday 2009, Kontonasiou, Lugg, Ucci et al 2011).

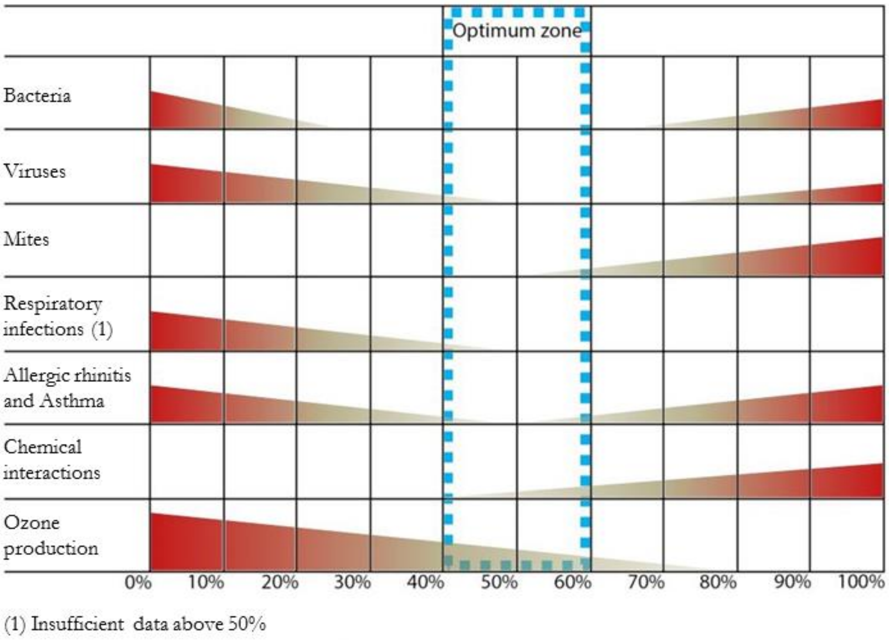


Figure 2-13 Optimum relative humidity ranges for health. Adapted from Sterling (1985)

2.3 Moisture transport in building envelopes

2.3.1 Moisture transport theory

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). A brief description of the main aspects of moisture transport theory relevant to this research, based on the work of Künzel (1995) and Peuhkuri (2003), is presented below.

Moisture content of building materials can be in the form of gas, liquid or solid depending on the boundary conditions. Since the ratio of each of these individual states is difficult to measure and it is constantly changing, it is more common to refer to the total moisture content of materials.

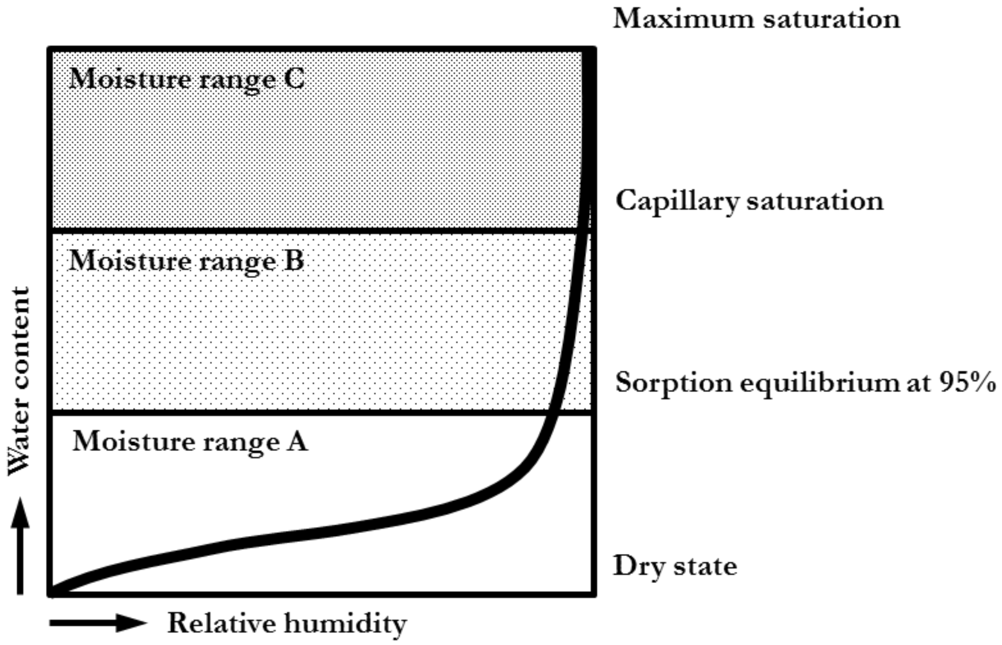


Figure 2-14 Schematic diagram of the moisture storage function of a hygroscopic capillary active building material. Adapted from Künzel (1995)

Relative humidity is the main environmental parameter defining the moisture storage of capillary-active materials (those that absorb moisture when in contact with water). The moisture storage function, represented in Figure 2-14, describes the relationship between moisture content and the relative humidity of materials. Künzell divided this function in three regions: hygroscopic, capillary water and supersaturated regions. The first region ranges from a dry state to the moisture content of a material at equilibrium with ambient air with a relative humidity of 95 %. In the second region, the moisture content increases until reaching the free water or capillary saturation. That is, the equilibrium moisture of a material in contact with water. The supersaturated region is therefore the only one with no equilibrium states.

Only hygroscopic materials, which are the majority of building materials, present the three regions. In non-hygroscopic and non-capillary-active (hydrophobic) materials (like most of the synthetic insulating materials) only the supersaturated region occurs. Those materials will only store moisture in liquid form. The effect of temperature in the first two regions is negligible and therefore the ability of materials to store hygroscopic moisture is described by means of sorption isotherms (Figure 2-15). The difference between sorption (moisture uptake) and desorption (moisture release) is referred to as the hysteresis effect and also varies between materials.

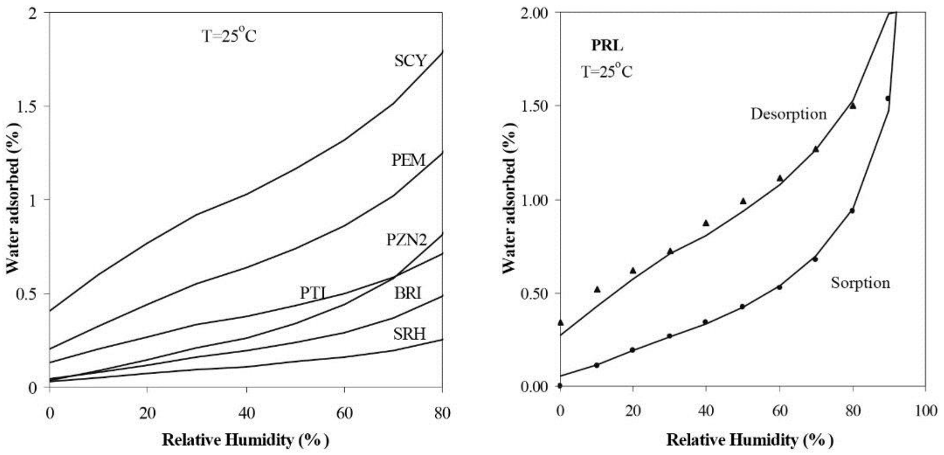


Figure 2-15 (left) sorption isotherm of building materials and (right) sorption and desorption isotherms of plaster (Moropoulou et al. 2005)

In conventional moisture transport theory, the solid matrix is considered not active in the transport processes. Within the porous structure of materials, moisture can be transported by several mechanisms, either diffusive or convective. Diffusive mechanisms are dependent on the gradient of the driving force (vapour pressure, temperature or moisture content). Convective fluxes are, on the other hand, dependent on the medium where the flux occurs (e.g. air) and the density of the moisture transported. The transport fluxes can involve moisture as water vapour, liquid water or a combination of both (Figure 2-16). Ice, as a solid phase, is not considered in the moisture transport theories (Rode 1990). The main moisture processes that are considered in the calculation of building physics are vapour diffusion and liquid capillarity. These processes, and the intermediate stages, are illustrated in Figure 2-17.

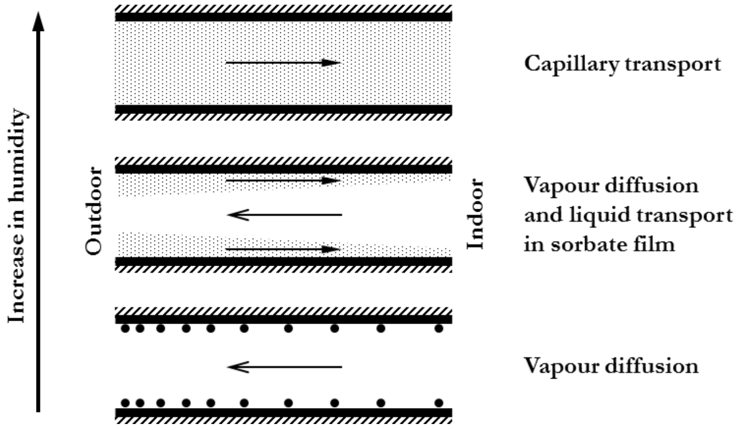


Figure 2-16 Moisture transport in capillary pores. Adapted from Künzel (1995)

The transport of water vapour is referred to as isothermal or non-isothermal depending on whether or not a temperature gradient is applied. In isothermal processes, the transport is regarded as the diffusion caused by the differences in water vapour mass and with the only limitation of the pore structure (Fick's diffusion) (Figure 2-17 stage 1). The diffusion on very low density materials can be therefore compared with diffusion in air. Non-isothermal diffusion based on temperature gradients (also called Soret effect) is often neglected in building physics applications. The main non-isothermal effect considered in most of the calculations is the dependence between temperature and saturation vapour pressure. A temperature gradient produces an increase in the permeability across the moist material.

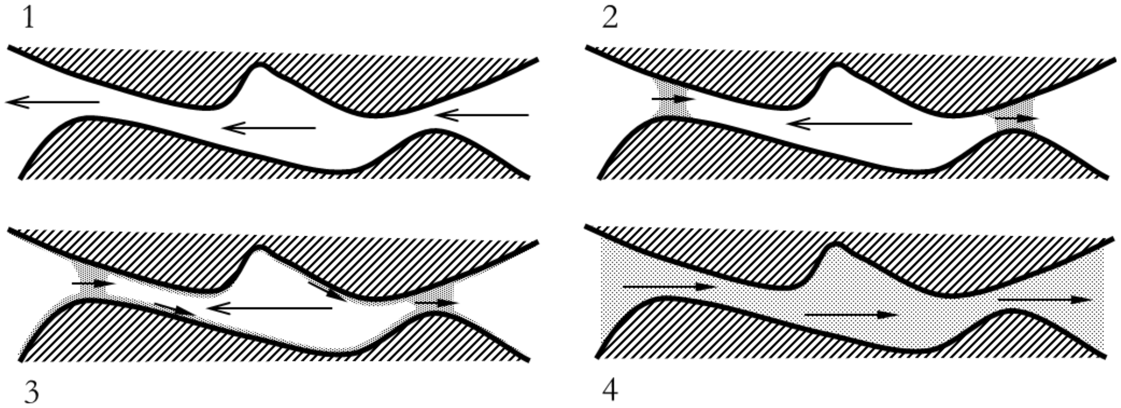


Figure 2-17 Different moisture transport processes at the microscopic pore scale, depending on the moisture content in pores. Stage 1 refers to low humidity, where therefore exists pure vapour diffusion. Stage 2 refers to series transport of vapour and liquid. Stage 3 refers partly to the series transport and partly to surface diffusion, also called vapour-liquid parallel transport. Stage 4 represents hydraulic flow for saturated media. Adapted from Peuhkuri (2003)

Liquid transfer starts with the existence of a continuous liquid phase (Figure 2-17 stage 3). From that point, the processes of water vapour transport decrease with the increase of the moisture content until reaching saturation. One of the main reasons for the separate study of liquid transport is the movement of soluble salts across the envelope (Nicolai 2013). Isothermal transport of liquid water was explained, using Darcy's law, as a flux density with suction pressure as the driving force. In non-isothermal transport, three temperature dependent mechanisms are considered: a change in the viscosity of the liquid, a transfer across the gradient from warm to cold and a relative humidity gradient that produces surface diffusion.

Pure vapour (stage 1) or liquid (stage 4) transport of moisture are rarely found under normal conditions. The intermediate scenarios (stages 2 and 3) are more often the case of moisture transport in building envelopes. Surface diffusion in sandstone, for instance, starts at 60 % relative humidity (Künzel 1995). The presence of islands of water in the pore structure produces cells of air in which condensation occurs inducing a transport of moisture across the wall following the temperature gradient. In scenarios with higher moisture content, but not enough to reach saturation, a sorbate layer of water can appear on the pore's wall. In that case, the transport of moisture would be a combination of vapour diffusion and liquid transport driven by the relative humidity.

2.3.2 Hygrothermal performance of building envelopes

The increased understanding of moisture transport in materials has led to more accurate evaluations of all the moisture related damages (mould, mildew, rot, frost, salt attack, corrosion, cracks, swelling, etc.) that can cause a failure of the service life and durability of building envelopes (Hens 2014). Failure has been defined as the *"termination of the ability of an item to perform a specified function"* (Viitanen & Salonvaara 2001, p.66). Since building envelopes provide several functions (structural, climatic and aesthetical), their performance also depends on several factors. The parameter that is evaluated to determine the performance of an envelope changes with the *"type of failure"* studied (physical, chemical or biological processes) (Viitanen & Salonvaara 2001).

The risk of interstitial condensation of water vapour is probably the main aspect evaluated in any hygrothermal assessment of building enclosures (Browne 2012). In fact, the standard BS EN ISO 13788:2012 (ISO 2012) focuses primarily on this phenomenon for the analysis of the envelope. Condensation is the result of vapour diffusion through the wall and therefore the moisture generated by the occupants' activity is a crucial parameter for its formation as it determines the internal vapour pressure. As illustrated by Padfield (1998), from a hygrothermal point of view, people are merely sources of water (Figure 2-18). The internal air temperature is also important because warmer air implies higher vapour pressure at the same relative humidity (Figure 2-19). Moreover, high temperature gradients create stack pressure differences that contribute to greater migration of moist air through the permeable materials (Sanders 2014).

Figure 2-18 Humans, from the point of view of building physics, are merely sources of water (Padfield 1998).

Analysing the annual moisture balance of the wall has been suggested by authors like Künzel & Holm (2009) or Kaufmann et al. (2006) to detect any sign of moisture accumulation that may indicate an inadequate assembly. Analysis of moisture balance also allows for the determination of the time needed to reach the equilibrium in the wall (Browne 2012). The aim is to design an envelope that not only does not accumulate moisture but also has a high drying potential in order to keep the construction dry in case of any accidental water ingress (Häkkinen 2012). Besides the risk for durability, the accumulation of moisture can be detrimental to the final performance of the envelope. Higher levels of moisture lead to an increase in the thermal conductivity of the insulation and as a consequence to greater heat losses (Klõšeiko et al. 2014; Ramos et al. 2010; Bishara et al. 2015; Häkkinen 2012).

Time of wetness (TOW) is a concept used frequently in the hygrothermal assessment of buildings to refer to the transient evolution of moisture damages (Al-Neshawy et al. 2010; Häkkinen 2012; Bjarløv et al. 2015; dos Santos et al. 2009). TOW can be defined as the interval of time when both relative humidity and temperature are above their respective critical values (RH_{crit} and T_{crit}). The critical values of temperature and humidity vary depending on the mechanism studied. The degree of damage due to any of the four main types of degradation of building materials (corrosion, swelling, subflorescence and biological damage) is directly proportional to the TOW (Mukhopadhyaya et al. 2006).

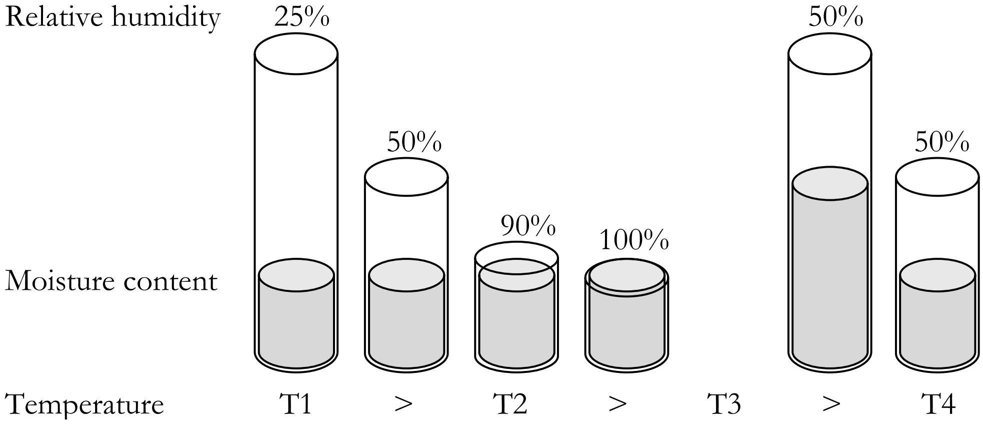


Figure 2-19 Figurative representation of temperature and humidity interaction. Adapted from (Neila González & Bedoya Frutos 1997)

The risk of biological damage is a crucial aspect in the assessment of insulated walls and can be found in numerous recent studies (Morelli & Svendsen 2012; Klõšeiko et al. 2014; Mukhopadhyaya et al. 2006; Haldi 2015; Johansson & Sc 2011; Bjarløv et al. 2015; Häupl 2004; Abdul-Hamid et al. 2015; Altamirano-Medina et al. 2009). Minimising mould growth is important to *"ensure a healthy environment and to avoid social and economical damage"* (Vereecken & Roels 2012). In theory, *"the absence of air in a perfect construction technically means that mould growth is not possible"* (Browne 2012, p.58). However, the application of foams, fibre or beams within the narrow cavity between the lath and plaster and the masonry will most certainly produce *"thin air spaces left between layers"* (Hens 2014, p.147). This phenomenon can be seen in Figure 2-20, as well as in other examples of internal insulation found in the literature (Jack & Dudley 2012; Jenkins 2012b; Grot & Chang 1983).

Figure 2-20 Trial application of PUR foam in a narrow cavity (Courtesy of Kishorn Insulation)

Evolution of the mould growth intensity (Figure 2-21) is calculated to identify whether it accumulates or declines over time. Viitanen (2011) developed the concept of *"Mould Index"* (MI) (Table 2-4) to evaluate the evolution of mould growth in building components. Moon & Augenbroe (2008) proposed the use of a mould risk indicator (MRI) to minimise the uncertainties related to building parameters and help decision makers in the remediation of mould growth.

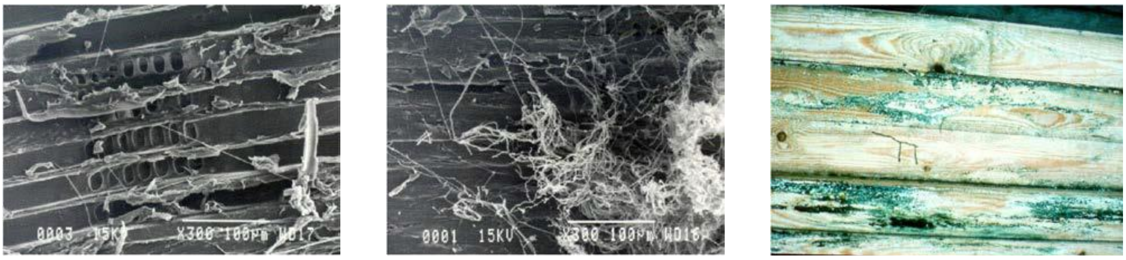


Figure 2-21 Illustration of the different levels of mould growth. From Häkkinen (2012)

Table 2-4 Mould Index. Adapted from Viitanen (2011)

Index	Description of the growth rate
0	No growth
1	Small amounts of mould on surface (microscope), initial stages of local growth
2	Several local mould growth colonies on surface (microscope)
3	Visual findings of mould on surface, <10% coverage, or <50% coverage of mould (microscope)
4	Visual findings of mould on surface, 10-50% coverage, or >50% coverage of mould (microscope)
5	Plenty of mould growth on surface, >50% coverage (visual)
6	Heavy and tight growth, coverage about 100%

Beyond the growth of mould, high levels of moisture can eventually lead to the decay of wooden elements. Decay must be considered in any assessment of the durability of structures as it reduces the load bearing capacity of timber dramatically (Foliente et al. 2002). In fact, Häglund (2008) proposed considering the variation in moisture conditions along with other ordinary loads when dimensioning timber elements. The risk of wood decay has been frequently analysed (e.g. Morelli & Svendsen 2012) by looking at the moisture content (MC) of the material. If a threshold of 20% MC was not reached, the assembly was said to be safe. However, laboratory tests have proven that this simplistic approach is not suitable for reliable assessments (Kehl et al. 2013). Based on a detailed model elaborated by Viitanen et al. (2010), Kehl et al. proposed a simplified wood decay model with a relative humidity threshold dependent on the temperature (Equation 2.2).

$$RH_{crit} = 95 - 0.3 \times T$$

Equation 2.2 Wood decay model (Kehl et al. 2013)

Another common form of biological damage found in retrofitted envelopes is the growth of algae on exterior surfaces (Häkkinen 2012). Nevertheless, this type of biological growth is mainly aesthetic and does not have any effect on the durability of the materials. Insulation of the envelope might increase the risk of superficial condensation on the façade at night due to the temperature gradient reduction across the wall. That would increase the risk of biological development since the algae needs liquid water to grow. Moreover, temperature reduction of the external surface can also lead to frost damage (Figure 2-22) in porous stones or weathered blocks (Urquhart & Young 1998) that can quickly degrade the original masonry wall (Häkkinen 2012).

Figure 2-22 View of stone masonry deterioration from freezethaw following the installation of thermal insulation on the building interior (Carpenter et al. 2010)

2.3.3 Monitoring moisture transport in retrofitted envelopes

In the last few years, several studies have used test walls (either in climatic chambers or in existing buildings) to monitor the effect of internal insulation on solid walls. Additionally, monitoring was also carried out in un-refurbished buildings to evaluate its feasibility prior to the intervention. Kramer et al. (2010), for instance, carried out long term monitoring of non-insulated sandstone walls in an historic building in Washington. The results of this monitoring showed that winter rains kept the porous stone wet during the entire season and that drying only started to occur in spring. In the UK, Marincioni & Altamirano-Medina (2014) carried out a field study to monitor the effect of the external climate on walls with high values of water absorption. The results registered in a 16th century building insulated with wood fibre boards showed that direct solar radiation (especially on the South elevation) accelerated the wall drying process significantly.

The effect of wetting processes on walls after their insulation has been monitored in climatic chambers by Guizzardi et al. (2015) and Johansson, Hagentoft, et al. (2014). Guizzardi et al. monitored the performance of historic brick walls after the application of a new insulating render whereas Johansson et al. monitored the effect of VIPs as internal insulation. In both cases, walls were exposed to controlled driving rain. Both experiments registered high levels of relative humidity at the interface between insulation and masonry, proving the dependence of porous constructions on the external climate. In Johansson's study, the final drying capacity of the wall to the interior was seriously compromised by the VIPs. Additionally, Johansson evaluated the effect of insulation on the joists embedded in the wall and found that the higher relative humidity of the bricks around the joist led to higher moisture contents in the joists ends. Harrestrup & Svendsen (2015) also investigated the effect of insulation on the joist ends but they used a renovated building in Copenhagen as a case study. In this case, the insulation was interrupted 200 mm above the floor level to minimise the risk of moisture accumulation in the joist. Monitoring results did not show any moisture related risk in the wall and the reduction in the total heat saving was only 3 kWh/m^2 lower than with a fully insulated wall.

The drying potential of insulated walls was investigated by Alev et al. (2015). They monitored the performance of a test log house in Estonia to assess the effect of different construction details and materials. The results of their study highlighted the importance of allowing the materials to dry out to prevent the formation of mould in the wall. The assemblies with VCL could not dry the initial moisture content to the inside and reached relative humidity values above 80 % for more than six months whereas the permeable construction was around 10 % lower despite the higher levels of initial moisture. Klõšeiko et al. (2014) also monitored different materials for internal insulation in Estonia but in this case they used the masonry walls of a historic school building as a case study. The rooms were controlled to simulate the conditions of moisture and temperature of dwellings with high humidity loads. The results of the different materials showed the effect of the built-in moisture and the risk of mould growth in the interface between the masonry and the insulation in walls that were not able to dry.

To evaluate the moisture buffering potential of materials, Lewis (2010) built two identical test cells and compared the performance of hemp-lime mortar and conventional dry-lining insulation systems. The results revealed that hemp-lime buffered peaks of relative humidity showing that hygroscopic materials can minimise the risk of interstitial condensation in insulated walls.

2.3.4 Numerical simulation of moisture transport in building envelopes

Although monitoring of physical structures provides accurate and reliable data, the exploration of scenarios is limited by the time consuming nature of the process and the availability of resources. Thus, as stated by Künzel & Holm (2009) *"while monitoring will only provide the current status, hygrothermal simulations can also predict what will happen when the construction is altered or the indoor climate changed"* (p. 85). For that reason, the use of numerical simulation is becoming increasingly popular in studies related to the assessment of internal insulation of fragile structures.

As summarised by Hens (2014), hygrothermal calculations go back to the 1930's but it was not until the publication of Glaser's work in the 1950's that the evaluation of moisture transfer processes achieved enough accuracy. The later development of computing capabilities allowed for the evaluation of transient calculations and more recently for the calculation of two and three dimensional models. Nowadays the protocol proposed in BS EN 15026:2012 (CEN 2007) for the transient calculation of the coupled effects of heat, air and moisture is applied in the great majority of research studies looking at the hygrothermal performance of building components. The software packages generally used for these calculations have been thoroughly validated by the developers (The Fraunhofer Institute for Building Physics 2016; Institut für Bauklimatik 2016) and in independent studies (Marincioni et al. 2014; Kramer et al. 2010; Häupl 2004; Stopp et al. 2001).

The use of numerical calculation software allows for the simulation of many different scenarios. For instance, Huijbregts et al. (2012) made use of numerical simulation to explore the impact that shifting climates zones in Europe due to a global climate change could have on historic buildings. However, and as pointed out by Carpenter et al. (2010), the assessment of building envelopes with simulation software also carries some risks if the model is not accurate enough. Carpenter et al. points out that one-dimensional models that do not consider air movement or changes in heterogeneous walls could lead to oversimplification and therefore to some important errors in the results. The feasibility of simplified models has to be analysed case by case. Vereecken & Roels (2013), for instance, studied the effect of mortar joints on the moisture fluxes of massive brick walls in Belgium.

They concluded that under real climate conditions, the impact of mortar was negligible and the wall could be simplified as a homogenous layer of brick. The importance of material characterisation has also been stressed by Browne (2012) who carried out a sensitivity analysis to compare the effect of different bricks and found that the choice of the brick was decisive in the peak content of water of a wall receiving wind driven rain (WDR).

The impact of the external boundary on internally insulated masonry walls has been investigated repeatedly. Mukhopadhyaya et al. (2006), Hanc et al. (2014) and Nielsen et al. (2012) simulated different scenarios to identify the most determining aspects of the external climate and concluded that the amount of solar radiation and WDR received by the wall was crucial for the performance of the envelope. Nielsen also included different assemblies of the wall to determine that the effect of VCL was negligible when compared with the external climate. However, the role of VCL has been the focus of numerous studies and the results are not conclusive. The results differed notably depending on the characteristics of the boundaries and the build-up of the wall. Thus, while the results obtained by Arumägi et al. (2015) and Morelli (2013) did not show any risk associated with the use of VCL, Browne (2012) emphasised the use of VCL as *"the most concerning variable"* since it could cause a complete failure of the envelope. Vereecken et al. (2015) only recommended the use of vapour tight assemblies in walls that are frost resistant and Labat & Woloszyn (2015) found that the performance of the wall improved with the use of vapour permeable materials.

Several studies have explored the performance of walls insulated with hygroscopic and capillary active materials as an alternative to the use of VCL and vapour tight constructions (Bishara & Plagge 2012; Hendrickx et al. 2013). The use of woodwool panels as a buffering material was tested by Ferreira et al. (2014). They found a reduction of the interior relative humidity oscillation of 26 %. In line with that study, Hall et al. (2013) highlighted the benefits of using materials with high buffering potential to control the internal climate of British dwellings without the use of mechanical systems that require additional energy consumption. However, and according to Bjarløv et al. (2015), the use of capillary active materials in masonry walls would only be feasible in cool temperate climates if the wall is protected against the WDR.

The effect of convection has been explored by Riesner et al. (2004) and Kehl et al. (2013). Riesner et al. found that natural convection could occur within the pore structure of the insulation pumped into a cavity increasing the risk of mould growth and condensation at the top cold edge of the cavity. Additionally, Kehl et al. highlighted the negative effect that the convection of air from the internal climate to the gaps around a joist end could have on the durability of the structure. The impact of the internal insulation on the joists embedded in masonry walls has also been studied by Morelli & Svendsen (2012), Harrestrup & Svendsen (2016) and Ueno (2012). These studies explored different approaches to increase the temperature of the joist end in order to reduce the risk of moisture accumulation. Morelli and Harrestrup opted in favour of leaving a gap between the floor level and the end of the insulation whereas Ueno found that the best solution to increase the temperature in smaller joists was the use of metal spreader plates.

As the development of thermal and hygrothermal simulation models run parallel, some studies have investigated the potential for its combined use in the assessment of retrofit options. Moon et al. (2014) explained the importance of hygrothermal assessments as part of retrofit evaluations pointing out that the final energy consumption of a residential building when considering the effect of moisture was 4.4 % higher than in exclusively thermal calculations. Holm et al. (2008) also used both models simultaneously to explore not only the performance of the wall but also the hygrothermal behaviour of the rooms. That raised new questions regarding the interaction between the envelope of traditional buildings and their indoor environment (Antretter et al. 2010). Some of these questions, as formulated by Künzel et al. (2005, p.554), are:

- *What happens to the building envelope when the indoor environment of a historic building is severely changed?*
- *How do different envelope components react to fluctuating indoor air conditions of buildings with temporary occupation?*
- *What humidity control strategies should be employed to preclude mould formation on the external and internal surfaces of the building envelope?*

2.3.5 Internal humidity models

The accuracy of any hygrothermal assessment will be ultimately dependent on the accuracy of the design criteria established in the first place. Therefore, the definition of the boundary conditions is as important as using the correct material properties (Holm et al. 2008; Steskens et al. 2009; Antretter et al. 2010).

Several models can be used to predict the interior humidity conditions of buildings (Cornick & Kumaran 2008). For instance, the model developed by the British Research Establishment (BRE) calculates the difference between moisture generation and loss rates. In addition to that, this detailed model includes a moisture admittance model to consider the absorption/desorption by interior finishes and furniture (Jones 1993).

Alternatively, the ASHRAE 160P (2008) model proposes three different levels of detail: simplified, intermediate and full parameter method (Cornick & Kumaran 2008). The simplified method describes internal relative humidity as a function of the 24-hour running average external temperature (Equation 2.3). Analogously, the internal temperature is related to the average external temperature and for external values below 18.3 °C the internal temperature is set to 21.1 °C. For external temperatures above 21.1 °C, the internal temperature is fixed to 23.9 °C. In between those values the internal temperature is 2.8 °C higher than the 24-hour running value (Antretter et al. 2010).

$$RH = \begin{cases} 40\% \; if \; T_{o,daily} \leq -10°C \\ 40\% + \left(T_{o,daily} + 10\right) if - 10°C < T_{o,daily} < 20°C \\ 70\% \; if \; T_{o,daily} \geq 20°C \end{cases}$$

Equation 2.3 ASHRAE 160P Internal relative humidity simplified model

The intermediate method, similar to the BRE model, proposes an indoor vapour pressure product of the external daily temperature, the moisture generation rate and the ventilation rate. The ventilation rates can be inferred from the air exchange rate whereas the value of moisture generation, in residential buildings, can be estimated based on the number of bedrooms. The full parametric evaluation requires the independent calculation of several parameters such as the initial moisture conditions, pressure data or rain loads.

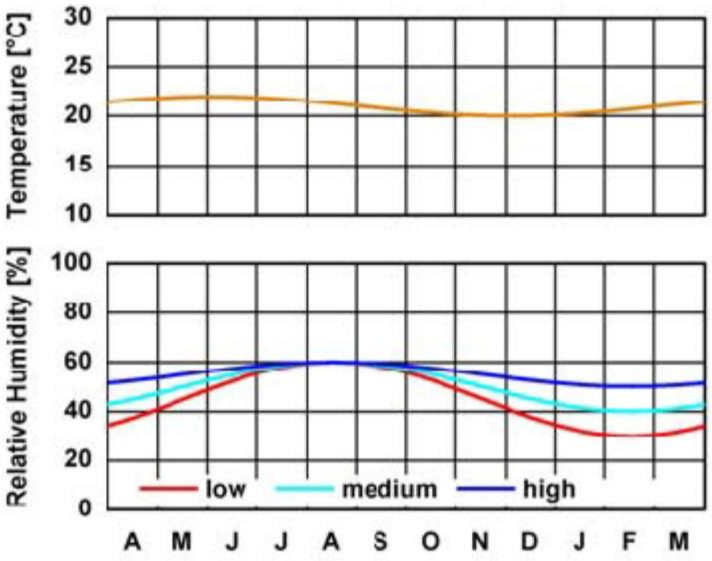


Figure 2-23 Transfer functions for indoor air temperature and relative humidity in dependence of the 24-hour variable average value of outdoor air temperature (Holm et al. 2008)

The German WTA-Directive 6-2-01 (Holm et al. 2008) proposes a simple model with sinusoidal annual curves to design the internal climate. While there is only one curve proposed for the definition of the internal temperature, the relative humidity can be chosen between three different categories: low, medium or high (Figure 2-23).

The models proposed by international standardisation bodies like the Comité Européen de Normalisation (CEN) or the International Standards Organisation (ISO) play an important role in the definition and assessment of the internal climate. Standards such as US ANSI/ASHRAE 55-2010 (ASHRAE 2010) or BS EN 15251:2007 (British Standard Institution 2007) establish some recommendations for the definition of the thermal environment, air quality or ventilation rates. Then, standards like BS EN 15026:2007 (CEN 2007) use those criteria as boundaries for the assessment of the hygrothermal performance of buildings. BS EN 15026:2007 is, as explained above, the governing international standard that sets the guidelines for numerical simulation of moisture dynamics. This standard recommends the use of measured data to define the internal boundary. However, where internal air conditions cannot be obtained, the standard proposes the use of a simplified approach to set the conditions of temperature and humidity as a function of the external air temperature (Figure 2-24). The standard considers two levels of expected occupancy (normal and high) when calculating the relative humidity values. No additional information about the selection criteria for the level of occupancy is provided.

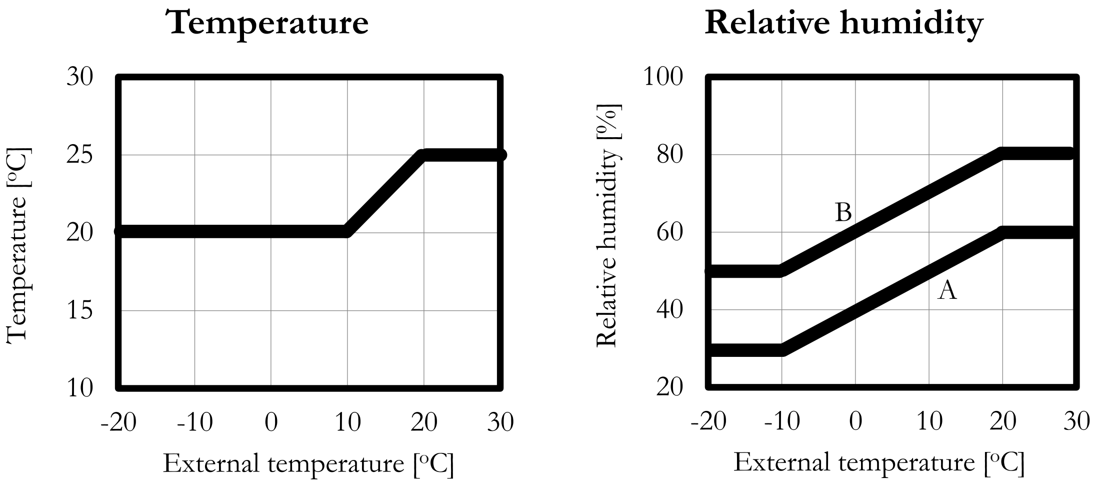


Figure 2-24 Internal boundary conditions as proposed in BS EN 15026:2007. Daily mean internal air temperature (a) and relative humidity (b) (A: normal occupancy, B: high occupancy) in dwellings and office buildings depending on the daily mean external air temperature.

The other international standard concerning hygrothermal performance of buildings is BS EN ISO 13788:2012. This standard, however, limits the use of the previous charts of temperature and relative humidity to continental and tropical climates and proposes the use of internal humidity load classes for maritime climates (Figure 2-25). The standard identifies five different classes, assigning Class 2 to residential buildings. The classes are represented in a chart with the upper limit values of internal moisture excess or vapour pressure excess for each class. The limits are, again, function of the external temperature.

The criteria used for the design of internal environment are based on comfort indices such as ‘predicted mean vote’ or ‘predicted percentage of dissatisfied’ - BS EN 15251:2007 and BS EN ISO 7730:2005 (ISO 2005) - or derived from measured data - BS 5250-2011 (British Standard Institution 2011) -. However, previous studies have shown important disparities between predicted and actual conditions of internal environment. Holm et al. (2005), Kalamees et al. (2005), Antretter et al. (2010), Hens (1992) and Rodríguez-Suarez et al. (2004) have carried out extensive research in countries like Germany, Estonia, Finland, USA, Belgium and Spain to verify the extent to which the boundaries proposed in the standard were representative of their specific contexts.

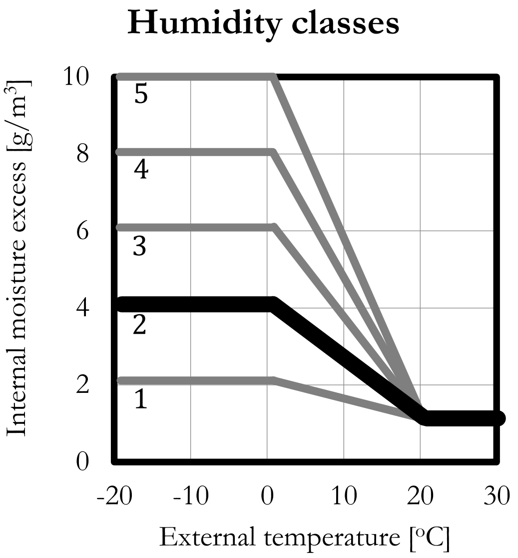


Figure 2-25 Internal boundary conditions for maritime climates as proposed in BS EN ISO 13788:2012. Variation of internal humidity classes with external temperature. 1: Unoccupied buildings, storage of dry goods; 2: Offices, dwellings with normal occupancy and ventilation; 3: Buildings with unknown occupancy; 4: Sports halls, kitchens, canteens; 5: Special buildings, e.g. laundry, brewery, swimming pool.

In the Scottish context, no study focused on the full characterisation of the internal climate of traditional buildings has been found. However, previous studies carried out in the UK revealed important discrepancies on the internal temperature of residential buildings when compared with the standards. A review of several monitoring projects carried out by BRE showed that the average temperature of residential buildings in the UK was 16.5 °C, far from the minimum values established in the standards (20 °C) (Milne & Boardman 2000). Similar values were obtained in other studies carried out in the 1980's (Hunt & Gidman 1982) or more recently by Hong et al. (2009), Lomas & Kane (2013) and Huebner et al. (2010). In addition to that, Hunt & Gidman (1982) found a relationship between the age of the dwellings and the internal temperature. Homes built before 1914 were around 3 °C cooler than those built after 1970. Besides, as pointed by Huebner et al. (2010), although the models assume *"rigid heating patterns"* the results of the studies showed a great variability between households.

The relevance of users in shaping the internal boundary and therefore the performance of insulated walls is well known (Janssens & Hens 2003; Künzel & Holm 2009; Holm et al. 2008; Haldi 2015). As stated by Nielsen et al. (2012), the final outcome of similar refurbishment methods can be completely different because of the differences in the indoor climate caused by the habits of the occupants. However, due to the difficulty in obtaining and modelling this information, the internal climate has often been neglected and extremely simplified in the past. Currently, the relevance of the effect of user behaviour on the actual performance of retrofit projects is increasing and an emerging body of research is being developed. As stated in the final report of the IEA Annex 41 - Whole Building Heat, Air and Moisture Response (MOIST-EN):

> *"For whole building HAM analyses, it is important to understand how people use and heat their houses for acceptable thermal comfort" (Kumaran & Sanders 2008, p.23)*

2.4 User behaviour & internal climate

2.4.1 User interaction with the building

The wide range of different indoor climates measured in previous studies proved a strong relationship between the internal boundary conditions and the occupants' behaviour. Within the internal boundary, several factors determining environmental conditions are directly related to the users' behaviour: hours of heating use, number of rooms heated, temperature settings, ventilation patterns or cooking and laundering habits.

Behavioural patterns are often studied in the context of energy consumption reduction and therefore the majority of the investigations are focused on identifying the driving factors for space heating demand. According to Wei et al. (2014), those factors can be classified as environmental, building and system related or occupant related. Some of the most relevant drivers identified in the literature are summarised in Table 2-5.

In addition to the exploration of the use of space heating systems, several studies have focused their investigations on the ventilation and moisture related patterns of the users. According to Andersen et al. (2009), the operation of windows is strongly related to the external temperature and the users' perception of the environment. In line with these results, Haldi & Robinson (2009) observed two different triggers for the users' interaction with windows. The opening actions of windows were related to the internal conditions whereas the closing actions were determined by the external conditions.

Table 2-5 Driving factors for occupants' heating behaviour (Wei et al. 2014)

Category	Driver	Effect	References
Environmental	External temperature	Dependence on external temperature in winter nights	(Newman & Day 1975; Pimbert S 1981)
	Internal Relative Humidity	Changes in the relative humidity lead to more frequent setting adjustment	(Taylor et al. 2013)
Building and system related	Building age	No effect	(Vine 1986)
		Older homes tend to be colder or use more energy	(Hunt & Gidman 1982; French et al. 2007; Guerra Santin et al. 2009; BRE 2005)
	Room type	Living rooms are heated up to higher temperature and for longer periods	(Hunt & Gidman 1982; Summerfield et al. 2007; Conner & Lucas 1990; Oreszczyn et al. 2006; French et al. 2007; Isaacs et al. 2010; Guerra Santin et al. 2009; Yohanis & Mondol 2010)
	Heating system	No clear correlation	(Hunt & Gidman 1982; Andersen et al. 2009; Kavgic et al. 2012)
	Level of insulation	Lower temperature in insulated buildings	(Verhallen & Raaij 1984; Love 2014)
		Higher temperatures in living room and bedroom when insulated	(Pimbert S 1981; Haas et al. 1998; Shipworth et al. 2010; Love 2014; Martin & Watson 2006)
User related	House ownership	No relationship	(Vine 1986; Milne & Boardman 2000; BRE 2005)
		Higher demand in rented housing	(Rehdanz 2007; Andersen 2009; DEFRA 2008)
	Household income	No relationship	(Vine 1986; French et al. 2007; Guerra-Santin & Itard 2010; Isaacs et al. 2010)
		Less energy spent for space heating in families with lower income	(Newman & Day 1975; Hunt & Gidman 1982; Day & Hitchings 2009; Weihl & Gladhart 1988; Vringer et al. 2007)
	Household size	Higher temperature in bigger households	(Conner & Lucas 1990; Oreszczyn et al. 2006; Weihl & Gladhart 1988; Sardianou 2008)
		No relationship	(Guerra-Santin & Itard 2010; Isaacs et al. 2010)
	Occupant age	Elderly demanded high temperature	(Parsons 2002; Guerra-Santin & Itard 2010; Day & Hitchings 2009; Guerra Santin et al. 2009; Oreszczyn et al. 2006; Weihl & Gladhart 1988; Sardianou 2008; Raaij & Verhallen 1983; Andersen 2009; Kane et al. 2010; Xu et al. 2009)
		Children demanded high temperature	(Weihl & Gladhart 1988; Raaij & Verhallen 1983; Xu et al. 2009)
		No clear relationship	(Kavgic et al. 2012; Vine 1986; Isaacs et al. 2010)

The review carried out by TenWolde & Pilon (2007) revealed that the moisture production patterns of occupants were independent of the levels of humidity in their homes. Moreover, the survey conducted by Rousseau et al. (2007) showed that households with higher occupancy did not necessary account for higher levels of internal humidity or moisture related problems. The implications of domestic laundering on energy consumption and indoor air quality of Scottish dwellings were investigated by Porteous et al. (2013). Prevalence of passive indoor drying caused an increase in the internal moisture levels and therefore an increase in dust mite and airborne mould spores concentrations. Besides identifying the drivers of user behaviour, it was also necessary to identify and investigate whether occupants' behaviour changes after the improvement of the envelope. Changes in the energy consumption have already been investigated in several studies (Milne & Boardman 2000; BRE 2005; Martin & Watson 2006; Hong 2010) 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 final energy use. In general, Pelenur (2013) found that a change in the building efficiency did not produce any clear change in the energy behaviour of the occupants. Both Weihl & Gladhart (1988) and Shipworth et al. (2010) identified higher set-point temperatures in energy efficient homes while Verhallen & Raaij (1984) found lower thermostat settings in dwellings with higher levels of insulation.

Existing research on the heating periods (number of hours of active heating) is still very limited. Martin & Watson (2006) monitored heating use before and after a refurbishment, however the results of these longitudinal studies have not been made available. Only Shipworth et al. (2010) and Love (2014) have published some data about the changes that occurred after the envelope improvement. These studies reported changes from small samples and acknowledged many limitations to the results. Love, for instance, found a reduction in the number of daily heated hours after the insulation due to the users' perception of the heat being retained longer in the dwelling after the heating was switched off. Regarding the number of rooms heated before and after the insulation, only qualitative data has been collected (Gilbertson et al. 2006). According to that 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 & Raaij 1984; Haas et al. 1998; Oreszczyn et al. 2006; Martin & Watson 2006; Hong 2010; Love 2014), however it is difficult to come to any valid conclusion as the variation in temperature differs greatly between studies. It is not possible to explain these results without considering sociological aspects such as the household size (Huebner et al. 2010), family income (Sardianou 2008), thermal sensation (Weihl & Gladhart 1988) or occupant age (Deutsch & Timpe 2010). It is necessary to highlight the study carried out by Critchley et al. (2007) to investigate persistent cold temperatures in retrofitted properties. In their study, pre-1930 buildings were the predominant type of homes that remained cold after the improvement.

The variation in the internal relative humidity was measured by Love (2013). According to these results, internal humidity decreased around 10-20 % after the insulation. Verhallen & Raaij (1984) also noticed changes in users' ventilation behaviours with more airing of rooms in highly insulated buildings but no record of humidity was provided.

All these studies had their focus on existing buildings, but, as acknowledged by May & Rye (2012, p.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".*

It is also important to emphasise the role that modelled behavioural profiles played in the study of users' effect on building performance. According to Verhallen & Raaij (1984, p.148), *"a segmentation approach based on behavioural patterns provides better insights in the interaction of energy behaviour, attitudes, house characteristics and sociodemographics".* This approach was also used by Love (2012), Fabi et al. (2012), Corgnati et al. (2014), Verhallen & Raaij (1984), Hashemi & Khatami (2015) in their respective studies. For instance, Corgnati et al. (2014) classified the users according to their patterns of window opening and heating set point as 'active', 'medium' or 'passive'. Thus, active users were those who interacted with the building most frequently by changing the heating thermostat and operating the windows. Passive users on the contrary are depicted as *"lazy operators"* and their behaviour was not triggered by their interest in saving energy but by a new cause of discomfort. A similar approach was chosen by Hashemi & Khatami (2015) to look specifically at drivers that affected energy performance, indoor air quality and risk of condensation in domestic properties. They found that occupants' lifestyles can be a major contributor affecting not only fabric's performance but also users' health and wellbeing. According to their results, households with *"wet"* occupancy conditions were at high risk of condensation independent of the air permeability of the envelope or trickle vents present in the dwelling.

2.4.2 Effect of user behaviour

The effect of user behaviour on the actual performance of retrofit projects was investigated by Shrubsole et al. (2014) as part of a systematic review of unintended consequences of policies designed to improve energy efficiency in UK housing stock. They found more than 100 unintended consequences affecting the building fabric, occupants' health and the environment. User behaviour was identified as one of the causes for these unexpected outcomes.

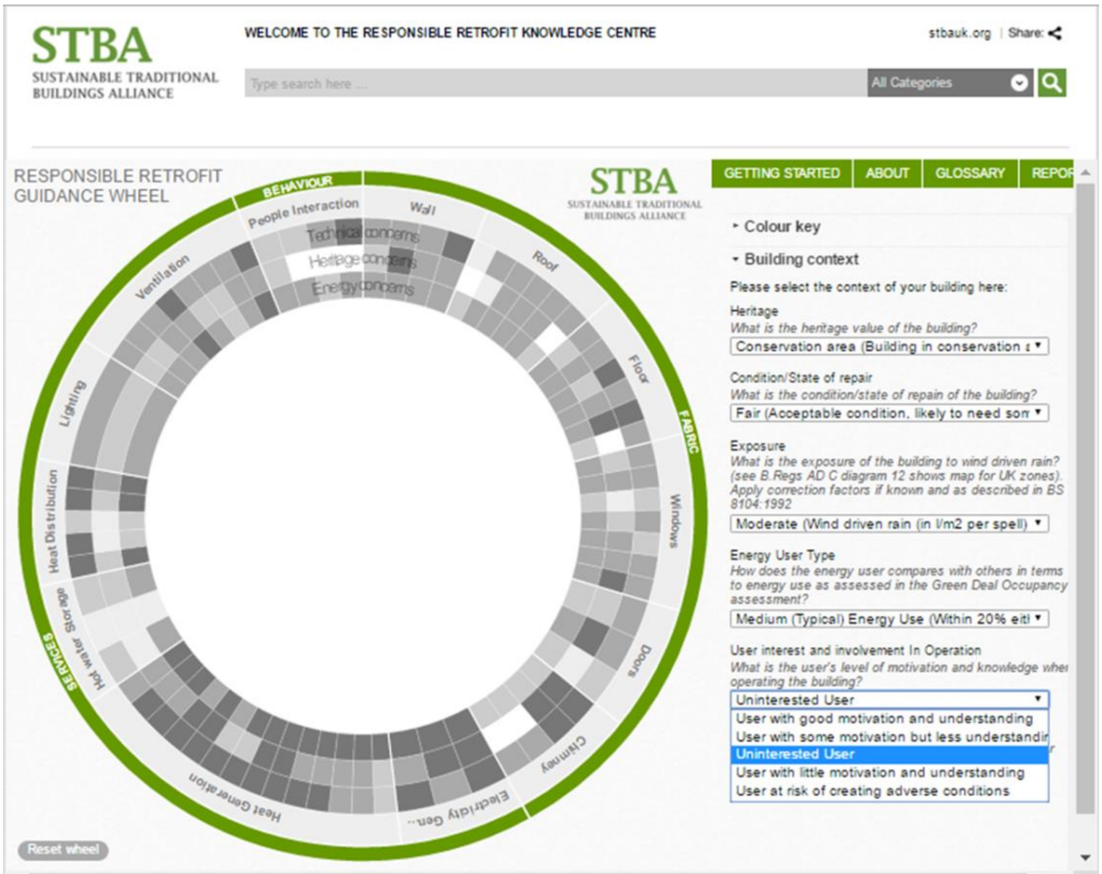
Shrubsole et al. provided several examples of measures that failed, or do not achieve the expected results, because of the lack of consideration of the users´ interaction with the systems. Beyond the well-known rebound effect (or comfort take-back) (Sorrell 2007) they found evidences of other user-related consequences such as: high ventilation heat losses in air tight properties due to increased window opening to compensate for the lack of natural noise; high levels of relative humidity due to clothes dried indoors; increased occupant interaction with systems leading to the heating system being activated more often; low ventilation rates as a result of trickle vents closed to prevent draughts; or systems being disconnected or switched off because of the disruption caused during night time hours.

Hancock & Stevenson (2009) highlighted the importance of communication with the occupants during the handover of the project to ensure adequate ventilation to facilitate drying of materials' initial moisture content. In line with Hancock & Stevenson's work, Brunsgaard et al. (2011) pointed out the need to *"inform, educate and communicate with the occupants on how to live in a passive house"* (p. 450).

The work carried out by Pisello et al. (2015) is another example of a study looking at the effect of user behaviour on the performance of retrofit measures. The results of their work on innovative cool roof tiles for historic buildings showed the necessity to consider the effect of human attitudes together with the effect of physical retrofits to obtain a reliable estimation. Furthermore, based on the study of how comfort is perceived by the occupants, Hellwig (2015) concluded that the occupants' level of satisfaction can be increased if they feel that they can control how the building is operated. That would ultimately improve the effect of the user behaviour on the building performance.

2.5 The decision making process

The importance of user behaviour was highlighted by the STBA in their exhaustive review of all the available (and reliable) information about retrofit of traditional buildings. As part of their conclusions they stated that *"user behaviour hugely affects the energy use and health of buildings"* and that the *"complexity of interactions between occupants, fabric, and services makes it essential that users are considered in the retrofit of any building"* (May & Rye 2012, p.56). In their final recommendations, they urge the decision makers to improve consideration and involvement of users in the assessment, planning, delivery and use of retrofit measures. In addition to that, and following on from the report, they included a user related criterion in the "Responsible Retrofit Guidance Wheel" developed later (STBA 2016). In this online guidance tool designed to help owners and practitioners in the adoption of retrofit measures, the user was included as one the risk factors of the building context. This context is defined by the heritage value of the building, its condition or state of repair, the exposure to WDR, the number of sides exposed, the energy user type and the user interest and involvement in the operation. The latter is classified in a qualitative scale from *"user with good motivation and understanding"* to *"user at risk of creating adverse conditions"* (Figure 2-26).



Please select the context of your building here:

Heritage
What is the heritage value of the building?
Conservation area (Building in conservation ε ▾

Condition/State of repair
What is the condition/state of repain of the building?
Fair (Acceptable condition, likely to need sor ▾

Exposure
What is the exposure of the building to wind driven rain? (see B.Regs AD C diagram 12 shows map for UK zones). Apply correction factors if known and as described in BS 8104:1992
Moderate (Wind driven rain (in l/m2 per spell) ▾

Energy User Type
How does the energy user compares with others in terms to energy use as assessed in the Green Deal Occupancy assessment?
Medium (Typical) Energy Use (Within 20% eitl ▾

User interest and involvement In Operation
What is the user's level of motivation and knowledge whei operating the building?
Uninterested User ▾
User with good motivation and understanding
User with some motivation but less understandir
Uninterested User
User with little motivation and understanding
User at risk of creating adverse conditions

Figure 2-26 Responsible Retrofit Guidance Wheel (STBA 2016)

2.5.1 User behaviour & decision making

Energy-led projects are usually focused on *"overcoming technical problems and optimizing the technical and economic performance of houses"* (Vlasova & Gram-Hanssen 2014, p.514). Occupants are often overlooked when assessing the feasibility of a retrofit option despite the direct influence they have in the use of the heating and ventilation systems. As stated by Vlasova & Gram-Hanssen (2014) the "*success of energy focused retrofit projects in terms of energy saving is conditioned by their compatibility with the everyday practices of the users"*.

Existing research on the role of users during the decision making process is fairly limited and just a few relevant examples have been found. As part of a wider investigation on indoor climate and comfort in refurbished dwellings, Liu & Thoresson (2013) conducted interviews with members of a team involved in a low-energy retrofit project. The results of their research showed that the team members were trying to improve building performance as a response to a *"perceived societal pressure to reduce energy use"* while indoor air quality or user comfort was only discussed as a side benefit. Based on the idea that *"comfort for the residents is simplicity"* the project made use of invisible measures that could not be adjusted or modified by the users and therefore did not affect their daily lives.

The research developed by Vlasova and Gram-Hanssen (2014) also looked into the relationship between energy retrofits and daily lives of the occupants. Looking at three different case studies, they tried to find whether the retrofits designs considered the future everyday habits of the occupants. They found that the users were only considered when trying to achieve higher norms of comfort. The authors suggested that the actual behaviour of the occupants should be considered during the decision making process in order to develop further sustainable practices.

A study analysing several projects developed under the 'Retrofit for the Future' programme (https://retrofit.innovateuk.org/) identified the key aspects of decision making process in different project teams (Lowe et al. 2011). In general, conventional practice paid little or no attention to the characteristics and needs of the occupants. In addition to that, the communication between designers and users was difficult during the entire process. However, those teams that adopted a more integrated approach designed interventions *"more responsive to occupants' needs and more adaptable to occupants' lifestyles and behaviours"* (p. 18). The main pitfall identified by the researchers was the poorly planned handover processes, especially in cases with hard-to-understand system interfaces. The final recommendations of the study were directed towards an enhancement of the participation of the user in the process in order to improve their feeling of control over the build process and of the implemented systems. Additionally, Gupta & Chandiwala (2010) highlighted the potential benefits of analysing the behaviour of occupants prior to the refurbishment. That could influence the adoption of user-centred measures and increase the final efficiency of the intervention. Besides, they suggested that it would help to build a more robust learning process for owners, occupants, designers and managers.

Table 2-6 Assessment of user related criteria in different decision support tools. Adapted from Strachan (2013) (Pt: partially).

	1. EPIQR (Flourentzos et al. 2000)	2. TOBUS (Flourentzou et al. 2002)	3. XENIOS (Dascalaki & Balaras 2004)	4. BEMS Data Based DST (Doukas et al. 2009)	5. GA-Based DST (Juan et al. 2009)	6. Hybrid DSS (Juan et al. 2010)	7. Knapsack (Alanne 2004)	8. Multivariant Design and MCA (Kaklauskas et al. 2005)	9. Knowledge and Device DST (Kaklauskas et al. 2005)	10. Two-factor method (Martinaitis et al. 2007)
Occupants views considered during the refurbishment intervention suitability assessment	No	No	No	No	No	No	Pt	Pt	No	No
Level of intrusiveness is included during refurbishment intervention acceptability assessment	Pt	Pt	No	No	No	No	Pt	Pt	No	No
Occupants opinions re indoor environment quality have been considered during refurbishment intervention acceptability assessment	Yes	Yes	No	No	No	Pt	Pt	Pt	Pt	No

Despite the described benefits of incorporating occupants' views in the process, the assessment of ten different decision support tools for building refurbishment carried out by Strachan (2013) revealed that occupants' opinion is barely considered in most of the cases. The review compared methodologies against a list of attributes that the researchers defined as desirable in a decision support tool. One of the categories evaluated in their review was 'user acceptability', including whether the occupants' views were taken into account, the disruption caused during the refurbishment and whether the occupants' opinions about the indoor environment were discussed. Her results (Table 2-6) showed that there was no single tool addressing all the needs of the final user. In fact, most of the evaluated tools did not take into account the occupants' opinion of the current state of the building or the measures to be implemented.

2.5.2 Motivations and barriers to traditional building refurbishment

As stated in the previous chapter, the renovation rate of buildings in Europe is very low. The renovation rate of traditional 'hard-to-treat' buildings is arguably even lower. Nevertheless, the investigation of the motivations and limitations for the energy retrofit of traditional buildings is still limited.

As part of the project CALEBRE (Consumer Appealing Low Energy technologies for Building Retrofitting) (Loughborough University 2016), Mallaband et al. (2012) analysed previous experiences of 20 owners of solid wall properties in the improvement of their homes. The main barriers for improvement identified in the research were: (1) householders' values & preferences, (2) cost, (3) professionals' availability & expertise, (4) time and (5) preservation of property features. The research identified other barriers such as the life stage of the occupants, their attitudes to older houses, the perceived difficulty of the task, existing regulations, the availability of parts and products, the disruption caused to their daily lives or lack of consensus in the household. Personal circumstances of owners played a crucial role and up to 70 % of the households abandoned the idea of improving their homes because of *"their personal set of values"* (p. 7).

As stated by Vadodaria et al. (2010) in a different publication from the CALEBRE project, householder perception of the benefits of improving the building must exceed the disruption caused, regardless of the costs factor. In the case of traditional buildings, owners' personal values included the building appearance and the effect that the improvement might have on its aesthetics.

The importance of aesthetics for owners of traditional buildings has also been noted by Sunikka-Blank & Galvin (2016). Their qualitative interviews carried out with home owners in Cambridge revealed that *"retrofitters"* found it difficult to balance the improvement of the buildings' efficiency and the preservation of the aesthetic values of their properties. In fact, the importance of aesthetics was in the majority of the cases as important as the economic criteria. Most of the properties included in the sample were not listed nor in a conservation area (*"heritage by designation"*) but were perceived by the owners as having an aesthetic value (*"heritage by appropriation"*). Besides, the owners did not share a common vision of aesthetics or heritage and they rather need to be understood individually.

Additionally, Friedman & Cooke (2012) suggested that the lack of consistency in the retrofit application and planning policies by the local authorities might be acting as a barrier for the adoption of low-carbon measures in traditional buildings.

2.6 Conclusions

The literature review presented in this chapter has shown the particularities of Scottish traditional buildings and the important role that the built heritage is going to play in the achievement of established carbon reduction targets. Internal insulation, and more specifically the insulation of the narrow cavity between masonry and internal finish, has a notable potential to reduce the energy demand of traditional buildings. It would improve the envelope thermal performance significantly and solve most of the limitations and concerns expressed by home owners when retrofitting their properties (cost, disruption and aesthetics).

However, from a hygrothermal point of view, internal insulation of solid walls and elimination of the air flow in the cavity can have negative consequences for the long term performance of the fabric. Moreover, assessment of insulated walls performance can only be as accurate as the definition of their boundaries. Previous research has demonstrated that simplified models used for the definition of internal climates might not be able to represent the complex interaction between users and buildings and changes in the user behaviour after the retrofit.

The review of the existing literature has also shown that the available research is mainly focused on individual aspects of buildings energy performance. Researchers have explored either the user behaviour or the wall moisture dynamics. Furthermore, the reviewed studies suggested that the role of users is not fully understood by the decision makers and, consequently, it is not considered in the assessment of the retrofit measures.

The aim of this work is therefore to look at the relationship between user behaviour and hygrothermal performance of envelopes in the context of Scottish traditional buildings. In the next chapters, the feasibility of internal insulation of solid walls will be evaluated using a holistic approach that includes the exploration of the decision making process, the effect of user behaviour on the internal climate and the hygrothermal performance of insulated walls under realistic scenarios.

3 RESEARCH METHODOLOGY: FROM SOCIAL SCIENCES TO BUILDING PHYSICS

In this chapter the research framework presented in Chapter 1 is further developed. First, the methodological approach taken in this research is presented. The next section of this chapter describes the research design in detail. Methods, samples and limitations of each of the three main stages are discussed below. Lastly, the ethical considerations of the research are discussed.

3.1 Methodological approach

From the objectives presented in Chapter 1 (Figure 1-1), it could be anticipated that both qualitative and quantitative methods were necessary to answer the research sub-questions. In fact, the established sub-questions are scattered across the qualitative-quantitative continuum (Figure 3-1). Thus, Objective I sub-questions are close to the pure qualitative end, whereas Objective III could only be answered using a quantitative approach. Sub-questions from Objective II would require mixing qualitative and quantitative methods to answer sub-questions 3/4 and 5 respectively. Therefore, this research, as a whole, had to be approached using a mixed methodology.

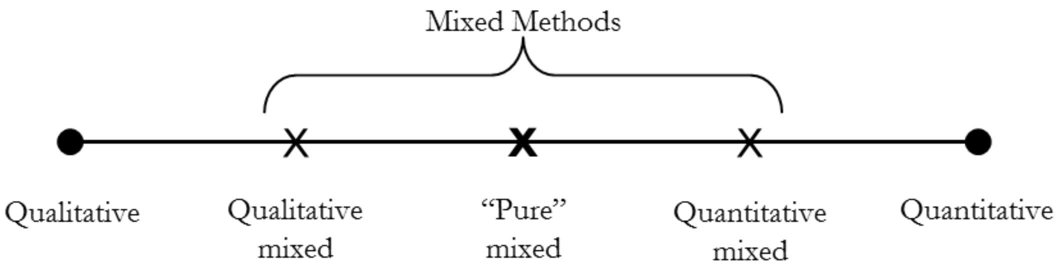


Figure 3-1 Mixed methods research in the qualitative-quantitative continuum. Adapted from (Johnson et al. 2007)

Due to the different nature of the methods needed, it was important to establish a common methodological approach that could be applied throughout the research. Behavioural sciences, and more precisely the scientific method application in behavioural research, offered a solution to define this research framework. Based on the concept of 'empirical cycle', this research was conceptualised as a series of linked cycles. The empirical cycle, as defined by (De Groot 1969), serves as *"a basic construct in our logico-methodological approach to scientific inquiry, thought, and reasoning"* (p. 27). The empirical cycles proposed in this research respect the five steps defined by De Groot (Figure 3-2):

i. Observation: collection and grouping of existing empirical materials. The cycle starts by reviewing existing knowledge and gaps in the literature.
ii. Induction: formulation of hypotheses. A subsequent inductive process allows for the formulation of the research hypotheses.
iii. Deduction: collection of new empirical data. The hypotheses are further developed into *"testable predictions"* that serve as a basis for the collection and analysis of new data (van Wesel et al. 2011).
iv. Testing: testing of hypotheses. The predictions are then compared with reality, in the form of new empirical data.
v. Evaluation: evaluation of the testing outcome. The final evaluation serves to either accept or discard the hypotheses and provides feedback to the theory, and also suggests issues for additional research (Heitink 1999).

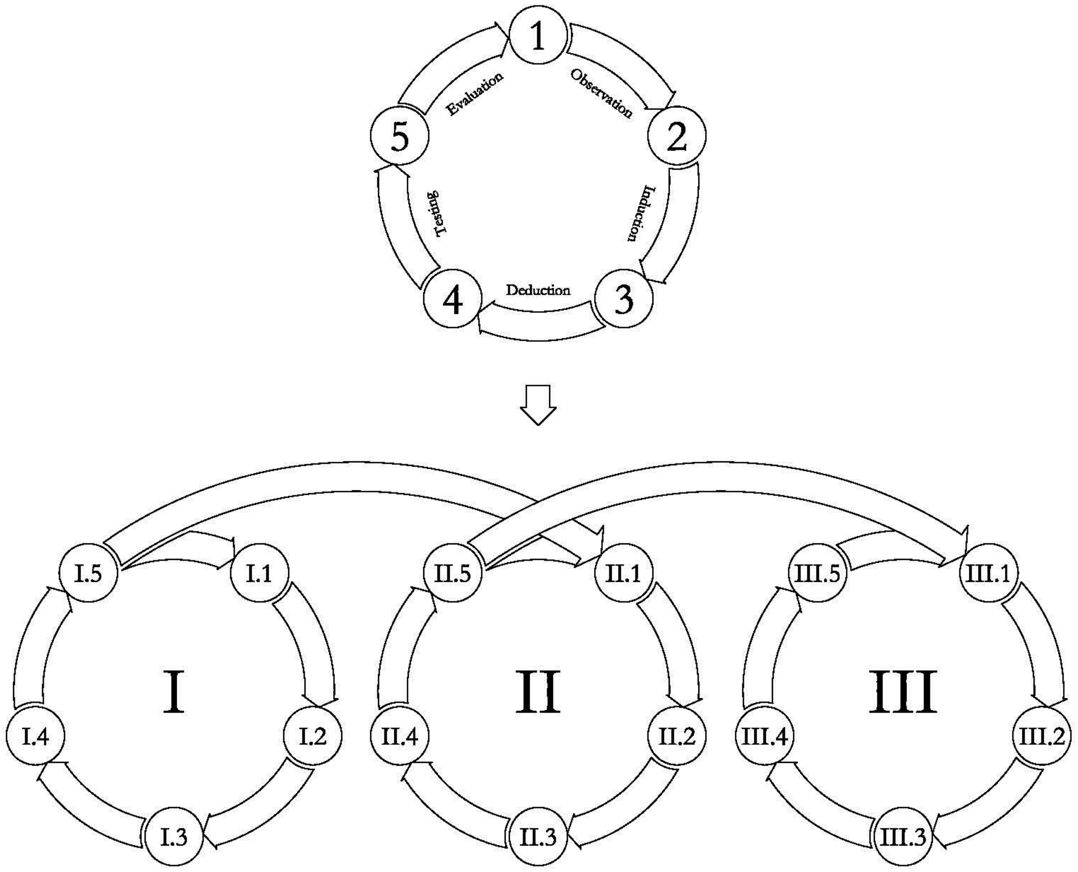


Figure 3-2 The empirical cycle and its adaptation for the implementation in this research. Adapted from (Mietus 1994)

This research was designed as three stages according to the three objectives established above. Each objective was developed as one empirical cycle. Moreover, the research was designed in a way that the last step of each cycle ('evaluation') was linked to the first phase ('observation') of the following cycle (Figure 3-2). In this way, the concatenation of cycles allowed for a logical transition from one end of the qualitative-quantitative continuum to the other.

I. Decision making analysis

The first stage, or empirical cycle, of the research corresponds to the decision making process exploration. It answers the first two sub-questions: "What are the driving factors for decision makers when adopting energy efficient technologies in traditional buildings?" and "How are user behaviour and comfort needs considered when adopting energy efficient technologies in traditional buildings?" These questions were answered following the five steps of the cycle:

- I.1. The first step was completed by reviewing the existing literature in two fields: the implementation of energy efficient technologies as part of a refurbishment and the analysis of decision making processes.
- I.2. The conclusions of the review were used to formulate the following hypothesis:

"Decision makers do not take into account the effect of user behaviour on the building performance when retrofitting a traditional property"

- I.3. In the third step, the collection of new empirical evidence was carried out by means of semi-structured interviews with decision makers involved in energy retrofits.
- I.4. The use of templates facilitated the identification of drivers and barriers which arose during the decision making process.
- I.5. The acceptance of the hypothesis in the last step of the cycle moved the research into a new research stage where the behaviour of the users was investigated.

II. User behaviour and the internal climate

The second cycle of this research was focused on users' behaviour in residential traditional buildings and their interaction with the buildings services and fabric. Looking at answering sub-questions 3, 4 and 5 the following steps were developed:

- II.1. The observation phase was carried out by contrasting the outcomes of the previous stage with the conclusions from the review of previous research in the field of household energy use and international standards of building performance.
- II.2. The resulting hypotheses suggested that:

"When trying to achieve comfort, people living in traditional buildings interact with the building in a different manner depending on the level of insulation"

"Internal climates of residential buildings presented in the international standards are not representative of the traditional Scottish building stock"

- II.3. A comprehensive multi-case study was designed to gather new data to examine these hypotheses. By means of interviews, questionnaires and home tours with the users and monitoring of physical variables, new empirical evidence about the energy patterns of the users and the internal climate was collected.

- II.4. To check whether or not predictions were fulfilled, two different analyses were carried out. The results from the behavioural study were analysed to unveil the structures of comfort practices in the indoor environment. The data obtained with the monitoring campaign were compared with other internal climates found in the literature.
- II.5. As a result, the first hypothesis was rejected and the second one validated. The data collected with the environmental monitoring were used to model new and more accurate scenarios of the internal climate.

III. Moisture dynamics in the wall

The last cycle of the research used the results from the previous stage to explore the user behaviour effect on the building performance in order to answer sub-questions 6 and 7. The investigation was developed as detailed below:

- III.1. An exhaustive review of recent research on moisture dynamics in building envelopes was carried out during the observation phase.
- III.2. Outcomes of the observation phase suggested the following hypothesis formulation:

> *"The hygrothermal performance of internally insulated solid granite walls is greatly dependent on the characteristics of the internal climate"*

- III.3. New data was generated using numerical simulation that quantified the effect of the different types of climates, which resulted from the previous stage.
- III.4. Examination of the new empirical data was carried out by comparing the results from the simulation with commonly accepted thresholds for fabric performance.
- III.5. After the evaluation, and acceptance, of the final hypothesis, efforts were made on two directions: highlighting the gaps that need to be covered in further research and providing some conclusions that could be used in the form of recommendations for future decision makers.

3.2 Research design

This section describes the different research methods used in this work. The methods are grouped according to the three stages of the research presented previously.

3.2.1 Decision making analysis

Qualitative methods were chosen to identify the different variables influencing the approach taken by owners and stakeholders when refurbishing an old building. Of the self-reported research methods - those that take the approach of asking the person directly (Barker et al. 2002)- , qualitative interviews were chosen as the most suitable.

3.2.1.1 Methods

When seeking personal opinions or impressions, interviews are usually an easier and more effective system for the respondents than questionnaires. Interviews have proved to be especially useful when trying to get the story behind a personal experience as the interviewer can pursue in-depth information around the topic (McNamara 2012). Face to face interviews have the benefit of being a synchronous communication in time and place and therefore social cues can be taken into account as part of the data collection process (Opdenakker 2006). Interviewees' voice, intonation and body language give an extra piece of information to the researcher that can be added to the verbal answer. As opposed to structured interviews, semi-structured interviews may uncover some issues that were previously unknown and therefore not included in the script (Wilson 2014a). This method has already been proven successful in previous similar research regarding energy efficient retrofits such as Gilbertson et al. (2006), Townsend (2010) and Lowe et al. (2011).

The interviews with private home owners and key members of management teams were conducted during the winter of 2013. The 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. The interviews took place in the participants' home or the owning organisations' facilities. All the members of the family or the decision making team were invited to be present for the interview. During the interviews, the following subjects were discussed: motivations for purchasing an old building, reasons for retrofitting, energy use and comfort requirements, agents involved in the project and information consulted and finally a description of the adopted measures and the process for the implementation. Each interview, including a site visit, lasted between 60 and 120 minutes. Focusing the conversation on a recent project allowed the identification of the actual mechanisms behind the decision making process while limiting the effects of idealised or intended behaviour (Perrin & Barton 2001).

3.2.1.2 Sample

Participants were selected from those who owned a traditional building and had decided to do some refurbishment work in order to improve the energy efficiency of the property. Recruitment for the interviews was done using different approaches. Private owners were first contacted at energy-related events (e.g. All-Energy conference (Reed Exhibitions 2016)) and then word of mouth from participants themselves (also known as snowball sampling (Marshall & Rossman 2006)) allowed contacting new owners in the same area. In addition, invitation letters were sent to a total of 26 organisations (see Appendix 1), including rural landlords, housing associations, property developers and estates departments. 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 in the study.

The sample was formed by 11 interviews that included a total of 16 respondents. In one of the cases, the interviewees reported their experiences in different cases, the refurbishment of their own home and the improvement of other properties they own and lease. These two experiences were analysed independently due to their different nature, resulting in a sample of 12 cases. The characteristics of the sample are summarised in Table 4-1 in Chapter 4.

A differentiation has been made between those occupying the building object of the refurbishment (owner-occupiers) and those who are not the end user of the building (owner-non occupier). The latter is formed by individuals or organisations that own and lease a building (either private landlords, registered social landlords or housing associations) and organisations that use the buildings as facilities for their activities (in this case, two Higher Education institutions). Of the 12 cases, six were owners-occupiers and six non-occupiers.

The occupiers sample was formed by private owners of detached or semi-detached houses in the councils of Aberdeen City, Aberdeenshire and Angus (Figure 3-3). Five of them had occupied the building for more than a year at the time of the interview and just one of the respondents had recently acquired the property. Among the non-occupiers, one was a private landlord in Aberdeenshire, two were rural landlords of Aberdeenshire, one was a member of a housing association in Aberdeen and the last two interviews were held with members of the estates departments of two Higher Education institutions in Aberdeen.

Although the sample did not try to be representative, the wide range of scenarios included in the study allowed the exploration of very different approaches and experiences in order to create a general understanding of the actual situation (Haines et al. 2010).

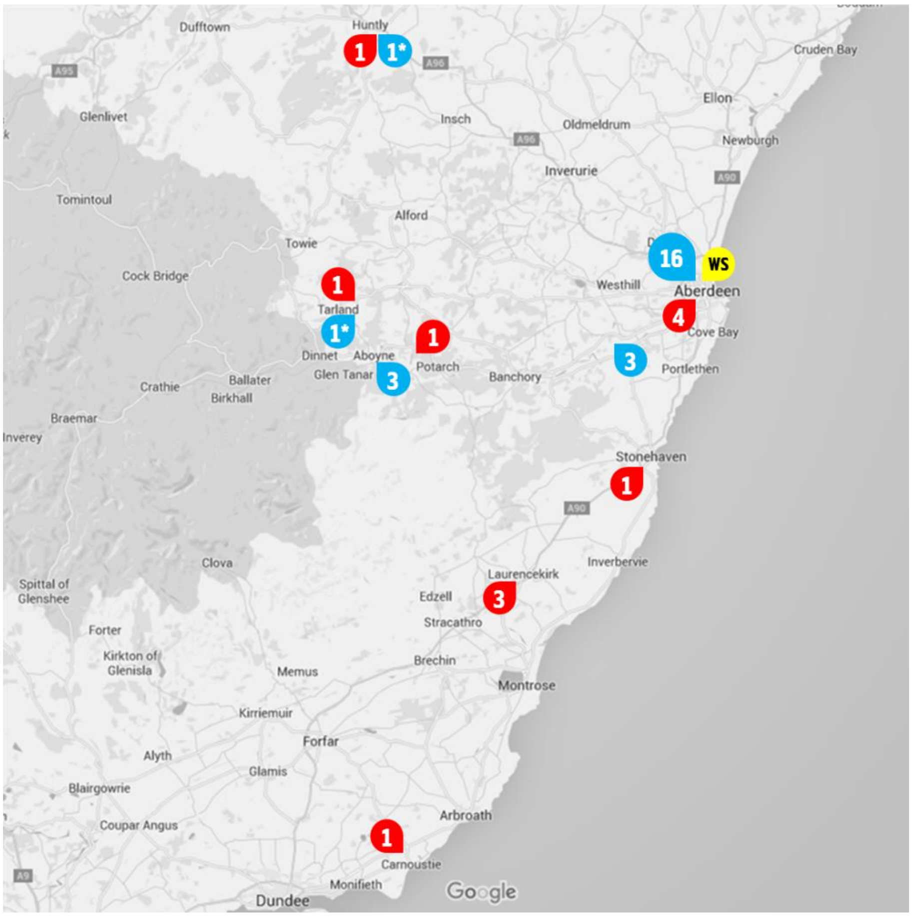


Figure 3-3 Sample location. In red, location and number of decision makers interviewed, in blue, location of case studies and, in yellow, location of the weather station. Properties monitored before and after retrofit are marked with an asterisk (Source: Google Maps).

3.2.1.3 Limitations

When using interviews as a main source of data, it is important to take the so-called *"interviewer effect"* into account (Denscomber 2003). What people say they do, they prefer or they think does not always reflect the truth as they might respond differently depending on how they perceive the researcher. Some attributes of the researcher are 'givens' that cannot be adapted for the interview (gender, age, origin, accent, etc.), while others aspects can be, and must be, controlled. The approach taken in this research to minimise this effect consisted in adopting a *"passive and neutral stance"* as interviewer by remaining non-committal on the statements and representing a non-provoking role (conventional clothes, cordiality, receptiveness, etc.).

Besides the interviewer effect, there is a risk of giving some unintended cues while asking that might lead the respondents into a particular answer (Wilson 2014a). This risk was minimised by using the predesigned outlines. The risk of inconsistency between the interviewers (Wilson 2014a) did not exist, as all the interviews were carried out exclusively by the author.

A formal pilot study was not undertaken. Instead, a complete evaluation of the process and results was carried out after the first three interviews. This process allowed the identification of weaknesses in the structure of the interview and recording methods. Data obtained in these first interviews were still used since *"contamination is less of a concern in qualitative research"* (Van Teijlingen & Hundley 2001, p.3).

Although the sample presented in this thesis cannot be considered statistically representative, it provides a robust scenario for analysis. Previous research has proved that saturation can be found within the first twelve interviews and basic patterns are visible after only six interviews (Guest et al. 2006). Furthermore, due to the qualitative nature of the analysis, the size of the sample does not compromise the validity of the results.

3.2.2 Multi-case study

User behaviour was explored using a multi-case study approach. According to Yin's definition, a case study is "an empirical enquiry that investigates a contemporary phenomenon within its real-life context when the boundaries between phenomenon and context are not clearly evident, and where multiple sources of evidence are used" (Yin 1984, p.13). A multi-case study is seen as a "collection of case studies" and can either be used when seeking replication of the findings from a case study or to look for common themes resulting from the analysis of the entire sample (Burns 1997). In this case, the second approach was chosen and the sample was analysed as a whole in search of common patterns.

3.2.2.1 Methods

Since the study involved both qualitative and quantitative data, different methods were developed for the collection. The description of the methods adopted is sorted below according to the nature of the method: qualitative for the behavioural study and quantitative for the environmental monitoring. Analogously the results of these two different methods are presented in two separate chapters (Chapters 5 and 6).

3.2.2.1.1 User behaviour study

The users were the focus of this study and explaining the reasons for their behaviour the main goal of the investigation. To ensure that all factors involved in the energy behaviour of the households were taken into account, a study with different stages of data collection was designed. For the development of the survey, the following methods were used:

- Semi-structured interviews

The same reasons that were argued for the selection of this method in the previous stage apply here as well (ease for the participants, depth of information, synchronicity or flexibility). In this case, however, due to the time consuming and resource intensive nature of the method and the larger size of the sample, the formal interviews were limited to 14 cases. The semi-structured interviews were focused on the users' energy related patterns. Information regarding the heating, ventilation and moisture production habits was collected in order to achieve a better understanding of user behaviour effect on the internal climate. As with decision makers' interviews, the questions followed a predefined outline (a full copy of the script is included in the Appendix 4) allowing users to speak freely about their experience inhabiting their home.

- Questionnaires

Two types of questionnaires were used as part of the study. All the participants were asked to fill out a demographic questionnaire along with the consent form. This questionnaire included some generic questions about age, gender, ownership, time living in the building, etc. (see Appendix 4). The second type of questionnaire was used in those cases where the formal interview did not take place. It was designed, based on answers to the interviews, as an alternative method to collect information about users' heating, ventilation and moisture production patterns (see Appendix 5). The design of the questionnaires also included open boxes for the participants to add comments. According to Denscomber (2003), questionnaires are at their most productive *"when the social climate is open enough to allow full and honest answers"*. In this case, the design of a longitudinal study with several visits to interact with the users helped to create this favourable environment.

- Home tour

A visit with the tenant through the property was planned in order to take photographs of relevant features mentioned in the questionnaires/interviews and to contextualise the answers (Haines et al. 2010). Walking around the property gives the participant the opportunity to point out specific features and to show the researcher how they usually operate with the building (Love 2014). Exploring users' understanding of comfort in their own domestic environment is an excellent way to understand their habits (Hong et al. 2009; Heerwagen & Diamond 1992; Behar 2011; Crosbie & Baker 2010).

- Informal interviews

Informal, or unstructured, interviews are a method originally developed in the field of sociology and anthropology to *"elicit people's social realities"* and they rely on the interaction between the researcher and the respondent (Zhang & Wildemuth 2009). According to Wilson (2014b), the use of less formal and more conversational approaches facilitates building a rapport with the participants more easily than during semi-structured interviews. The interviews focused on users' perception of comfort and the ways they dealt with thermal discomfort. Due to the duration and design of the study, it was possible to hold several informal interviews as part of the follow-up study (Salkind 2010; McNamara 2012). As argued by Patton (2002, in (Zhang & Wildemuth 2009)), this type of unstructured conversation is built on the spontaneous generation of questions in the natural flow of an interaction. The informal meetings in this study helped to gather more information about users' behaviour and comfort perception as well as minimising the effect of seasonality on the answers (Pelenur 2013).

3.2.2.1.2 Environmental monitoring

To minimise the uncertainty associated with the indoor climate, this research aimed to use real data collected in situ from traditional dwellings to model accurate retrofit scenarios. The environmental monitoring campaign was designed to record the two main quantitative variables that define the internal climate: temperature and relative humidity. These variables were monitored at 15 minutes intervals in two rooms per property (living room and main bedroom) along with recordings of external conditions by a dedicated weather station (Figure 3-3). The sensors were placed away from direct heating sources and users' reach in order to reduce both disruption and variability in the measurements (Figure 3-4).

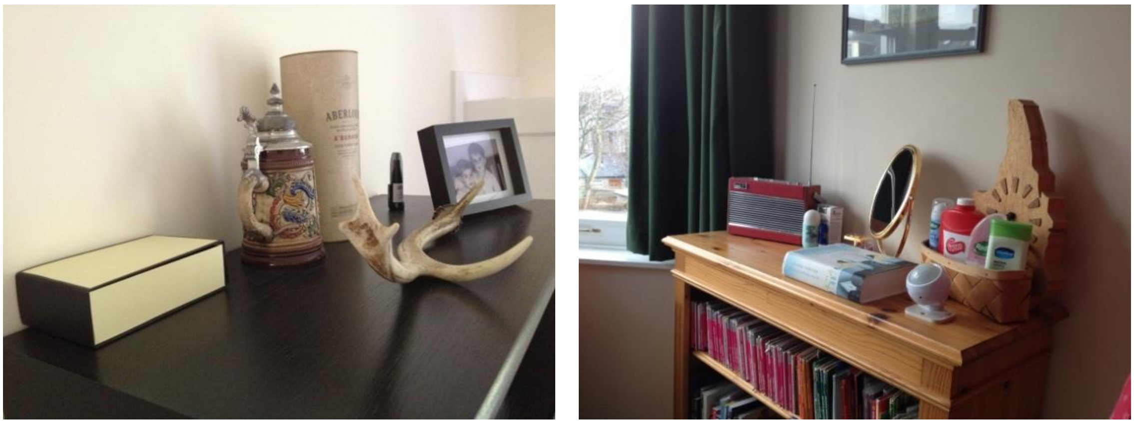


Figure 3-4 Examples of sensors placed in the case studies

Two different types of sensors were used during the monitoring campaign: LASCAR EL-USB-2 and Aeotec MultiSensor 5 by Aeon Labs (Figure 3-5). The specifications of both sensors are summarised in Table 3-1. The Aeotec sensors are also able to record lighting level and motion. However, and for the sake of consistency, only the temperature and relative humidity values were used in this research. The use of two different sensors was exclusively due to practical reasons (cost and access to the equipment). Since both types of sensors have similar measurement and accuracy ranges the use of different devices was not a cause of concern.

Figure 3-5 LASCAR EL-USB-2 (left) and Aeotec MultiSensor 5 (right).

Table 3-1 Sensors specifications

Sensor		Range	Accuracy	Internal resolution	Logging rate	Operating temperature
Lascar EL-USB-2	Temperature [°C]	-35 to +80	±0.5	0.5	10s to 12hr	-35 to +80
	Relative humidity [%]	0 to 100	±3	0.5		
Aeotec Multisensor 5	Temperature [°C]	-10 to +50	±1	1	4m to ∞	-10 to +60
	Relative humidity [%]	20 to 80	±5	1		

In addition to the environmental monitoring, air pressure tests were carried out in nine dwellings to measure the permeability of the envelope and its effect on the internal climate (Figure 3-6). The tests were carried out using an Air Leakage Measurement System or Blower Door test. The chosen model, E3 220v fan (Infiltec), had a resolution of 0.1 Pa, the range was from -750 Pa to +548 Pa, and the pressure accuracy was 1% of reading or 1 digit.

Figure 3-6 Air pressure tests

The external weather conditions were monitored with the Vantage Pro2 station (Figure 3-7). The station recorded temperature (maximum, minimum and average), relative humidity, dew point, wind speed, wind direction, wind chill, heat index, atmospheric pressure and rain fall.

Figure 3-7 The external weather station installed in the city centre of Aberdeen

3.2.2.2 Sample

The sample was formed by 24 households located in the North-East of Scotland (Figure 3-3). All the buildings were originally built to have similar construction characteristics (solid masonry granite walls, pitched roofs covered with slates, timber floors and single glazed sash and case windows with timber frames) but nowadays presented different levels of insulation and air-tightness (see Table 5-2). Although most of the buildings had some energy related improvements (mainly the substitution of the original single glazed windows), the dwellings were at different levels of conservation; while some buildings had kept the original lath and plaster others were completely renovated. For the analysis, buildings were categorised as 'retrofitted' or 'non-retrofitted' according exclusively to the insulation of the external wall. Two of the dwellings were monitored before and after the insulation and therefore, regarding the environmental monitoring, were considered as two different households, resulting in a total of 26 dwellings.

Participants' recruitment was completed using several approaches. Private landlords and housing associations were contacted to request their participation in the project. Two rural landlords agreed to take part in the study and contributed with four cases. Nine of the participants were already participating in a parallel research project aiming to improve the insulation of solid walls. The participants were tenants of the same tenement owned by a housing association. Another two participants had already participated in the first stage of the research as owners of the properties. The rest of the participants were contacted using the same snowball sampling approach as in the previous stage.

3.2.2.3 Limitations

Although not extremely common, a case study approach has been used both in user behaviour studies and energy retrofit research projects (Pelenur 2013; Love 2014). This method has sometimes been criticized for lacking rigour, obtaining results difficult to generalise and for being too difficult to conduct (Yin 1984; Zainal 2007). However, all these limitations, besides the risk of bias towards verification, were refuted by Flyvbjerg (2006) in his well-known paper *"Five misunderstandings about case-study research"*. He defended the validity of case studies to *"contribute to the cumulative development of knowledge"* as in the study of human affairs context-rich or context-dependent knowledge is often more valuable than trying to predict unavailing theories. In this case, due to the complexity and relevance of the context, the use of this method was particularly suitable to explain the mechanisms of comfort adaptation.

The generalization of results from a multi-case study usually has some limitations due to the relatively small size of the sample and the unrepresentative sampling methods used. However, Tsang (2014) points out the validity of case study as a form of theory testing by means of *"falsification"*. This test, named by Popper (1959), is one of the most rigorous when evaluating a scientific prediction and it is based on the idea that *"if just one observation does not fit with the proposition, it is considered not valid generally and must therefore be either revised or rejected"* (Flyvbjerg 2006, p.228). This method of generalization seemed especially appropriate for this research, considering that one of the hypotheses formulated in this study was based on the assumption of important discrepancies between international standards and actual characteristics of the dwellings. Finding a case study different to those proposed in the international standards would provide evidence to validate the hypothesis and enough qualitative data to explain the reasons for the discrepancies.

The strategy adopted for the case selection plays a very important role in the success of the study. Long term monitoring of internal spaces requires owners' consent and the engagement of the users during long periods of time and accordingly sample selection is laborious (Summerfield et al. 2007). Two selection strategies can be followed: random sampling or information-oriented sampling. Random sampling may increase generalisation but it does not help in explaining the causes behind a given problem and its consequences. Therefore, and having in mind that *"the 'representative' single neighbourhood does not exist"* (Small 2009, p.28), an information-oriented approach with maximum variation between cases was adopted.

Regarding bias and the risk of confirmation of preconceived ideas, Flyvbjerg (2006) defends that case study does not contain more bias than any other form of inquiry. In fact, *"experience indicates that the case study contains a greater bias toward falsification of preconceived notions than toward verification"*.

3.2.3 Numerical simulation

The third and final stage of the research was designed to quantify the effect of different climatic scenarios on the moisture dynamics of internally insulated solid granite walls. The hygrothermal assessment of buildings is a complex process that requires the evaluation of heat, air and moisture (Ramos et al. 2010). The use of numerical simulation allows for the coupled effect calculation of these parameters.

3.2.3.1 Methods

To develop the numerical simulation of the moisture dynamics in the envelope this research project made use of Heat, Air and Moisture (HAM) software. The simulations examined the impact that a range of different internal climates have on granite solid walls with different types of insulation 'pumped' into the cavity between the inner face of the granite and the lath and plaster lining.

Previous research has shown that moisture balance in insulated walls is achieved 5 to 10 years after the insulation, although in some cases it can take up to 20 years (Browne 2012, p.68). The use of numerical simulation was especially appropriate in this research because it helped to simultaneously explore the changes in the wall's performance under different conditions and for long periods of time.

After the evaluation of the different HAM software available for commercial and research purposes (summarised in Table 3-2), DELPHIN was chosen to be used in this research. DELPHIN is a simulation program developed by J. Grunewald at The Institute for Building Climatology at Dresden University of Technology in the 1990s. The software, validated conforming to EN 15026:2007 (CEN 2007), has been repeatedly used in previous studies (Häupl 2004; Scheffler 2008; Morelli & Svendsen 2012). Häupl (2004, p. 8), for instance, stated that a *"very good agreement between two-dimensional calculation and measurement is to be noted"*. The governing equations for moisture mass balance and air mass balance are as follows (Delgado 2013):

$$\frac{\partial}{\partial_t}\left(\rho_w\theta_1+\rho_v\theta_g\right)=-\frac{\partial}{\partial_\chi}\left[\left(\frac{\rho_w}{\nu}-j_{disp}-j_{diff}\right)\theta_1+\left(\frac{\rho_v}{\nu}+j_{diff}\right)\theta_g\right]$$

Equation 3.1 Moisture mass balance

$$\frac{\partial}{\partial_t}\left(\rho_a\theta_g\right)=-\frac{\partial}{\partial_\chi}\left[\left(\frac{\rho_a}{\nu}-j_{diff}\right)\theta_g\right]$$

Equation 3.2 Air mass balance

where ϱ_w is the liquid moisture partial density (kg/m^3), θ_1 is the volumetric content of the liquid phase (m^3/m^3), ϱ_v is the mass density of water vapour (kg/m^3), θ_g is the volumetric content of the gaseous phase (m^3/m^3), ν is the humidity by volume in the surrounding air (kg/m^3), j_{disp} is the dispersive flux, j_{diff} is the diffusive flux and ϱ_a is the air partial density (kg/m^3).

The dimensions used for the modelling of the wall are directly taken from the surveys carried out during the multi-case study. Especially useful was the survey of the tenement building of cases 2-10. This building, as mentioned before, formed part of a parallel research project. One of the goals of that project was the installation of several moisture sensors in the wall, providing a unique opportunity to study the different types of wall existing in the property and to take in-situ measurements of the different elements (Figure 3-8 & Figure 3-9). The final dimensions of the modelled wall are in line with those found in the literature (Young 2007; Baker 2011; Buda et al. 2012; Peuhkuri et al. 2010).

Figure 3-8 Probe installation (left) and floor joist exposed during the survey (right)

Regarding the insulation of the cavity, three different materials have been studied: two polyurethane based foams (closed and open cell) and blown cellulose. These materials have been tested in practical research of recent years (Curtis 2012; Jenkins 2012c; Abdel-Wahab & Bennadji 2013) and therefore provide a credible scenario for the simulations. All the materials used in this research but one come from the DELPHIN library. The only material that did not belong to the in-built database was the Sprayed Polyurethane Foam (open cell) and it was obtained from the North American database included in a different simulation software (WUFI 5.3). The need for a different library was due to the reduced number of insulating materials in the DELPHIN database that could be "pumped" into a narrow cavity. Unfortunately the number of suitable materials for cavity insulation in both databases is fairly limited at the moment and no other compatible materials were found.

Table 3-2 Hygrothermal simulation tools assessment. Adapted from (Delgado 2013)

Name	Material Properties														External Boundary conditions										Internal Boundary			
	1	2	3	4	5	6	7	8	9	0	1	2	3	4	A	B	C	D	E	F	G	H	I	J	i	ii	iii	iv
1D-HAM	X		X	X	X	X							X		X	X	X	X				X			X	X		
BSim2000	X	X	X	X	X	X						X		X	X	X	X	X	X	X		X	X		X	X	X	
Delphin5	X	X	X	X	X		X	X	X		X		X		X	X	X	X	X	X	X	X			X	X	X	
EMPTIED	X		X	X		X		X					X		X	X	X								X	X	X	
GLASTA	X		X	X		X	X								X	X		X				X			X			
hygIRC-1D	X		X	X	X	X		X	X				X		X	X		X	X	X	X		X	X	X	X		X
HAMLab	X		X	X			X			X		X			X	X			X	X		X	X		X			
HAM-Tools	X	X	X	X	X	X		X			X		X		X	X	X	X	X	X	X	X	X		X	X	X	
IDA-ICE	X		X	X	X	X						X	X		X	X	X	X	X	X		X			X	X		
MATCH	X	X	X	X	X	X		X			X	X		X	X	X		X	X		X	X	X		X	X		
MOIST	X		X	X	X	X		X	X				X		X	X		X	X	X			X		X	X		
MOIST-EXP	X	X	X	X	X	X		X	X		X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
UMIDIS	X	X	X	X	X		X								X	X		X	X	X					X	X		
WUFI	X	X	X	X	X	X			X	X	X	X			X	X		X	X	X	X	X	X		X	X		

1	Bulk density
2	Porosity
3	Specific heat capacity
4	Thermal conductivity
5	Sorption isotherm
6	Vapour permeability
7	Vapour diffusivity

8	Suction pressure
9	Liquid diffusivity
10	Diffusion resistance factor
11	Water conductivity
12	Specific moisture capacity
13	Air permeability
14	Hysteresis in sorption

A	Temperature
B	Relative humidity/Dew point
C	Air pressure
D	Solar radiation
E	Wind velocity
F	Wind direction
G	Precipitation
H	Long-wave exchange
I	Cloud index
J	Water leakage

i	Temperature
ii	Relative humidity
iii	Air pressure
iv	Interior stack effect

Figure 3-9 Measurements of the internal lining (left) and cavity width (right).

The internal climates used during the simulations were the result of the analysis developed during the multi-case study. Based on the data collected during the study new curves for the design of internal climate were created. These curves, explained in more detail in Chapter 6, show the moisture load of a dwelling (in g/m^3) as a function of the external temperature. The three new different curves, representing three different internal climates (Classes I, II and III), created for each scenario (non-insulated and insulated buildings) were used as internal boundaries of the simulation.

3.2.3.2 Sample

In this case, the sample of the study was equivalent to the final number of simulations performed. The characteristics of the different scenarios simulated, summarised in Table 3-3, are explained in more detail in Chapter 5.

Table 3-3 Summary of simulations' characteristics

Model	Duration	Wall section	External climate	Climate	Cavity	N (128)
1D	10 years	Front wall (V.1) Front wall (V.2) Front wall (V.3)	Average data	Constant Class I Class II Class III	Cavity Cellulose PUR closed PUR open	48
2D	10 years	Front wall	Average data	Constant Class I Class II Class III	Cavity Cellulose PUR closed PUR open	16
	2.5 years	Front wall Gable wall Floor junction	Monitored data	Constant Class I Class II Class III	Cavity Cellulose PUR closed PUR open	52
	2.5 years	Front wall	Monitored (No_Rad) Monitored (WDR) Monitored (WDR_South)	Constant Class I Class II Class III	PUR open	12

3.2.3.3 Limitations

As stated by Little et al. (2015, p.94) *"every assessment method is a simplification of reality"* and therefore the use of numerical simulation also has some limitations. These weaknesses are mainly associated with the accuracy of the input data and the simplifications made in the model. While access to reliable data for the external boundary is reasonably easy, hygrothermal material data is still very limited, especially when it comes to non-standardised elements such as local materials used in traditional constructions or innovative insulation products.

DELPHIN material database has a large selection of materials, a total of 566 materials in the version 5.8.1 used in this research. However, the lack of specific materials makes the assignment *"ultimately arbitrary"* (Browne 2012, p.71) and laboratory measurement of local traditional building materials would increase the accuracy of the assessments. The development of such datasets is of crucial importance if new retrofit programs, like the now extinct Green Deal, are to be implemented.

The adoption of insulating materials responded primarily to the availability of compatible materials. This research has only used the hygrothermal properties of generic materials and no specific product or commercial formulation has been used. No conclusions or recommendation regarding the feasibility of specific insulating materials will be drawn from this work.

As for the level of detail of the model, the limitations are imposed only by the available computing resources. Two-dimensional calculation of masonry walls is very resource intensive and the processing power required increases exponentially with the level of detail of the structure. The simplification used in this research was in line with the models proposed by Baker (2010b) and Little et al. (2015). Although the model simplified the core of the wall greatly, the inner and outer leaves have been carefully designed to maintain the mortar/stone ratio. These were the most critical parts of the wall, as they acted as interfaces with the boundaries, and therefore they had to be carefully modelled to ensure results accuracy.

3.3 Ethical considerations of the research

This section outlines the ethical issues associated with the research. Every potential ethical issue that arose during the research was carefully examined according to the Research

Ethics Policy of the Robert Gordon University. The "Research Ethics: Student and Supervisor Appraisal" (RESSA) form was successfully completed and submitted for evaluation in December 2012.

- Research participants

Participants of both in-depth interviews and the multi-case study were informed in detail about the purpose of the research. Prior to starting the interview, participants were provided with a consent form and a briefing explaining the purpose of the research and the objectives of the interview (see Appendix 4). They were also informed of the possibility of withdrawal from the project at any moment. It can be confidently said that participants were genuinely willing to participate and fully aware of the aims of the research.

Most of the information gathered can be considered private and therefore involved some ethical concerns. Management of the collected information guaranteed confidentiality and anonymity of data and participants at all times. Interviews and questionnaires were coded during the transcription to preserve anonymity and the raw data has not been shared.

- Monitoring equipment

Aeotec MultiSensor 5, used in some properties, works as a part of a smart home monitoring network and is designed to be connected to the Internet so data could be accessed remotely. The system was configured to transmit wirelessly the last record only and all the previous data were stored on a memory card locally. The participants were informed of that particularity and no issue arose during the study.

The Aeotec sensors and the smart home systems necessary to control them were borrowed from the Energy Technology Institute. An agreement letter establishing the terms of the loan and the characteristics of the equipment was produced by Energy Technology Institute.

- Publication of research findings

The names and other details of the interviewees have been changed to ensure the anonymity of the participants. Photographs and quotes are only used with the explicit consent of the participants.

3.4 Summary

This chapter presented the methodology and research design proposed for the development of the thesis. The following aspects have been discussed:

- The project's nature and the need of a mixed methods approach. The research is presented in the qualitative-quantitative continuum and the necessity for a common methodology is discussed.
- The concept of empirical cycle and its application in this research. The application of the scientific method in behavioural sciences is discussed as a suitable approach for this research.
- The structure of the three data collection stages. That includes a justification of the methods used, a description of the samples and a discussion of the limitations associated to each of the stages.
- The research ethical aspects. Special attention has been paid to the awareness and consent of the participants and the management of the data collected.

4 EXPLORING THE DECISION MAKING PROCESS

In this chapter, the role that users play during the decision making process is investigated by looking at specific energy retrofit projects in traditional buildings. As discussed in Chapter 3, this thesis made use of semi-structured interviews with private owners (owner occupiers) and key members of management teams (owner non-occupiers) involved in recent renovation projects. During the winter of 2013, 11 interviews were carried out to identify the different variables considered during the decision making process and their significance in the final adoption of the improvement measures (Table 4-1). The interviews with the decision makers (DMs) explored their perception of users' everyday practices and whether they were considered as a criterion during the process.

Table 4-1 Characteristics of the sample of the interviews with Decision Makers

	#	Date	Respondents	Building type	Occupier
Decision Maker 1	1	2013/09/17	2	Detached house	Yes
Decision Maker 2	2	2013/09/27	2	Detached house	Yes
Decision Maker 3	3	2013/10/04	2	Detached house	Yes
Decision Maker 4	4	2013/10/17	2	Detached house	Yes
Decision Maker 5	5	2013/11/25	1	Semi-detached house	Yes
Decision Maker 6	6	2013/11/26	1	Detached house	No
Decision Maker 7	7	2013/11/28	1	Detached house	No
Decision Maker 8	8	2013/12/02	1	Teaching facilities	No
Decision Maker 9	9	2013/12/04	2	Detached house	Yes
	10			Detached house	No
Decision Maker 10	11	2013/12/09	1	Tenement	No
Decision Maker 11	12	2013/12/13	1	Teaching facilities	No

4.1 Data analysis

A full transcription of the interview audio recordings was the first step of data analysis. The process of coding the transcripts facilitated an initial exploration of the interview content and identification of the most relevant topics. Topics were considered relevant either due to repetition throughout the interview, because it was explicitly said by the interviewee or because of their connection with other participants' answers (Berg 2001).

The initial analysis of the transcripts exposed the similarities existing between the decision making process of energy retrofit projects and the purchases of sustainable technological products. The latter was investigated by Oates et al. in a project focused on *"The trade-offs in decision-making of sustainable products"* (ESRC 2015). The researchers found that even though the purchase processes were usually different, some basic principles were common to all of them. They summarised these principles, including constraints, context, selection criteria and information sources in a 'purchase process model'. The model was used as a tool to compare the different decision making processes and to look for common patterns (Young et al. 2006).

In this study, the purchase process model created by Oates et al. (2008) was used as a coding template for the interview analysis. The use of templates to code themes is an approach for qualitative analyses of texts developed recently (Waring & Wainwright 2008). This approach consists of the elaboration of a predefined themes template and its application to the raw data in order to identify and focus on particular aspects of the text (Crabtree & Miller 2015). When coding a large volume of text, the template allows the interpreter-researcher to reduce the amount of data and facilitates making connections between related fragments of the text.

A good template allows for easier organisation of the text into themes and it also helps to organise the themes hierarchically by introducing different levels and sublevels to unitise and categorise the data (Truong & Simmons 2010). The template should summarise all the key themes and organise them in a *"meaningful and useful manner"* (Brooks & King 2014). It can be modelled based on previous research or from a preliminary observation of the transcripts (Miles & Huberman, 1994 in (Crabtree & Miller 2015)).

The development of the template formed a central part of this analysis. The initial template was derived from Oates et al. work and it was applied to all the interviews in a first round of analysis. The results resulting from this initial analysis were revised to produce an updated version of the template as part of an *"ongoing analysis"* (King 2004 in (Cassell & Symon 2004)). The keywords presented in Table 4-2 are the outcome of the analysis carried out with the last and most developed version of the template.

Table 4-2 Coding template (Adapted from Oates et al. 2008 and King 2002)

First-level code	Second-level code
Context	Reasons for purchase Occupancy patterns Experience of inhabiting
Drivers	Motivation Intention Values
Filters	Constraints Information sources Fixed (strong) filters Variable (weak) filters Non-criteria
Outcome	Measures applied Measures discarded

As for the role of the user in the decision making process, the analysis was approached following a 'grounded theory' stance (Strauss & Corbin 1998). That is, no predefinition of user related factors was made and all the criteria discussed in the next sections emerged exclusively from analysis of the data using the template.

4.1.1 Definition of terms

Prior to discussion of the results, a clarification of some of the terms used in the analysis is provided. Most of the terms below were adapted from Oates et al. work, and so were their definitions.

- Context. Every retrofit occurs in a specific setting. This term comprises all the interdependent factors that shaped that specific circumstance (time of purchase, previous experiences, lifestyle, living arrangements, working patterns, etc.).
- Driver. It refers to the attitudinal aspect of a decision. That is, drivers report the intention and motivations behind the retrofit of the building (e.g. improving comfort).
- Constraint. The criteria that were external to the process and were not in the immediate control of the decision maker (e.g. product availability).

- Filter. The mechanisms that individuals used to narrow the range of available options. They were classified as strong or weak.
    - Strong filter. It was considered strong when it worked as a barrier. It involved those criteria that the decision maker was not willing to compromise (e.g. conservation of a historic feature).
    - Weak filter. It was considered weak when it worked as a limitation. Those were the criteria that the decision maker may consider to negotiate during the process (e.g. level of disruption to the tenants).
- Non-criteria. There were many criteria that were not included in the decision making process. However, this term referred only to those that were explicitly mentioned as irrelevant in the process.
- Outcome. The result of the process. The outcome could also be a decision to postpone or cancel the retrofit.

4.2 Results

The results presented below are organised according to the two sub-questions presented in Chapter 3:

- Sub-Question 1. What are the driving factors for decision makers when adopting energy efficient technologies in traditional buildings?
- Sub-Question 2. How are user behaviour and comfort needs considered when adopting energy efficient technologies in traditional buildings?

First, all the driving factors involved in the decision making process were identified (Section 4.2.1). The next section (4.2.2) focuses exclusively on the role of user and how it is perceived by the DM.

4.2.1 The driving factors in the process

Analysis of the interviews looked at both attitudinal (intention, motivations and values) and behavioural (kind of activities, amount of activities and consistency of activities) constructs of decision-making (McDonald et al. 2012). These allowed for the identification of numerous factors that were classified as ‘driver’ or ‘filter’ according to their role in the process. The results presented below are sorted following that classification.

4.2.1.1 Drivers: motivations for retrofitting

Despite the limited size of the study, the sample included a wide range of scenarios with different motivations and attitudes towards the energy efficiency improvement of traditional buildings. All the drivers found during the analysis were grouped in five categories presented in Table 4-3. Often, the interviewees referred to (explicitly or implicitly) more than one criterion as motivation for the retrofit. In general, it was found that the owner-occupiers have a richer and more comprehensive approach as they take more factors into account when deciding to retrofit their building.

Table 4-3 Drivers for retrofit reported by the DMs

	Occupier						**Non-occupier**					
	1	2	3	4	5	9	6	7	8	10	11	12
Environment		X	X		X			X				
User	X		X	X	X	X	X			X		
Regulation							X	X	X		X	
Self-Reliance	X	X		X		X						
Economics	X	X	X			X						X

The environmental benefits of improving the building efficiency were suggested as a motivation for the refurbishment by four DMs. In fact, achieving a reduction in CO_2 emissions was found to be a very important driver for some of them (Interview 5. Occupier). Environmental concern was mainly found among the private owners and it was always used along with other drivers like users' comfort or energy bills.

> *"We realised that burning gas in the old boiler was just ridiculous. In global terms is not the huge thing but (it is) our contribution" [Interview 3. Occupier]*

The user was mainly considered a driver for the retrofit among the DM that sought to improve occupants' comfort. That was primarily pursued by means of an increase in the internal temperature but also by reducing the amount of work involved in operating the system. This driver was suggested by both occupiers and non-occupiers. However, while home owners mentioned aspects like *"cosiness"*, landlords were trying to make the properties *"more appealing to people who might want to live there"* [Interview 10. Non-occupier]

Performance requirements established by some regulations acted as an imposed driver for some DMs, especially for those who did not occupy the building. These regulations were imposed by compulsory legislation or voluntary schemes such as BREEAM (Reed et al. 2010). For instance, the forthcoming implementation of a new Energy Efficiency Standard for Social Housing (The Scottish Government 2015) was a common concern among the landlords and their main driver for the retrofit.

> *"We are painfully aware that there is that deadline ahead of us and we need to start" [Interview 6. Non-occupier]*

Another important driver for the private home owners was the improvement of their self-reliance or future-proofing in terms of energy dependence. Some owners followed a long-term strategy when refurbishing their buildings and included future energy demand as a key aspect in their decisions.

> *"I think it's obvious that hydrocarbons will be depleting more significantly at some point in the future and I certainly want to have less exposure to that" [Interview 3. Occupier]*

In addition to self-reliance, economics played an important role as a motivation for the DMs. This driver relates to the reduction of the running costs of the building during the operational phase. These costs mainly referred to the heating system and therefore the goal of the improvement was the reduction of heat losses. This driver was mainly considered by owner-occupiers as the DMs generally understood that the improvement benefited exclusively those paying the energy bills.

> *"We would be probably doing some insulation work but it would be on the basis that, we will insulate it, we will charge you a bit more rent because you are going to save a little bit of money in your fuel bills" [Interview 7. Non-occupier]*

4.2.1.2 Filters: restrictions for retrofitting

The second part of the analysis focused on the filters used by the DMs to either choose or discard specific measures of energy efficiency. The filters were related to the particularities of the context or the preferences of the DMs and were expressed differently by each interviewee.

For a better comparison, the responses were organised in six categories, as shown in Table 4-4. Filters, as described above, were labelled as weak or strong according to the respondents' narratives of the decision making process. The factors were marked as non-criteria only when explicitly mentioned by the DM during the interview.

Table 4-4 Strong (+) and weak (-) filters and explicit non-criteria (○) identified in each interview

	Occupier						**Non-occupier**					
	1	2	3	4	5	9	6	7	8	10	11	12
Environment	○		+	○	+	-		-	+			
User	-	-	-	-	-	+	+	+	-	-	+	-
Conservation	+	-	-	○	+	+	+	○	+			-
Risk	+	+		+	-	○	-	+	-	+	-	-
Resources	+	-	+	-	-	-	+	-		+	+	
Economics	-	+	+	-	-	+	+	+	+	+	+	+

The DMs generally narrowed the environmental filters to just one aspect. Thus, despite the different levels of awareness of the environmental implications of any retrofit found in the interviews, the final aspect considered was mainly the reduction of non-renewable fuels consumption and greenhouse gases emission. Other aspects such as the use of natural or recycled materials in order to reduce the environmental impact associated to the production were often ignored or explicitly presented as non-criteria.

> *"I'm definitely less interested in eco-friendly materials, like sheep wool and that sort of things (…) Modern materials are more efficient but I admit that it is less ecologically friendly" [Interview 4. Occupier]*

When the user was considered in the selection of measures two main concepts were discussed: the controllability of the system and the disruption caused during the installation of the measures.

> *"What we find is that is quite a disruption to the tenants to do internal wall insulation" [Interview 11. Non-Occupier]*

Due to the particularities of traditional buildings, conservation of the original features and compatibility of energy efficiency measures with the existing structure were important criteria for some DMs when choosing the specific measures.

> *"There is no way we would try to take out the woodwork to make it (the building) more energy efficient" [Interview 5. Occupier]*

The perception of risk and the negative effect that a certain measure would have on the value of the property can have a great importance during the process. The same measure can be seen as perfectly safe in one case while other DM could consider it dangerous and not worth the risk.

> *"[Have you ever considered insulating the cavity?] I would be frightened to. It may work but I'm not prepared to take the risk..." [Interview 5. Occupant]*

The DMs also evaluated the amount of technical and human resources that the implementation of the measures would require. The lack of resources (or funding to provide them) could make unfeasible options that were appealing to the DMs.

> *'We decided to do that ourselves. The rolls for £3 each, it's almost a no brainer. But you have to be willing to do the actual physical stuff yourself" [Interview 2. Occupier]*

> *"This is a building that, just now, could receive 100% funding for the whole internal (insulation). But they don't have the resources to do it" [Interview 11. Non-occupier]*

Along with resources there are several financial factors that are taken into account by the DMs during the process: upfront cost, pay-back period, running costs or funding availability. This is an important filter for most of the DMs, but in some cases it becomes crucial.

> *"Cost is clearly an issue for us. And it is a barrier" [Interview 7. Non-occupier]*

The weight that the DMs assigned to each of these filters varied greatly between cases. For instance, factors like conservation of the original features in a building were a strong filter for some DMs (Interview 5) while in other cases it was just a negotiable filter (Interview 2) or it was not even considered as a filter at all (Interview 4).

The analysis of the interview data identified numerous criteria that DMs considered as part of a complex process. The use of templates in the interview analysis exposed the differences between attitudinal and behavioural constructs. Thus, regulation or self-reliance were only mentioned as motivations for the retrofit while building conservation, risks or technical and human resources appeared exclusively as filters for the selection of the measures to be applied. On the other hand, environment, user and economics were present at both stages even though their perception changed notably during the process. For instance, when economics was the driver of the retrofit, the goal of the DM was to reduce the running costs. Whereas, when economics was used as a filter for the selection of measures, the cost of the technology was usually more determining than its potential savings.

The analysis of the transcripts revealed the influence of the type of ownership on the decision making process. Whether the DM is an occupier or not of the building has proven to have an important effect on the motivations for the retrofit. For instance, self-reliance was exclusively a driver for home owners, while regulation was only a motivation for those who were not occupiers of the building. The differences between occupiers and non-occupiers were also clear when analysing the adoption of filters. Improving users' comfort was the main goal of the retrofit for most of owner occupiers and therefore they prioritized the measures that they thought could offer the best results in achieving an increase in the internal temperature. Non-occupiers, on the other hand, were mainly driven by external obligations (regulations) and prioritised the rationalisation of funding and resources required for the intervention.

These findings led to the identification of a new analogy between the decision making processes in retrofit projects and the purchases of sustainable products. In sustainable consumption research it has been argued that there is no green or grey consumer, in the sense of green consumers being the consumers who prefer products or services which do least damage to the environment and support forms of social justice and grey consumers are those who consistently do not engage with or have no interest in such issues (McDonald et al. 2012). Consumers are rather suspended in some kind of tension between grey and green purchasing. In this case, a similar scenario appeared. The DMs formulated their decisions as a balance between economic factors (cost and resources) and the rest of the criteria. In general, the DMs non-occupiers were shifted towards the more financial aspects (economics, resources and risk) whereas the occupiers prioritized the non-economic criteria (environment, users and conservation).

4.2.2 The perception of users' role

The analysis of the interviews showed that DMs had very different approaches towards the role of users as a criterion in the process. These approaches were shaped by the importance given to the user as a driver or filter of the retrofit. Thus, the DMs can be distinguished between those who see the user as the 'beneficiary' of the improvement, a potential 'customer' or the 'operator' of the system, as presented in

Table 4-5. The differences between these roles are summarised below.

Table 4-5 The DMs' perception of the users' role

	Occupier						Non-occupier					
	1	2	3	4	5	9	6	7	8	10	11	12
User as a Recipient	X	X	X	X								X
User as a Customer								X		X	X	
User as an Operator					X	X	X		X			

4.2.2.1 The user as beneficiary

Although not exclusive to private owners, this approach to the user role was mainly found among the owner-occupiers. They generally understood that they were going to be the end users of the retrofit and therefore they would eventually benefit from any improvement made to the building.

The analysis showed two different ways in which the DMs perceived that the user benefited from the building efficiency improvement: higher comfort and lower bills. First, an increase in the internal temperature would improve the comfort conditions of the user and produce a healthier environment. Despite the different contexts present within the sample, the perception of users' comfort was similar for most of the DMs. An increase in the mean temperature is usually perceived as the main, if not the only, way to achieve higher norms of comfort. Achieving a healthier environment was specifically suggested as an important driver in two cases. In the first case, the owners were trying to create a healthier environment for their young son while in the second the owners were trying to avoid previous health problems experienced while inhabiting an old house. In both cases, a complex term such as health was narrowed to a single criterion: a higher mean internal temperature.

> *"I like to be cosy and also because my health reasons. I am very susceptible to cold and I need the houses to be warm and comfortable" [Interview 4. Occupier].*

Reduction in the running costs was also weighed heavily in the final decision of retrofitting the building. If the preferred temperature was already achieved, the main driver for the improvement was the reduction of the costs. Therefore, in those cases the expected outcome was a reduction in the energy bills.

When it came to the selection of measures, the DMs prioritised any option that could achieve the anticipated outcome (either temperature increase or reduction in energy bills) without requiring or expecting any change in the user behaviour. On the other hand, the disruption that the works caused to the users was accepted - in most of the cases - without hesitation in return for a better environment after the completion of the renovation.

4.2.2.2 The user as customer

The majority of the DMs that did not occupy the building perceived the user as a customer. This approach towards the user was found in three (out of four) cases where the owners were renting the properties for housing. The contexts of these DMs, however, were very different. One of them was a private owner renting a cottage in a small town, the second DM was a rural landlord renting properties under the affordable housing scheme and the last DM was a project manager of a registered housing association operating within the city centre. While the private landlord was trying to improve the property in order to make it more appealing to potential tenants, the other two DMs were primarily driven by imposed regulations.

Users and economics were crucial for all the DMs despite the differences in contexts. Running costs were very important either because the DMs were hoping that a low energy bill would attract potential tenants or because of landlords' commitment to provide affordable housing to people with limited income. Upfront or investments costs were also important because of the limited funding and resources available.

The disruption that the implementation of the measures would cause to the tenants was a common concern to all the landlords. Therefore, the DMs chose measures that did not interfere with the normal life of the tenants or they only acted on the properties when they were vacant. In that case, time was an important constraint as they needed to finish the works as quickly as possible in order to rent the property again.

> *"Clearly, how disruptive an activity is, is going to be an issue" [Interview 7. Non-occupier]*

In all three cases, the convenience or controllability of the system was a secondary factor when choosing the measure. It weighed much less than the total investment cost or the potential reduction in the final energy bills.

Since the user of the building was seen as a client, the DM had to consider their acceptance of the measures. They presented users' approval as a balance between the benefits - a warm and affordable household - and the disruption, especially during the implementation of the measures. Therefore, the outcome of the intervention was expected to provide a warm environment that was cheaper to run without imposing the users to make any change in their daily practices of comfort.

4.2.2.3 The user as operator

The last approach found among DMs was the representation of users as the building operators. This approach was evenly distributed between owner occupiers and non-occupiers. Although the DMs shared the same approach towards the user, the drivers for upgrading the building varied greatly between them (Table 4-3). An environmental concern was the main reason for the retrofit for a private owner (Interview 5). In the other cases, the drivers were less altruistic and the intervention sought to ensure users' comfort (Interview 9) or simply complying with imposed (Interview 6) or self-imposed regulations (Interview 8).

Consideration of the interaction between user and building services was one of the main filters in the selection of retrofit measures for all of them. The user was seen as a barrier for the implementation of certain technologies as they required some specifications in terms of convenience and controllability of the systems. Disruption, on the other hand, was less important as owner-occupiers were willing to accept it in exchange for more efficient systems and the non-occupiers always carried out the works when the buildings were vacant.

Context was very important in shaping the retrofit strategy. The different motivations found in the sample were heavily affected by the type of ownership. While private owners were driven by environmental and economic reasons, the non-occupiers were obliged by regulations. The filters adopted, on the other hand, were not influenced by the ownership but by previous experiences. For instance, one of the private owners (Interview 9) presented the retrofit of the envelope almost as a consequence of a change in the heating system. A biomass boiler was first installed to fight unpleasant internal temperatures and high running costs. The biomass system solved the original problems but created new ones. After the implementation of the boiler, the DMs learned the hard work involved in the collection, processing and storage of wood and the inconvenience of operating the boiler every few hours because of the high heat losses of the house. The next intervention (insulation of the envelope) was therefore aimed to increase users' comfort not by increasing the temperature but reducing the use of the heating system.

In the case of the DMs that did not occupy the buildings, experiences of previous retrofits carried out in other properties were crucial when adopting new technologies. One of the DMs (Interview 6) had discarded the installation of any biomass heating system after the unsuccessful implementation of multi-fuel stoves in a previous project. The stoves were installed with the intention of helping tenants with limited income by giving them the opportunity to use alternatives sources of energy. However, the intervention failed due to the users' negative reaction to heating systems that were not programmable and more difficult to operate.

> *"The problem is that you come back in the evening, the house is cold, you have to light up the fire and it takes a time before the house gets warm. To be honest, people prefer the convenience of controllability, even if it costs more" [Interview 6. Non-occupier]*

A similar approach was found in the case of the other owner non-occupier (Interview 8). The DM was responsible for the renovation of a neglected building to be used as part of their teaching facilities. Previous experiences had proven to the DM that the users of their buildings liked to feel in control of the environment. On the other hand, that had often caused high levels of energy consumption and disputes between users with different thermal preferences. DM's solution was to design a heating system with two levels of adjustment. The system allowed the facilities management team to set a central thermostat with a range of predefined temperatures while leaving certain level of flexibility to the users to adjust the temperature of the room a couple of degrees.

4.3 Discussion

Previous studies have proven the crucial role that users play on the final performance of any energy related retrofit measure (see Chapter 2). Based on that, this study was performed to investigate the way in which users were considered during the retrofitting process. The profiling of DMs (

Table 4-5), based on identified drivers and filters, helped to determine which aspects of the user were considered. Three different approaches towards users were found in the study: the DMs that saw the user as the beneficiary of the improvement, those that depicted the user as a customer and the DMs that presented the user as operators of the building and its services.

The results found when comparing the drivers and filters of DMs with different approaches revealed very different processes in the adoption of retrofit measures. Among the DMs that saw the user either as a beneficiary or a customer, the interaction of the user with the building was seldom discussed and when it happened it was simplistic or partial. Usually, only one aspect of the user was considered at a time. More specifically, the discussion involved either the satisfaction of the users' requirements in terms of comfort or the disruption caused to the occupants during the implementation of the measures. A similar result was obtained by Vlasova & Gram-Hanssen (2014) in their research of energy retrofits in Denmark. Their investigation, that included three case studies, found that everyday practices of the inhabitants were only considered in order to achieve higher norms of comfort.

A one-sided assessment of users' needs and behaviour can lead to unexpected and undesired consequences. For instance, an increase in the airtightness of a dwelling is expected to have a positive impact on the occupants' health and well-being while also reducing energy consumption and GHG emissions. However, it has been found that for some individuals the lack of natural sound produces anxiety and sense of isolation (Evans 2003; van Kempen et al. 2012; Lorenc et al. 2014) and they increasingly open the windows to compensate the lack of noise. This leads to higher heat losses and energy consumption producing the opposite of the desired effect (Shrubsole et al. 2014).

The DMs that looked at the user as the beneficiary or a customer tended to have a narrow and short term vision for the performance of the building based only on the current requirements of the users. The measures adopted were chosen to cope with the users' current expectations of comfort and to accommodate their daily routines. No reflection was found on future behaviours of users and their effect on the final performance of the building.

When the user was presented as the building operator the reflection on the interaction between users and systems was much more profound. DMs generally accounted for future behaviour of users and its effect on the building performance. The retrofit project described in Interview 8 is a clear example of a DM that presented users as operators and that reflected on their behaviour. In that case, users' behaviour was an important criterion for the selection, design and implementation of the heating system. The system was successfully installed and operated, matching the results established a priori in terms of energy consumption and users' satisfaction. DMs that explore present and future users' requirements can make a much better informed decision that will often lead to better performing buildings (Leaman & Bordass 1999).

Among the DMs that viewed the users as operators, the understanding of user behaviour and its effect on the building performance was mainly based on their past experiences. Thus, DM 6 favoured systems controllability after the unsuccessful installation of multi-fuel stoves and DM 8 designed the retrofit project to avoid problems faced in the past with the users' control of heating system. Owners of large portfolios of properties can increase their awareness and understanding of the interaction between users and buildings as they retrofit the buildings. However, for many of the decision makers, especially private owners, this sort of improvement is a one off action (Haines et al. 2010) and therefore they do not have the opportunity to learn from previous projects.

In general, users' interaction with the building and its services was not sufficiently considered during the decision making process. Even among the DMs that presented the user as an operator, the user impact on the internal climate and its compatibility with the implemented measures was not always discussed during the decision making process. The results of the interviews suggested that it was basically due to the lack of awareness and understanding of the effect that user behaviour can have on the final performance of the building.

Considering the proven effect of user behaviour, a change in the DMs' approach to the retrofits is highly recommended. The results of this study have shown that DMs should not be targeted based exclusively on the type of ownership but instead they have to be approached universally. DMs should be encouraged to perceive the users as operators and to reflect on the interactions between users and buildings. That would urge DMs to consider future users' requirements when adopting retrofit measures and to discuss the effect that user behaviour would have on the building performance. The shift in the DMs perception of the users' role should come together with an increase in the awareness of the potential unintended consequences. Dissemination of successful - and unsuccessful - cases through manufacturers, practitioners and public organisations would help to increase the understanding of the interactions between users and buildings among the DMs.

4.4 Conclusions

The hypothesis formulated in the previous chapter as a result of the literature review suggested that:

> *"Decision makers do not take the effect of user behaviour on the performance of the building into account when retrofitting a traditional property"*

The results of this study confirmed the validity of this hypothesis. Although the user is often considered as part of the decision making process, it has been found that there is almost no discussion of how users' everyday practices can or cannot be compatible with the implemented measures. It is commonly accepted among DMs that an increase in the internal temperature would increase comfort and lead to higher users' satisfaction levels. On the other hand, the users' behaviour and their interaction with the building is often perceived as something trivial that will not change after the renovation and that will not have an important effect on the building.

Considering the influence of users on the final performance of retrofitted buildings, an increase in the awareness and understanding of such relationships among the DMs is urgently needed.

The results obtained in this study led the research into the exploration of the actual behaviour of users of traditional Scottish dwellings and their effect on the buildings performance. Next chapter presents the results of a multi-case study covering retrofitted and non-retrofitted buildings. The study included an investigation of the energy related behaviour of occupants and the monitoring of the internal environmental conditions.

4.5 Summary

This chapter presented the results of an investigation on the decision making process of traditional buildings retrofits. Twelve semi-structured interviews with owners and key members of management teams were conducted to investigate the role of user behaviour in the adoption of low carbon measures in recent renovations of traditional buildings.

The interviews transcripts were examined using a template analysis. The template used in this study was developed based on the 'purchase model' created by Oates et al. (2008) as a result of their investigation on the acquisition of sustainable products.

Analysis of the interview data allowed for the identification of numerous criteria that DMs considered as part of a rich and complex decision making process. These criteria were clustered in the following eight groups: environment, users, conservation, regulations, self-reliance, risk, resources and economics.

The analysis of the user related criteria allowed for the profiling of DMs in three groups according to their perception of the users' role during the decision making process. DMs were found to depict the user as either a beneficiary, a customer or an operator.

Despite the differences in the approach towards the end user, it was found that the effect of user behaviour on the long term performance of the building was not sufficiently discussed. Only the DMs that thought of the user as an operator included some reflection on the interaction between them and the building. Representation of users' behaviour was however incomplete and an increase in the understanding of the potential consequences of user behaviour is needed for a more robust adoption of retrofit measures.

5 OCCUPANTS, COMFORT AND INTERNAL CLIMATE

After the investigation of the users' role in the decision making process explored in the previous section of the thesis, chapters 5 and 6 investigate the relationship between users and internal climate. The results presented here look at the daily practices of comfort of the occupants, while the physical characteristics of the indoor environment are discussed in the next chapter.

As explained in Chapter 3, a multi-case study approach was designed in order to gather the qualitative and quantitative data required to answer the questions formulated at the beginning of this research. The sample was formed by 24 households of traditional buildings located in the North-East of Scotland. A comprehensive study of the users' behaviour was carried out with the aid of interviews, questionnaires and home tours with the occupants. The characteristics of the households included in the sample are presented in Table 5-1. The buildings, that presented different levels of improvement, were classified as 'retrofitted' or 'non-retrofitted' based exclusively on whether or not the external wall was insulated. The characteristics of the buildings, as well as the details of the monitoring campaign, are summarised in Table 5-2.

Table 5-1 Multi-case study sample. Households' characteristics.

Household	Gender (1)	Age	Ethnicity (2)	Marital Status	Ownership	Time	Occupants	Education (3)	Occupation (4)	Income (5)		Gas cost	Electricity cost (6)
Case 1	Female*/Male*	25-44	WB/OW	Married	Buying	1-5	3	UD	PTE/FTE	E	NA	NA	NA
Case 2	Male	45-64	WB	Single	Renting	>10	1	NA	R	OA	NA	NA	£140
Case 3	Female	25-44	WB	Single	Renting	1-5	1	UD	SE	E	<20,000	NA	£50
Case 4	Female	25-44	WB	Single	Renting	6-10	1	SS	FTE	E	20-35K	NA	£40
Case 5	Female	>65	WB	Single	Renting	>10	1	SS	FTE	E	<20,000	NA	£110
Case 6	Female	45-64	WB	Single	Renting	>10	1	SS	FTE	E	NA	NA	£38
Case 7	Male	25-44	WB	Single	Renting	1-5	1	UD	U	JB	<20,000	NA	£80
Case 8	Female	25-44	WB	Single	Renting	1-5	1	UD	FTE	E	20-35K	NA	£125
Case 9	Female	25-44	WB	Single	Renting	<1	1	HE	PTE	H	<20,000	NA	£60
Case 10	Female	25-44	OW	Single	Renting	1-5	1	UD	SE	E	<20,000	NA	£48
Case 11	Female/Male*	45-64	WB	Married	Renting	<1	2	UD	FTE	E	35-50K	£110	£50
Case 12	Female*/Male*	45-64	WB	Married	Renting	<1	2	SS	FTE	E	20-35K	NA	NA
Case 13	Female*/Male*	25-44	OW	Married	Renting	1-5	4	UD	SE	E	35-50K	£100	£40
Case 14	Female*/Male*	25-44	WB	Single	Renting	1-5	3	HE	FTE	E+C	35-50K	£150	£50
Case 15	Female*/Male*	25-44	OW	Married	Renting	1-5	2	UD	FTE	E	>50,000	£100	£100
Case 16	Female/Male*	>65	WB	Married	Owned	6-10	2	UD	R	P+I	20-35K	£61	£40
Case 17	Female*/Male	25-44	WB/A	Single	Renting	1-5	3	UD	FTE/PTE	E+C	20-35K	£100	£100
Case 18	Female*/Male	25-44	OW/WB	Married	Renting	<1	2	UD/HE	FTS/FTE	E+OA	20-35K	NA	NA
Case 19	Female	25-44	OW	Single	Renting	<1	1	UD	FTS	OA	<20,000	£22	£21
Case 20	Female/Male*	>65	WB	Married	Owned	>10	2	UD	R	P	20-35K	£125	£30
Case 21	Female/Male*	>65	WB	Married	Owned	>10	2	UD	R	P+I+OA	35-50K	£118	£49
Case 22	Female*/Male	45-64	WB	Married	Owned	>10	2	UD	R	P+OA	>50,000	£140	£60
Case 23	Female/Male*	>65	WB	Married	Owned	>10	2	HE	R	E+P+OB	NA	£70	£40
Case 24	Male	25-44	OW	Single	Renting	1-5	1	UD	FTE	E	>50,000	NA	NA

(1) If more than one occupant, that/those who were interviewed are marked with *

(2) WB: White British; OW: Other White background; A: Asian background

(3) UD: University Degree; HE: Higher Education; SS: Secondary School

(4) FTE: Full Time Employed; PTE: Part Time Employed; SE: Self Employed; FTS: Full Time Student; U: Unemployed; R: Retired

(5) E: Earnings from employment; P: State retirement pension; C: Child benefit; JB: Job-seeker allowance; H: Housing benefit; OB: Other state benefit; I: Interest from investments; OA: Other regular allowance

(6) Both gas and electricity are cost per month

Table 5-2 Multi-case study sample. Buildings characteristics. Values in parentheses represent ± one standard deviation.

Household	House type (1)	Position	Storeys	Bedrooms	Bathrooms	Open chimneys	Exposed walls	Insulation	Heating system (2)	Monitoring period	Living room				Bedroom			
											Mean Temperature		Mean Moisture Load		Mean Temperature		Mean Moisture Load	
Case 1	D	NA	2	2	2	1	4	No	G	18/07/13-23/08/13	20.0	(1.7)	1.2	(1.1)	20.6	(2.2)	0.6	(1.0)
								Yes		25/08/13-12/02/14	16.6	(2.0)	2.6	(1.4)	15.5	(2.3)	2.3	(1.4)
Case 2	F	G	NA	1	1	0	2	No	E	23/02/14-08/02/15	18.3	(2.0)	1.8	(1.2)	16.4	(2.0)	NA	NA
Case 3	F	G	NA	1	1	0	3	No	E	23/02/14-02/03/15	13.4	(2.1)	1.4	(2.0)	14.3	(2.3)	1.2	(2.0)
Case 4	F	1	NA	1	1	0	2	No	E	23/02/14-03/02/15	14.7	(3.5)	1.5	(1.3)	16.4	(3.3)	1.6	(1.4)
Case 5	F	2	NA	2	1	0	3	No	E	23/02/14-05/03/15	19.3	(2.2)	2.7	(12)	17.5	(2.1)	2.2	(1.3)
Case 6	F	TP	NA	1	1	0	2	No	E	23/02/14-05/03/15	17.2	(2.0)	1.7	(1.5)	15.4	(2.5)	0.9	(1.1)
Case 7	F	G	NA	1	1	0	2	No	E	23/02/14-02/03/15	17.2	(2.0)	1.7	(1.5)	15.4	(2.5)	0.9	(1.1)
Case 8	F	G	NA	1	1	0	2	No	E/BG	23/02/14-10/12/14	19.4	(3.6)	2.5	(1.6)	18.5	(3.3)	2.8	(1.5)
Case 9	F	1	NA	1	1	0	2	No	E	23/02/14-05/03/15	18.5	(3.0)	1.7	(1.3)	16.5	(3.2)	1.8	(1.3)
Case 10	F	2	NA	2	1	0	3	No	E	23/02/14-03/03/15	16.7	(4.2)	2.5	(1.1)	18.5	(2.9)	2.7	(1.2)
Case 11	SD	NA	2	1	2	0	2	Yes	O/B	21/05/14-05/05/15	18.8	(2.2)	0.4	(1.3)	17.6	(1.0)	0.4	(1.3)
Case 12	D	NA	1	2	1	0	6	Yes	O/B	21/05/14-05/05/15	15.8	(3.0)	1.0	(1.4)	13.6	(3.4)	1.1	(1.3)
Case 13	D	NA	2	3	2	0	4	Yes	B	30/05/14-05/05/15	20.3	(2.4)	2.1	(1.7)	18.5	(2.1)	1.6	(1.8)
Case 14	D	NA	2	3	2	1	4	No	O/B	12/11/13-10/12/13	14.6	(3.0)	NA	NA	14.7	(3.6)	NA	NA
								Yes		30/05/14-05/05/15	18.2	(2.1)	1.0	(1.2)	19.0	(2.3)	0.9	(1.3)
Case 15	F	1	NA	1	1	0	2	No	G	06/12/14-07/05/15	15.7	(2.6)	3.0	(1.3)	16.0	(2.8)	2.7	(1.5)
Case 16	SD	NA	2	3	2	0	3	Yes	G/B	06/12/14-05/05/15	16.0	(2.9)	2.4	(1.6)	13.4	(3.0)	2.4	(1.3)
Case 17	F	1	NA	3	1	0	3	No	G	09/12/14-14/04/15	15.7	(1.6)	2.5	(1.4)	12.4	(1.9)	2.4	(1.3)
Case 18	F	G	NA	2	1	0	3	No	G	08/12/14-08/05/15	17.4	(2.0)	2.4	(1.4)	15.9	(2.5)	2.0	(1.4)
Case 19	F	3	NA	1	1	0	2	No	G	07/12/14-07/05/15	14.9	(2.5)	0.9	(1.2)	12.8	(2.4)	0.4	(1.1)
Case 20	SD	NA	2	3	2	1	3	Yes	G/B	10/12/14-11/04/15	16.9	(2.7)	1.6	(1.5)	14.9	(1.2)	2.0	(1.2)
Case 21	SD	NA	3	4	2	2	2	No	G/B	11/12/14-30/04/15	15.7	(2.8)	0.1	(1.2)	14.0	(1.5)	0.1	(1.1)
Case 22	SD	NA	2	3	2	1	3	Yes	G	15/12/14-05/05/15	15.9	(2.5)	0.9	(1.4)	17.4	(1.6)	1.2	(1.4)
Case 23	SD	NA	2	4	2	1	3	Yes	G	05/02/15-05/05/15	14.6	(2.1)	1.9	(1.1)	16.2	(2.7)	1.9	(1.2)
Case 24	F	2	NA	1	1	0	1	Yes	G	16/12/14-30/01/15	14.5	(2.0)	0.1	(1.0)	12.9	(2.3)	0.5	(1.1)

(1) D: Detached; SD: Semidetached; F: Flat

(2) G: Gas; O: Oil; E: Electricity; B: Biomass; BG: Bottled gas

5.1 The meaning of comfort at home: daily practices and indoor environment

As part of her research on reduction of energy consumption in buildings, Janda illustrated the importance of users' role saying that *"buildings don't use energy, people do"* (2011). This statement was challenged by Shove when saying that *"people do not use energy, water and other natural resources. They use the services that make these resources possible"* (Shove 2011). This idea is based on Warde's premise that consumption occurs in the course of engaging in particular practices (2005). That means that consumption of energy is not a goal per se but an outcome of ordinary practices adopted by the user such as heating, eating, cooling and showering. Consumption, therefore, cannot be equalled to demand (Harvey et al. 2001) and the efforts to reduce energy consumption should be directed to the understanding of how practices that require energy are reproduced and how they can be changed (Shove & Walker 2014).

This thesis uses an analogous rationale when exploring the effect of users on the indoor environment of traditional buildings. The internal climate is an outcome of users' practices of comfort (such as heating, ventilating or laundering), especially in residential buildings where householders are usually in charge of their own comfort (Tweed et al. 2013). Therefore, the efforts to explore the internal climate in traditional dwellings should be directed to understand how the practices of comfort that affect the environment are reproduced and how they can be changed.

In the following, an introduction to social practice theory is presented. Besides summarising the evolution of these theories, the relevance of social practice for this research is discussed and the way in which social practice theory was used in this study is presented. Next, the analysis methods used for the examination of the interviews are described briefly before the explanation and discussion of the results.

5.1.1 Social practice theory

In the last few years, the body of research focused on users' effect on space heating, energy consumption and indoor climate has grown rapidly. Some of the research recently developed in this field (Gram-Hanssen 2010a; Hargreaves 2011; Bartiaux & Salmón 2012; Butler et al. 2014) has adopted some ideas of social practice theory as an effective approach towards *"theoretical consolidation"* of the understanding of user behaviour (Warde 2005). The first ideas of social practice were suggested by Giddens (1984 and 1991) and Bourdieu (1984 and 1990). Giddens set a cornerstone for the development of practice as a theory when highlighting its relevance as a subject of study within the social sciences:

> *"The basic domain of study of the social sciences (…) is neither the experience of the individual actor, nor the existence of any form of societal totality, but social practices ordered across space and time" (Giddens 1984, p.2)*

A new and more practical approach to the subject has been developed recently by Reckwitz (2002), Schatzki et al. (2001) and Warde (2005). Although practice theory gathers a disperse body of theories (Gram-Hanssen 2010a), Reckwitz's definition of practice is commonly accepted among theorists:

> *"A 'practice' (Praktik) is a routinized type of behaviour which consists of several elements, interconnected to one other: forms of bodily activities, forms of mental activities, 'things' and their use, a background knowledge in the form of understanding, know-how, states of emotion and motivational knowledge" (Reckwitz 2002, p.249)*

Practice theories built upon Giddens' work facilitated a change from individualistic and rationalistic approaches of behaviour to more collective exploration of the organisation of practices. In fact, as explained by Hargreaves (2008), most of the researchers adopting this approach avoid the use of the term 'behaviour' (with traditionally individualistic connotations) in favour of 'practice' (which represents a social phenomenon with shared norms (Hards 2012)). In this research, following Hargreaves' example, both terms were used but with different purposes. Behaviour was only used to describe the individual implementation of practices, analogous to Schatzki's idea of practice-as-performance (Warde 2005), while practice refers to the abstract idea that is shared by the collective (practices-as-entities).

Despite agreement on the definitions of practice, "*there is no unified practice approach*" (Schatzki et al. 2001) and practice theory often lacks clarity and applicability in empirical research (Christensen & Røpke 2005; Spaargaren 2013; Hargreaves 2008). In this study, the approach proposed by Shove & Pantzar (2005) is adopted as it provides the most helpful framework for the empirical application of practice theory ideas (Hargreaves 2011). Shove & Pantzar structured practices around three main concepts (meaning, materials and competence) that are dynamically integrated by the practitioner. Being a practitioner therefore "*requires appropriation of the requisite services, possession of appropriate tools, and devotion of* *a suitable level of attention to the conduct of the practice*" (Warde 2005). The three components of a practice were defined by Shove & Pantzar as follows:

- Meaning. It refers to the images or symbolic aspects of the practice. The same practice will have different connotations for individuals when engaging in it. For instance, cooking can be seen as a relaxing and recreational activity for those who engaged in the practice as a hobby, while for professional chefs the practice of cooking is linked to work-related images.
- Materials. The physical objects and 'stuff' that are required to develop the practice. Practices can be limited, or enhanced, by the available materials. At the same time the requirements for the practice are directly related to the meaning given to it. Thus, a chef will require full professional equipment that goes beyond the basics pots, pans and a hob that any amateur cook would need.
- Competences. The performance of any practice requires certain skills to use the materials according to the meaning of that practice. Using cooking as an example again, the competences of a professional chef would have to be much more advanced than those required by an individual cooking a meal at home.

According to Shove and Pantzar (2005), the links between all these three elements are reproduced and maintained by the practitioners, represented as "*carriers*" of the practices. Moreover, practices emerge, develop and disappear as a consequence of the formation or dissolution of these links. New practices can therefore be generated by breaking the links between elements of existing practices and re-making them in a different manner (Hargreaves 2011). For the purpose of this research, that means that practices that are more compatible with the retrofit of traditional buildings could be generated if the links of existing unsuitable practices are identified and challenged. To that end, the first goal of this study was to explore users' behaviour to identify the elements, and the links between them, that shape their practices of comfort at home.

5.2 Data analysis

The multi-case study designed for this study explored the daily practices of comfort at home by gathering users' experiences of heating use, ventilation patterns and moisture producing habits. The study also investigated their perception of comfort and the ways they dealt with discomfort.

The first step in the data analysis was the transcription of interviews and field notes. Transcript coding resulted into a large compilation of *"disconnected static concepts"* (Hargreaves 2008). Since the purpose of a case study approach is to explore dynamic processes considering them as a whole, this type of analysis had to be discarded. A quantitative approach to the data was also considered in the initial stages of the analysis. This method was aiming to find a correlation between the results of the questionnaires and characteristics of the internal climate. However, this approach was also discarded as the size of the sample was not sufficient to support any statistically robust result. Instead, the approach eventually followed looked at the qualitative interviews to reconstruct users' narratives (Paddock 2015). Narratives, as stories, are often described as a fundamental tool to make our experiences meaningful. They help us to make sense of our daily lives and routines by telling stories to others and to ourselves (Hards 2012). The exploration of narratives has therefore the potential to contribute to the understanding of how users structure and make sense of their comfort practices (Shankar et al. 2015).

Although originally focused on literary criticism, narrative research can be found in the social sciences since the early 1980s (Hards 2012). The focus of narrative analysis techniques, as proposed by Riessman (2005), can go from the exploration of the content (thematic analysis), to the investigation of how a story is told (structural analysis), the analysis of the dialogue between teller and listener (interactional analysis) or even beyond the spoken word to the analysis of storytelling as a performance (performative analysis). In this case, the interviews' structure led to detailed descriptions of users' daily practices. Besides, the open nature of the interviews allowed the users to reflect and speak through biographical transitions revealing the context in which such practices occurred (Southerton 2006). Therefore, a thematic approach was preferred in order to focus mainly on the *"semantic of the narrated experience"* rather than on the syntax of the story (Paddock 2015).

Of the 24 households investigated, only the narratives of four of them are presented here. This approach – similar to those adopted by Paddock (2015), Gram-Hanssen (2010) or Tweed et al. (2013) – allows for a more detailed description of the practices and their context. The narratives were chosen on the basis that these households represented the most information-rich stories while presenting themes that were prevalent across the data. The narratives selected to be presented here, although they cannot be considered ideal types of any user, cover most of the topics found in the data. Besides, these narratives illustrated four very different scenarios. Two cases did not have any improvement of the envelope while the other two cases had been insulated and draught-proofed. The internal climates of the households also differed greatly. As described below in section 5.4, for each of the situations (insulated and non-insulated) one household had low concentrations of water vapour content while the other had very high values.

As discussed in Chapter 3, although generalisation of the findings from a case study has to be taken carefully, *"the force of example"* (Flyvbjerg 2006) provides a valuable tool for further exploration and scientific development.

5.3 Narratives: the difference between practices

In this section, the four narratives chosen to illustrate the daily practices of comfort are described in detail. The narratives cover a description of the users' background as well as the explanation of their heating, ventilating and other moisture producing related habits.

5.3.1 Case 6. Victoria

Victoria lives alone in a one bedroom flat in the city centre of Aberdeen. She is in her late 50's and works as a waitress in a hotel. During the week, she spends most of her free time at home. In the weekends, she enjoys going to her family farm. Victoria has been living in the same rented flat for the last 20 years. Although she would like to have some aspects of the flat changed (like the hot water tank), she feels quite comfortable in her home.

Victoria works five days a week. She is away from 6:00 in the morning until 4:00 or 4:30 pm. When she gets home, she likes to take a shower, cook her dinner and sit in the living room. It is normally easy for her to achieve a comfortable temperature in the living room as she does not need the house to be too warm and 16 to 18 °C is usually enough for her. Instead of having a very high temperature, she prefers to wear a jumper or a cardigan and have the doors closed to "*keep the heat in*". She also uses a draught excluder under the door to stop the cold air coming from the bedroom and the staircase.

The flat used to have gas supply but it was removed more than ten years ago and now it only uses electricity. There are two storage heaters (living room and hallway), two electric radiators (bedroom and bathroom) and an electric fireplace in the living room. Victoria thinks that the housing association that owns the building removed the gas supply for safety reasons and although she was not properly told how to use the new system, she has never had any problem.

> *"Just the chaps told me how they (storage heaters) work, not how to work them. But I suppose it's common sense, isn't it?"*

The storage heater in the living room is switched on every day while it is still cold outside, until mid-April normally. On the other hand, the radiator in the bedroom is only turned on if it is really cold, but she usually does not need it. As for the electric fire in the living room, Victoria tends to use it often in the weekends when she is relaxing at home. During the week days, she tries not to switch that one on. Electricity is expensive and Victoria tries to be careful with the use of heating. Comfort and money are equally important for her. She tries to balance between having a warm home and the cost of electricity. When she is asked about what it is important for her to feel comfortable at home she is clear:

> *"What do I want? A warm house... and cheaper!"*

Victoria likes to have fresh air while she is sleeping and the window in her bedroom is usually left open. She only closes that window for short periods of time (in the evenings when taking a shower) or on very cold days. The windows in the living room, on the other hand, are usually closed. Victoria finds the noise from the traffic too loud and prefers to keep them shut. She only opens that window if she is cooking something very steamy in the open plan kitchen. The extractor fan is also very noisy and she only uses it if she is "*boiling a soup*". There is a cellar in the building that can be used to dry the laundry, but Victoria never makes use of it. She feels that it is too much work walking the five floors of stairs and she prefers to dry the laundry in the hallway and leave the back window open. In summer, however, or when the weather is very nice, Victoria hangs the laundry on the clotheslines available in the back garden of the property.

5.3.2 Case 8. Amy

Amy lives with her new-born baby girl and a dog in a one bedroom rented flat in the centre of Aberdeen. She usually works five days a week as an office manager. At the moment, she is on maternity leave and her routine has changed considerably. She spends most of the time at home looking after the baby.

Warmth is the most important aspect of comfort for her. When she is at home, she likes to be cosy and she would like to have a much warmer environment. Her home entertainment devices are also important for Amy and she often has several items on when she is at home

(TV, DVD, Internet router, Apple TV, etc.). Also, to feel more comfortable, Amy always wears a dressing gown on top of her clothes and prepares hot drinks.

> *"I drink a lot of tea. My kettle is always on, never off"*

She has lived in the same flat for the last five years and feeling warm has always being a problem. The flat is equipped with electric storage heaters in the living room and hallway and electric radiators in the bedroom and the bathroom. Since she is back from giving birth, the radiator in the bedroom has been switched on 24 hours a day but she feels that *"the temperature is still quite cold"*. The radiator in the bathroom has a timer and it is usually on for seven hours a day. As for the storage heaters, Amy never fully understood how they work. She got a leaflet from the housing association but she never managed to get enough heat from the system.

> *"It says, you've got one input, or output… and you have got a boost. But, what is a boost?"*

A few years ago, after a cold winter, Amy decided to buy a portable bottled gas heater and she has been using it since then. It depends on the weather, but she usually has the portable heater turned on every day for around six hours and a bit longer in the weekends. In winter, she usually needs to replace the bottle every two weeks. In summer, they last longer and she consumes less than one bottle per month. For Amy the portable heater is a better option because it is cheaper and produces more instant heat.

> *"It works better and it lets me be cosy; although it's hideous"*.

In order to reduce draughts and heat loss, all the doors in the flat are kept closed and with draught excluders underneath. The window in the bedroom is also permanently shut and it has been partially covered with an insulating board (Figure 5-1). Amy does not even open the curtains as a measure to keep the heat in the room.

> *"It is just another way to keep the heat in. To close the curtains. It's ridiculous"*.

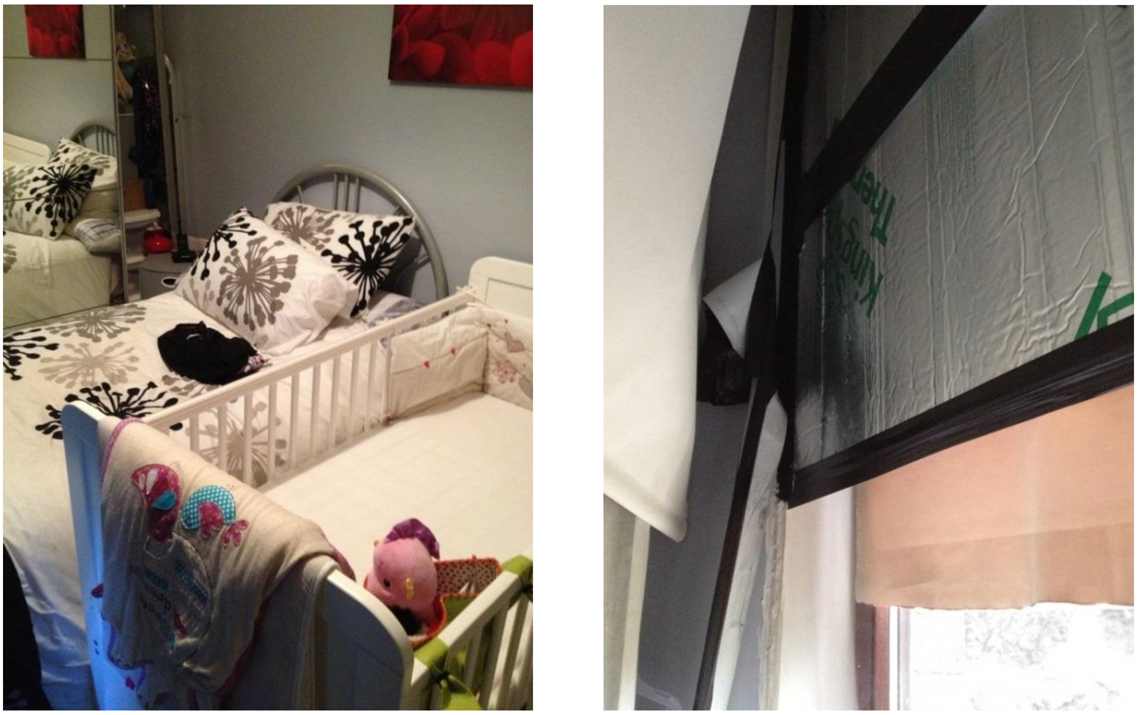


Figure 5-1 Case 8. Bedroom (left) and window partially covered with an insulation board (right).

The window in the living room can only be opened a couple of inches because of the curtain pole and is not used either. The extractor fan in the bathroom is connected to the light switch and it goes on automatically. The fan in the kitchen, on the other hand, has a different switch and it is barely used.

> *"The one (fan) in the kitchen is crap, so (I use it) very little. Just when I set something on fire".*

There is often condensation on the windows of both living room and bedroom. She would like to get some fresh air every so often but she prefers not to open the windows because "*it does not help with the condensation*" and prefers to keep the heat in. Amy has a washer dryer in the kitchen and she always uses it to do laundry and dry the clothes, despite the difficulties she sometimes has to afford the energy bills.

> *"Sometimes, at the end of the month, you can find that you run out (of money) and you have to find that little bit extra just to cover…"*

5.3.3 Case 12. Mark and Claire

Mark and Claire are in their 40's. They have been living in different houses in the same area of Aberdeenshire for the last twelve years. Claire works as a medical receptionist four days a week and Mark has a more flexible working pattern as an activity instructor. They are both *"outdoor people"* and enjoy going out for a hike or a bike ride. They moved to their current home, a recently renovated two bedroom cottage, about a year and a half ago.

Quietness is their first priority regarding comfort at home. It was also the main driver for them when choosing their new home. They like living in this fairly isolated setting,

> *"It is out of the way. I don't have to suffer other people and you can have the curtains open".*

Warmth is not the most important factor of comfort for them and the efficiency or level of insulation of the house was something secondary for them. They usually sit at home wearing their walking clothes (hiking trousers, thermal layer and a shirt) and neither of them likes feeling too hot at home. They joke saying that,

> *"When we are cold in the house, we go out for a walk and when we come back it feels good".*

They do not like to feel that air in the room gets too stuffy either. In Mark's own words,

> *"I would sooner have a draught than all sealed up. We have the windows shut now because I just washed them"*

Their heating system combines a wood burning stove with an oil boiler in the same circuit. It is a complex system, but Mark, a former racing car engineer, feels confident using it. Although the boiler has a thermostat and a timer, Mark prefers not to use any prescheduled system and he only switches the heating on when they need it. They usually do not use the heating for more than three hours a day. Even during the harshest weather they do not leave the heating on when they are not at home. They usually switch it on for just one hour in the morning before getting up and another hour when they come back from work to "*take the chill off*". If afterwards they feel cold, Mark would sooner light the stove than using the oil boiler. They never leave the fire on overnight as he does not mind lighting it again the next day if they need it. The TRV are generally not changed and they usually have the radiator in their bedroom closed.

There is also an electric immersion tank as a backup for the domestic hot water. They use it often during the long periods of time when they do not have the heating on. Although they say they are not particularly concerned about saving money on heating, they would only use the oil tank if *"really necessary"* and they prefer to use the stove. For Mark that is an easy choice:

> *"For me wood is cheaper than oil. There is wood everywhere, isn't there?"*

They ventilate the house often. The window in the bedroom is open most of the time and they open the window in the kitchen every time they are cooking, irrespective of the extractor fan. They also have passive vents in the bathroom and kitchen. These vents are automatic and they do not need to be operated. Mark and Claire do not really know how they work,

> *"I don't know whether it is something that expands. I have never been inside one to have a look".*

One of the doors in the house is also opened frequently. They often need to go to the shed where there is a workshop and they keep the tumble dryer and leave the door open. Also, after a couple of hours of having the stove on, they feel that the room is too hot and dry and they need to open the door to get some fresh air.

5.3.4 Case 13. Monika and Viktor

Monika and Viktor, together with their two children and a dog, live in a deeply renovated cottage in Aberdeenshire since 2012. They are in their late 30's and they are originally from Poland. The house setting and the rent were the main reasons for them to move into that house:

> *"We saw the view and we didn't need to see the house inside".*

Viktor is a geologist and works abroad most of the time. He spends around five months a year away from home. On the other hand, when he is home he does not work at all and tries to spend as much time as possible with the children. Monika is at home for most of the day, looking after the youngest child and working on her thesis.

When talking about the meaning of comfort, the answers vary greatly between them. Temperature is the most important factor for Monika, while Viktor, on the other hand, is never cold and the temperature is secondary for him. He values other factors such as having a quiet environment. Their different liking in terms of comfort is also visible in the clothes they wear at home,

> *"I'm pretty much like this, T-shirt and maybe shorts even. But my wife on the same day would wear a jumper or a fleece".*

They explain their heating patterns as a direct consequence of the heating system. After the renovation of the house, a new wood burning stove was installed as a main source for both domestic hot water and space heating. The stove heats the living room directly and stores the remaining heat in a hot water tank that feeds the radiator system and the taps. Although they only use the heating for six hours a day (two hours in the morning before waking up, two hours around lunch time and two hours before going to bed), they find it much more efficient to keep the stove permanently lit during the day. That involves a lot of work but it is the best way to have enough hot water for the taps and heating at all times. They do not adjust the TRV and keep all the radiators on with the exception of one right next to the stove that is permanently disconnected.

> *"This (TRV) doesn't control anything. As long as it is turned on between 2 and 4..."*

Because of the nature of the system, there is a significant temperature gradient in the house and the living room is much warmer than the rest of the house, especially the rooms upstairs. Viktor explained that he never fully understood how the system works. He blames the interface, as he finds it very difficult to adjust. They consider the amount of work associated to the heating system as the main downside of living in the house and they feel that the "*bloody system doesn't work as it should*".

Their ventilation habits are very influenced by the weather. The house is in a very exposed location and airing the rooms when it is raining is not possible since the wind often drives the rain into the house. If it is not raining or is not too cold, the windows in the main bedroom are open from morning until lunch time, and usually a couple of hours in the evening. Windows upstairs, on the other hand, are barely open apart from the roof window in the staircase. The trickle vents are also operated depending on the weather. When it is windy, only the vents on one side of the house are left open because otherwise "*you can feel the air coming through*". In winter, or when it gets cold, they just close them all.

Viktor explained that they found the air in the house very humid, so they decided to buy a dehumidifier (Figure 5-2). The dehumidifier is also very helpful for drying the laundry when it is raining and they cannot hang it outside. The tumble dryer is convenient but it is also very expensive and they usually prefer to hang the clothes in the bedroom during the day and move them to the living room at night.

Figure 5-2 Case 13. Wood burning stove in the living room (left) and dehumidifier (right).

5.4 Matching the narratives with the physical measurements

The environmental data measured in the households corresponding to the narratives presented above are summarised in Table 5-3. A full description of the physical measurements, together with the discussion of the results, is provided in the next chapter. Here, a snapshot of the measurements is presented to describe quantitatively the characteristics of the households and to compare them with the users' narratives of comfort. Based on the measurement of temperature and relative humidity, the moisture loads (difference between indoor and outdoor water vapour concentration) were calculated. Further details on the calculation equations are presented in the following chapter. For the analysis, data was sorted according to seasons. The 'winter' term was analysed using the measurements from December to March, while the 'summer' period included the measurements from June to September.

Table 5-3 Environmental conditions of the dwellings corresponding to the narratives presented in section 5.3. Values in parentheses represent ± one standard deviation.

			Internal Temperature [°C]	Internal Relative Humidity [%]	Moisture Load [g/m³]
Summer	C6	Living room	18.9 (1.9)	66.6 (5.8)	0.8 (0.8)
		Bedroom	18.3 (1.6)	65.6 (6.4)	0.2 (0.7)
	C8	Living room	21.8 (1.5)	65.2 (3.5)	2.5 (1.3)
		Bedroom	20.7 (0.9)	72.2 (2.9)	3.0 (1.3)
	C12	Living room	17.2 (1.9)	74.1 (4.5)	0.8 (1.1)
		Bedroom	16.6 (1.8)	76.2 (4.3)	0.8 (1.1)
	C13	Living room	21.3 (1.8)	59.5 (4.8)	1.1 (1.3)
		Bedroom	20.2 (1.3)	66.0 (4.0)	1.6 (1.3)
Winter	C6	Living room	16.2 (1.3)	64.7 (8.3)	3.2 (1.5)
		Bedroom	13.3 (1.4)	63.8 (5.2)	1.8 (0.9)
	C8	Living room	17.5 (2.1)	63.3 (1.9)	3.9 (1.6)
		Bedroom	17.6 (0.5)	66.5 (3.2)	4.3 (1.2)
	C12	Living room	13.7 (3.5)	58.9 (5.3)	1.7 (1.4)
		Bedroom	11.2 (3.5)	70.7 (10.4)	1.6 (1.2)
	C13	Living room	19.4 (2.5)	51.6 (4.8)	3.1 (1.5)
		Bedroom	16.9 (1.4)	64.2 (4.1)	3.7 (1.5)

In Case 6, the average temperatures of the living room and bedroom in summer were 18.9 °C and 18.3 °C respectively, while in winter the temperatures were 16.2 °C and 13.3 °C. The average temperature of the bedroom in winter was almost 3 °C lower than the living room as a consequence of the different use of the space heating explained by the user in the interview. The relative humidity was similar in both rooms during the entire year with values of 66.6 % (summer) and 64.7 % (winter) in the living room and 65.6 % (summer) and 63.8 % (winter) in the bedroom. The different patterns of ventilation described by the user only became clear when comparing the moisture loads. The average moisture load in the living room was 0.8 g/m^3 in summer and 3.2 g/m^3 in winter, while the loads in the bedroom were 0.2 g/m^3 (summer) and 1.8 g/m^3 (winter) due to higher ventilation rates.

Summer temperatures in the living room and bedroom of Case 8 were 21.8 °C and 20.7 °C respectively. In winter, the temperatures decreased to 17.5 °C and 17.6 °C. Despite the low levels of satisfaction reported by the user in Case 8, the average temperatures recorded in the dwelling were considerably higher than in Case 6. It is worth noting that both dwellings formed part of the same tenement and had very similar characteristics. The high values of moisture load recorded in both rooms of case 8 (2.5 g/m^3 and 3.0 g/m^3 in summer and 3.9 g/m^3 and 4.3 g/m^3 in winter) are in agreement with the user's description of how both rooms were poorly ventilated.

In Case 12, the low average temperatures recorded in winter (13.7 °C, 11.2 °C) and high standard deviation values (3.5 for both rooms) matched the description of the sporadic use of the space heating. Despite the high ventilation rates reported by the users, the levels of relative humidity found were considerable high (74.1 % and 76.2 % in summer and 58.9 % and 70.7 % in winter). These high levels were a consequence of the low temperatures and did not represent a high content of water vapour concentration, as the results of moisture load showed (0.8 g/m^3 in both rooms in summer and 1.7 g/m^3 in the living room and 1.6 g/m^3 in the bedroom during the winter term).

The average temperatures in Case 13 (21.3 °C in the living room and 20.2 °C in the bedroom in summer; 19.4 °C and 16.9 °C in winter) were similar to those found in Case 8. However, the satisfaction of the occupants in Case 13 was much higher and the complaints were mainly caused by the operation of the heating system. The different ventilation patterns across the year resulted in different levels of moisture. During the summer, the levels of relative humidity (59.5 % in the living room and 66.0 % in the bedroom) and moisture load (1.1 g/m^3 in the living room and 1.6 g/m^3 in the bedroom) were relatively low. In winter, despite the use of a dehumidifier, moisture load results were much higher (3.1 g/m^3 in the living room and 3.7 g/m^3 in the bedroom) and comparable to those obtained in case 8.

5.5 The mechanisms behind the practice of comfort

As stated by Shove "*routines and practices are not isolated, they connect during the course of a day and during the course of a lifetime*" (Shove 2011). Comfort practice in the indoor environment is the result of the combination of different practices occurring simultaneously in time and space. Practices such as the use of space heating and cooling, opening of windows and doors, use of domestic hot water, drying clothes or use of mechanical ventilation are connected as part of the comfort adaptation at home. Other factors such as the amount and type of clothing worn, the type of food and drinks consumed or the type and intensity of activity are also fundamental in the achievement of comfort at home.

In the following, the mechanisms of three 'comfort adaptive' practices are explored in more detail: heating, ventilation and drying clothes. Heating and ventilation are key aspects in the achievement of comfort at home. Besides, these practices (together with the moisture production habits) are fundamental in shaping the internal climate of the dwellings as they determine the content of water vapour in the room. Laundry drying has been chosen as an example of moisture production practice due to its important implications for energy consumption and IAQ (Porteous et al. 2014) and the high rates of water vapour released to the internal climate (between 2.2 and 2.95 kg of water for a standard load of 3.6 kg of dry clothes (TenWolde & Pilon 2007)). The narratives presented above were explored analysing each of the three elements that hold the practices together, as previously defined (meaning, material and competence).

5.5.1 Heating

Although 'warmth' was an image present in all the narratives in one way or another, the meaning of heating varied greatly between households. In Case 8, warmth was the main and almost only meaning associated to the practice. In the other cases, the images of warmth and cosiness were subordinated to other aspects of heating, such as the need to save money or the amount of work involved. It was also noted the different meanings associated to different heating systems. Thus, while central heating was tied to functional images where warmth and convenience were the most important aspects, a fireplace or a wood burning stove (or even an electric fire) was associated to 'cosiness' and it was used as part of more social or recreational practices of comfort.

Technology had a strong effect on the final outcome of the practice, proving that material structures enable or constrain certain practices (Gram-Hanssen 2010a). In Case 13, for instance, practice was entirely determined by the limitations imposed by the system. Although the users' meanings of heating predisposed for a discontinuous use of the system, the available technology *"prefigured"* the final action (Schatzki 2011).

Competence also played an important role on the final outcome of practices. Cases 6 and 8 had almost identical infrastructures but the understanding of the system functioning was diametrically opposed. That resulted in the occupant of Case 8 substituting the original system with a portable bottled gas heater. These heaters produce a great amount of pollutants (Burr et al. 1999) and moisture (100 grams of moisture per kWh of heat produced (British Standard Institution 2011) or around a litre of water per litre of gas or paraffin (Scottish Executive 2005) and are a common cause of condensation and damp in residential buildings.

The narratives also showed how all three elements of residential heating are closely related. Case 12 illustrates that having a certain technology and the competence to operate it confidently does not necessary mean that the occupant will use it unless he or she is *"engaged"* with the action (Warde 2005). In this case, a programmable heating system that was designed to be efficient and convenient for the user was not being used. However, it was not neglected because the users were not competent but because they were not engaged. They preferred to feel in control of the system at any time and therefore ignored the programmable options.

5.5.2 Ventilation

A dichotomy between positive and negative images of ventilation was found among the occupants when thinking about ventilating their homes. That is, users often had to choose between health and comfort (freshness) or cost and pollution (wastefulness). The ultimate meaning of ventilation, or the image that prevailed, was tied to the meaning of heating and comfort at home. Thus, in Cases 8 and 13 the more positive meanings of ventilation were overcome by the practical aspects and the outcome of the practice resulted in very low ventilation rates. In Case 12, on the other hand, the positive images of ventilation dominated the practice resulting in high air change rates throughout the year. It is also interesting to highlight how the same person can associate different images of ventilation to different parts of the dwelling. In Case 6, for instance, ventilation was perceived as healthy and advisable in the bedroom while in the living room was considered wasteful and unpleasant and it was minimised.

Although the technologies that enabled ventilation at home did not represent a challenge in terms of their operation, the understanding of the role of ventilation in the indoor environmental quality played an important role in the final outcome. For instance, the occupant in Case 8 did not consider the effects of the lack of ventilation on the internal environment (despite the use of a bottled gas heater) and therefore the practice was exclusively dominated by the eagerness to reduce heat losses. The purpose of trickle vents was not always clear either, resulting in the occupants not operating them and leaving the vents always in the same position.

The basic infrastructures for ventilation (windows, trickle vents, doors and extractor fans) were similar in all the cases. Although there were some differences in terms of size, age or performance, they did not have a great effect on the final outcome of the practice. In Case 8, the user complained about the extractor fan performance in the open plan kitchen and the windows layout in the living room. However the narrative showed that the meaning (reducing heat loss) and competence (poor understanding of ventilation purposes) were more influential elements in the configuration of the practice.

> *"I've got lots of condensation. I would open it (the window) in the winter just to let some fresh air in. But it doesn't help" (Case 8)*

Besides the basic infrastructures, specific technologies for ventilation were found in the retrofitted dwellings (Cases 12 and 13). Case 12 had an intelligent passive stack ventilation system installed (http://www.passivent.com/intelligent-passive-stack-ventilation-ipsv/p/3). The system worked automatically without requiring any operation from the user. The users of Case 13, on the other hand, decided to buy and install a dehumidifier as a solution to the high levels of humidity in the house. Despite being in the same area of Case 12 (both cases were barely 500 metres apart), increasing the ventilation rates was not a feasible option for the users in Case 13 due to the dominant high winds in the area and the exposed position of the building.

The last factor affecting the final rate of air changes was the permeability of the envelope. The results obtained with the air pressure tests carried out in the properties are presented in Table 5-4. Air permeability was higher in non-insulated properties despite the smaller envelope area. In case 13, the uncontrolled air infiltration was very low proving a very successful retrofit of the building.

Table 5-4 Air infiltration tests of the dwellings corresponding to the narratives presented in section 5.3.

Household	**Measured Flow [m^3/h@50Pa]**	**Air Permeability [ach@50Pa]**	**Envelope Area [m^2]**	**Volume [m^3]**	**House Type**
Case 6	2100	18.9	76.6	107.3	Flat (top floor)
Case 8(1)	2800	25.0	91.2	111.1	Flat (ground floor)
Case 12	2850	14.2	283.1	198.9	Detached (1 storey)
Case 13	2100	8.6	167.2	240.0	Detached (2 storeys)

(1) Air permeability test was carried out in Case 7 (a flat in the same block with identical characteristics).

5.5.3 Drying clothes

Material structure was very important in how clothes were dried. If easy access to outdoor facilities was not available, the action was prefigured by the materials and technologies available indoor (tumble dryer, clothesline, clotheshorse). However, having the infrastructure to dry the clothes outside did not ensure the outcome as the final action of the practice was mainly shaped by another element of the practice, 'meaning'.

Competence did not represent a major factor in shaping practices. In Case 6 for instance, the occupant said she was not using the cellar to dry the clothes in winter because it was too difficult for her to walk five floors of stairs carrying the laundry. However, the same user reported to hang the clothes outdoors regularly in summer. Therefore, it was not the ability to perform a certain practice but the associated meaning (freshness and cleanliness in the case of clothes hung outside in the sun) that configured the outcome.

As happened with the previous two practices, drying the clothes had to balance two different meanings. In this case, freshness and convenience. Hanging the laundry outdoors in a warm and sunny day in summer was a pleasant activity that provided clean and fresh clothes and that most of users were happy to adopt. In winter, when the weather was less enjoyable, the convenience of using a tumble dryer or hanging the clothes indoors prevailed. As for the use of tumble dryer, another aspect had to be added, the cost. Case 13 demonstrates how the cost was eventually shaping the practice as the clothes are hung in the bedroom despite having the materials and the skills needed for alternative methods less intrusive for the internal environment.

Drying the clothes was found to be an activity that is completely disconnected from the other two practices that defined the indoor environment and from the meaning of comfort at home itself.

5.6 Differences in the meanings of comfort

Narratives analysis showed very different meanings associated to the different practices involved in the achievement of comfort at home. The meaning of comfort, when depicted as a single practice, differed between users as much as the meaning of the individual practices involved.

Temperature was inarguably the first aspect mentioned by the majority of occupants when asked about 'comfort'. However, thermal comfort definition changed from one case to another. Thus, some users felt comfortable with temperatures in the range of 16-18 °C *("Anything over 18 °C is too much for me. I feel cold if it is about 12 °C degrees"* Case 5) while other occupants were dissatisfied with higher levels of internal temperature and tried to achieve a warmer environment *("If I'm not feeling warm then I feel quite uncomfortable"* Case 3). This discrepancy in the expectations of thermal comfort was constant throughout the entire sample. The users that felt comfortable with lower temperatures tended to have a common 'image' of comfort adapted to traditional buildings. Among those users, there was a shared perception that *"old is cold"* (Ingram et al. 2011) and the expectations of thermal comfort were adapted since no higher internal temperatures could be achieved.

> *"I'm kind of used of being so cold. My friends always say: I don't know how you can live like this" Case 4.*

Warmth or internal temperature was not the only aspect of comfort that occupants had in mind when thinking about their homes. In fact, warmth was not the most important factor in many cases. Fresh air, quietness, privacy and cleanliness were also important factors for several occupants. In those cases, the internal temperature stayed in the background when talking about their comfort at home. These occupants were willing to sacrifice thermal comfort, to some extent, by accepting lower levels of internal temperature if other aspects of comfort were fulfilled.

It is also important to mention two practical issues directly linked to the perception of comfort at home: affordability and environmental awareness. The need to reduce costs of energy bills or the willingness to reduce energy emissions also shaped the 'image' of comfort at home that occupants created. In both cases, comfort practices incorporated another meaning: 'consumptiveness'. Practices are not only seen as a means to achieve comfort but also as a process that involves consumption of energy or emission of pollutants. In both cases, the consequences were similar; these consumptive images imposed some limitations that lowered the final expectations of comfort at home.

The four narratives presented above, together with the physical measurements, illustrated four very different scenarios. The analysis has shown that the practice outcome is not exclusively dependent on the building characteristics (material structure) and that the meaning of comfort at home plays a central role that needs to be further explored.

5.6.1 Coping with discomfort: the effect of how easily comfort can be restored

Up to now, the exploration of narratives has been focused on the different practices involved in the achievement of comfort at home and the definition of comfort itself.

Within the small sample of four narratives presented here, very different meanings of comfort were found. However, beyond the differences in the meanings, what the comparison between narratives and measurements showed was that those households where comfort was more difficult to achieve (whatever meaning it had) were those with higher moisture concentrations.

The principle of adaptive comfort states, *"if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort"* (Nicol et al. 2012). Therefore, the high content of water vapour was a consequence of the mechanisms (or practices) developed by the users to cope with discomfort.

Literature on discomfort in buildings usually classify these mechanisms of adjustment as (i) environmental or technological (interaction with the building control systems such as heaters or fans), (ii) personal or behavioural (changing activity, clothing or posture) and (iii) psychological (managing emotions or thoughts about the situation) (Heerwagen & Diamond 1992; Azizi et al. 2015; Gauthier & Shipworth 2015). However, and in order to keep the same terminology used in this study so far, these terms can be easily likened to the elements of the practices (environmental as material, behavioural as competence and psychological as meaning).

The results of the study showed that the adjusting mechanisms chosen by the users (that is, the way in which users coped with discomfort) were heavily influenced by their perception of how easily comfort could be restored. If comfort was quickly achieved after the cause of discomfort ceased, then the users mainly engaged in temporary adjustments of material and competence (wearing a pullover on a cold night or closing the window if the road is too busy and loud). The changes were meant to provide *"rapid and noticeable changes in the environment"* (Heerwagen & Diamond 1992). However, when the cause of discomfort ceased the practices returned to their normal configuration and comfort was recovered easily. Thus, since the reaction to discomfort did not endure, the adjusting practices did not produce any lasting change in the internal climate.

On the other hand, the adjusting mechanisms adopted by users that felt that comfort was difficult to restore were almost permanent and involved changes in all the elements of practice. A mismatch between the meanings of comfort and the materials and competences was usually the cause of discomfort. In other words, the buildings characteristics (or the way it was used) were not able to provide the levels of comfort that users expected.

Therefore, the cause of discomfort was persistent and the mechanisms of adjustment were also permanent to prevent future discomfort.

The coping approaches were essentially of two types: the adaptation of meaning or the material structure modification. In the first case, the meaning of comfort at home was altered to match the actual conditions of temperature, humidity, noise, etc. that could be achieved with the available materials and competences. Heerwagen & Diamond (1992) explains this mechanism in plain terms saying that the users tried to ignore the discomfort or *"just put up with it"*.

The second coping approach consisted in the modification of the material structure, and its operation, in order to create an environment that matched the predefined images of comfort that users had. The narrative of Case 8 is a clear example of how the material structure is modified (new portable bottled gas heater; windows, trickle vents and curtains shut; bedroom window covered with an insulation board) as a response to an environment that did not match the expectations of comfort at home (steady high temperatures).

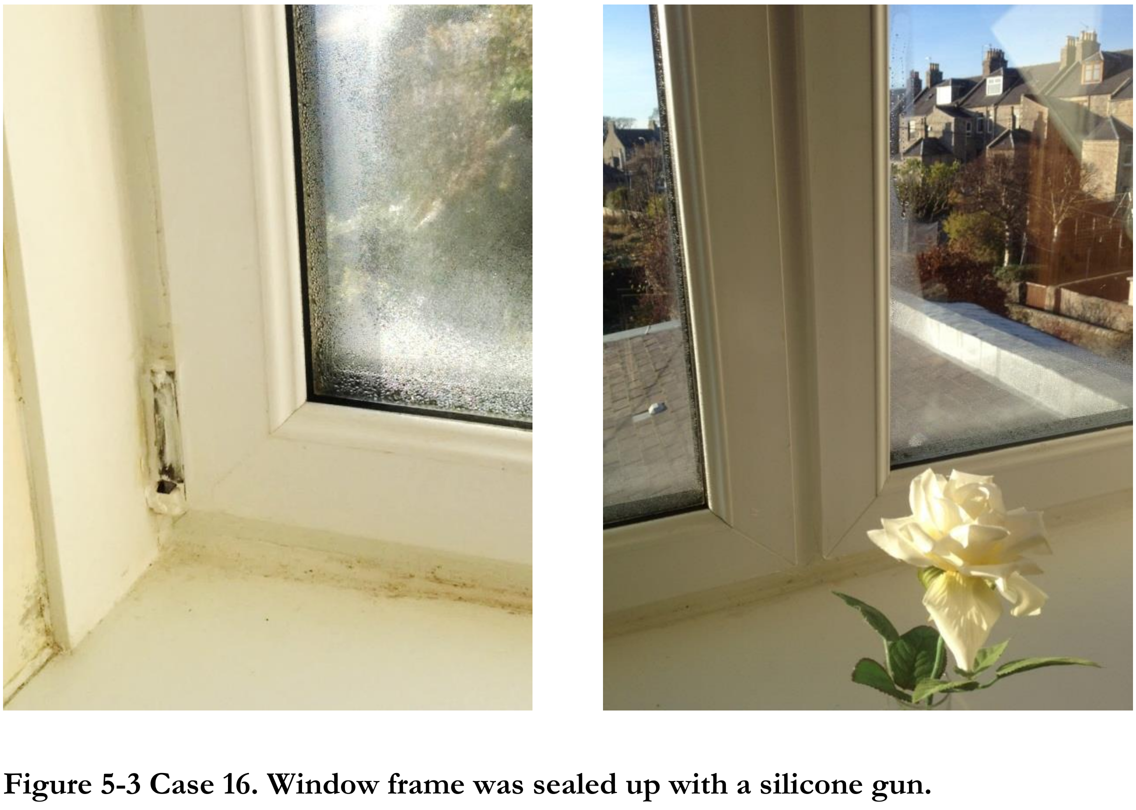


Figure 5-3 Case 16. Window frame was sealed up with a silicone gun.

Case 16 (included in the Appendix 6) illustrates a different situation of material and competence adaptation. In that case, the meaning that was dominating the practice of comfort was 'consumptiveness'. The users were willing to reduce their use of space heating in order to minimise their CO_2 emissions. The building was insulated and draught proofed and the heating system was configured to heat only the rooms that were being occupied. However, and despite the efforts made, the users felt that the building was still very leaky and decided to seal the frame around the bedroom window with a silicone gun to reduce heat loss (Figure 5-3). In both cases, the mechanisms of coping with discomfort involved some permanent changes to the material structure that were reflected in the internal environment in the form of high values of moisture load.

5.7 Discussion

There is a large of body of literature using quantitative approaches to explore the use of domestic space heating (Hong et al. 2006; Guerra-Santin & Itard 2010; Love 2014), ventilation (Haldi & Robinson 2009; Fabi et al. 2012) or laundry appliances (Porteous et al. 2014). However, the results of such studies have proven to be insufficient to explain the mechanisms of user behaviour and often reached opposite conclusions (Wei et al. 2014). For instance, when looking at the household characteristics, Vine (1986), French et al. (2007), Guerra-Santin & Itard (2010) or Isaacs et al. (2010) did not find any relationship between the use of space heating and household total income. On the other hand, Hunt & Gidman (1982), Day & Hitchings (2009), Weihl & Gladhart (1988) and Vringer et al. (2007) concluded that families with lower income used less energy for space heating.

This study opted in favour of a qualitative approach to explore the users' effect on the internal environment of traditional buildings. Thus, this approach allowed for an in-depth exploration of the narratives of comfort at home to identify the reasons behind user behaviours. The results aligned with those obtained by Tweed et al. (2013) who stated that being thermally comfortable has different meanings to different users. The results of this investigation, however, did not only point to the differences in thermal preferences but also to the different meanings of other practices of comfort like ventilation or laundering. As stated by Madsen (2014), comfort is not limited to temperature as it also includes aspects like "*light, functionality and homeliness*" (p. 1). In line with Gram-Hanssen's (2010b) work on standby consumption, the results showed that the internal climate is the outcome of a series of dispersed practices rather than an integrated practice. Gram-Hanssen argued that campaigns to make people aware of their standby consumption are trying to convert their dispersed habits into an integrated practice. Analogously, making people aware of their effect on the indoor environment will connect dispersed practices like laundering, forming one integrated practice.

The influence of awareness and understanding on users' comfort expectations and behaviour is a complex relationship already investigated by Brown & Cole in (2009). They concluded that users' knowledge of the building led to more and better use of the personal controls. On the other hand, an increase in the knowledge and personal control opportunities did not necessary affect the overall comfort of the users. In this study, knowledge (or competence) also played an important role in the final outcome of the practice. Narratives clearly illustrated how different levels of understanding of the ventilation effect led to very different practices. In their conclusions, Brown & Cole differentiated between the role played by comfort as a trigger for a change (discomfort caused users' reaction) or as an outcome of the change (the actions either improved or decreased users' comfort). The results of this study corroborated the relevance of discomfort in shaping the internal environment. The practices designed to tackle discomfort often ignored their effect on the quality of the indoor environment. Consequently, daily practices resulted in poor environments with high concentrations of humidity and low air change rates. These practices were shaped (in terms of meaning, materials and competence) to create the conditions the users considered acceptable, regardless of those predicted by conventional comfort theories (Tweed et al. 2013).

Although quantitative studies in the area of residential buildings are very scarce (Tweed et al. 2013), the reactions to discomfort in working places have already been explored in previous studies. Azizi et al. (2015) and Moezzi & Goins (2011) found a relationship between the material structure of office buildings and how the users' meaning of comfort is adapted to cope with discomfort. Azizi et al. stated that occupants of green buildings are more likely to accept discomfort and that they were *"engaged in less environmental adjustments, and adopted more personal and psychological coping mechanisms than those occupants in the conventional building"*. In this study, a relationship between material and meaning was only found among the occupants of traditional buildings who shared the perception that *"old is cold"*. As a consequence, they accommodated their expectations of comfort according to this pre-established image and adapted their practices accordingly.

On the other hand, no correlation between the level of insulation of the building and adaptive comfort practices was found. The results of this study challenged the idea that users of better performing dwellings *"have lower thermostat settings but air their dwellings more often"* creating healthier environments (Raaij & Verhalien 1983). In this case, the analysis of the narratives has shown that the meaning of comfort at home is more determining than the physical properties of the building. This investigation, therefore, aligns more closely with the conclusions from an earlier study on energy saving houses (Hamrin, 1979, in (Raaij & Verhallen 1983)) that linked the final success of the energy efficient measures (material) to the energy consciousness of the users (i.e. the meaning). Hamrin found that passive equipment, that involves active engagement of the users, is better suited to residents with high levels of energy consciousness. The conclusions of the study – i.e. the type of system (material) should match the occupants' meaning of comfort – can be directly extrapolated to this research.

This study also showed the relationship between the perception of how easily comfort could be restored and the practices finally adopted. Every user occasionally felt uncomfortable and therefore adapted their practices to restore the comfort. However, only those users that were not able to restore their comfort quickly engaged in practices that had a negative lasting effect on the internal climate. The high degree of changes made by the users to feel comfortable was also reported by Heerwagen & Diamond (1992). They introduced the term *"coping success"* to refer to the ability to effectively resolve the discomfort. They also suggested that the designers should include more opportunities of personal control to avoid environmental (material) changes and to increase coping success. In line with Heerwagen & Diamond's recommendations, the results of this study indicated the need to facilitate 'safe' options of adaptation that can provide users with comfort while preventing any undesired scenario.

5.8 Conclusion

It was hypothesized at the beginning of this research that:

> *"When trying to achieve comfort, people living in traditional buildings interact with the building in a different manner depending on the level of insulation"*

The analysis of the narratives has unveiled the different practices involved in the achievement of comfort at home and how those practices are performed differently by the users. This study has also shown how these practices can be explained as a function of the three elements of practice (meaning, competence and material) proposed by Shove & Pantzar (2005). Moreover, this investigation has looked into the different meanings of comfort at home and the consequences of coping with discomfort.

The results of this study did not present enough evidence to validate the hypothesis presented above and therefore it had to be rejected. Instead, the investigation showed that it is the ease of achievement of comfort at home that most greatly affects the outcome of the daily practice of the occupants. If comfort, whatever the meaning of comfort at home, is not easily achieved, the user will react to discomfort in a way that it is likely to produce a poor indoor environment with high values of moisture load.

In this chapter only the qualitative exploration of users' behaviour is presented. The quantitative analysis of the data collected during the monitoring of the environmental conditions of the internal climate is presented in the next chapter.

5.9 Summary

This chapter presented the first part of a multi-case study data analysis. As part of Objective II, the investigation was focused on the effect of user behaviour on the internal climate of traditional buildings before and after the insulation of the envelope. The analysis presented in this chapter, limited to the qualitative data collected by means of interviews, questionnaires and home tours with the occupants, answers sub-questions 3 and 4: What are the interactions between users, systems and fabric in traditional dwellings? Does user behaviour change after the improvement of the envelope?

The use of narratives of comfort, built upon the interviews transcript and the field notes, facilitated the analysis of the activities that users carried out to feel comfortable at home and that affected the internal climate (such as the use of space heating, ventilation or laundering).

The ideas of practice theory provided a useful framework for the narratives analysis. Using the elements of practice proposed by Shove, the narratives were analysed to identify the structure of each individual practice as well as the meaning and structure of comfort as a practice.

The results of the analysis revealed that the different practices that affect the internal climate are shaped as dispersed practices, rather than an integrated practice, and that the meaning of comfort has a crucial impact on how the practices of heating and ventilation are shaped. The chapter finishes rejecting by the hypothesis presented in Chapter 3. Instead, the final results associate the characteristics of the internal environment to the perception of how easily comfort can be achieved rather than to the building physical properties.

6 THE INTERNAL CLIMATE

This chapter resumes the analysis of the traditional buildings internal climate. Here, the analysis is focused on the quantitative data gathered during the multi-case study environmental monitoring. The aim of this part of the study was to complete Objective II by characterising the internal climate and to explore the changes that occurred, if any, after the retrofit of the envelope in order to answer the remaining sub-question 5: What is the internal temperature and relative humidity of traditional dwellings before and after retrofitting the building fabric? The characteristics of the sample and the details of the monitoring campaign have already been presented in Chapter 3 and are summarised in Table 5-1 and Table 5-2.

6.1 Characterising the internal climate

The environmental conditions were studied to obtain an accurate characterisation of the internal climate in terms of temperature and air moisture content. These parameters, as explained in Chapter 2, are fundamental in any numerical study of the hygrothermal performance of buildings (Rousseau et al. 2007). The literature review has also shown that the models to predict the internal climate proposed in the standards BS EN 15026:2007 (CEN 2007) and BS EN ISO 13788:2012 (ISO 2012) play a crucial role in the final result of the analysis of the hygrothermal performance of buildings. However, several studies carried out in Germany, Estonia, Finland, USA, Belgium and Spain have found significant discrepancies between the internal climates predicted by the standards and the actual conditions of monitored buildings. Thus, in order to evaluate the representativeness of these standards in the specific context of Scottish traditional buildings, this chapter compares the results of the environmental monitoring campaign with the internal boundaries proposed in both standards. This approach has been widely adopted in previous research (Kalamees 2006; Arumägi et al. 2014; Alev 2011; Geving et al. 2008).

The design criteria proposed in the standard 15026:2007 have been used to evaluate the results of temperature (Figure 6-1a) and humidity (Figure 6-1b). Internal conditions are obtained directly by entering the daily mean temperature of external air in the graphs. The standard considers two levels of expected occupancy (normal and high) when calculating relative humidity values.

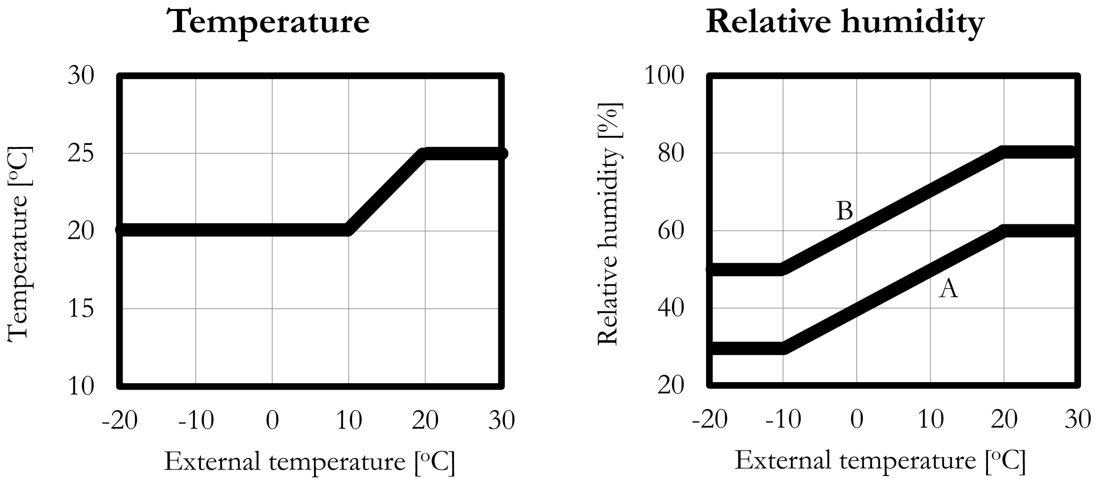


Figure 6-1 Internal boundary conditions as proposed in BS EN 15026:2007. Daily mean internal air temperature (a) and relative humidity (b) (A: normal occupancy, B: high occupancy) in dwellings and office buildings depending on the daily mean external air temperature.

Alternatively, 13788:2012 proposes the use of internal humidity load classes (Figure 6-2). The design curves suggested in 13788:2012 are derived from buildings in Western Europe and therefore are especially appropriate for comparison with the sample in this study. Difference between indoor and outdoor air water vapour, referred to as 'moisture load' in this thesis, is usually presented as:

$$\Delta v = v_i - v_e$$

Equation 6.1 Internal moisture excess or moisture load (BS EN ISO 13788:2012).

where Δv indicates the difference in moisture content (g/m^3), v_i the indoor air water vapour content (g/m^3) and v_e the outdoor air water vapour content (g/m^3). Moisture load is also referred to as internal excess, supply or increase of moisture, humidity or vapour in the literature (Kalamees 2006). The values of ν_i and ν_e were calculated following Equations 6.2 to 6.4 based on the measured results of internal and external temperature and relative humidity respectively.

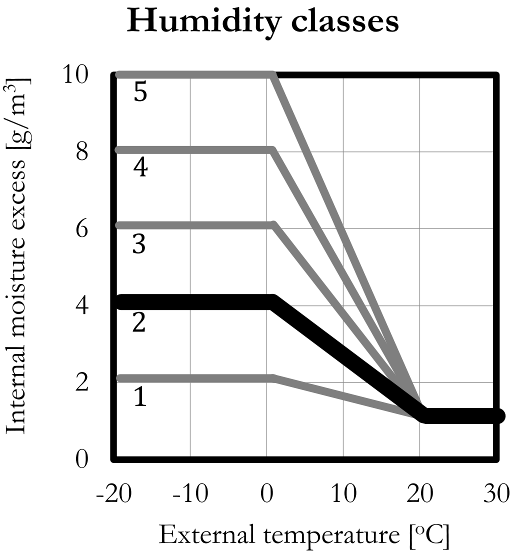


Figure 6-2 Internal boundary conditions for maritime climates as proposed in BS EN ISO 13788:2012. Variation of internal humidity classes with external temperature. 1: Unoccupied buildings, storage of dry goods; 2: Offices, dwellings with normal occupancy and ventilation; 3: Buildings with unknown occupancy; 4: Sports halls, kitchens, canteens; 5: Special buildings, e.g. laundry, brewery, swimming pool.

$$T_d = \left(\frac{RH}{100}\right)^{1/8}(112 + 0.9T) + 0.1T - 112$$

Equation 6.2 Dew point temperature

$$p = 611.2 \times exp\left(\frac{17.67T_d}{243.5 + T_d}\right)$$

Equation 6.3 Saturated vapour pressure of water (Bolton 1980)

$$\nu = \frac{p \times M}{[(273.15 + T) \times R]}$$

Where M molal mass of water (M = 18.02 g/mol)

R universal gas constant (R = 8.314472 Pa·m^3/(mol·K))

Equation 6.4 Volumetric humidity. Mass of vapour present in a unit volume of humid gas.

The function developed by Hukka & Viitanen (1999) to predict the risk of mould growth on wooden materials was also used to analyse the conditions of the internal climate. The World Health Organization recommends prevention of mould growth as it may lead to adverse health effects (Afshari et al. 2009). In this case, Hukka and Viitanen's model provided a useful framework to interpret the changes that insulation of the external wall produced to the indoor environmental quality. This function has been extensively used to evaluate the quality of the indoor environment (Arumägi, et al. (2015), Oreszczyn (2006), Alev et al. (2014)). The curve resulting from the application of the model (Equation 6.5) indicates the critical levels of relative humidity as a function of the internal temperature.

When T≤20°C $RH_{crit} = (-0.00267 \times T^3) + (0.\times T^2) - (3.13 \times T) + 100$

When T>20°C $RH_{crit} = 80$

Equation 6.5 Conditions favourable for initiation of mould growth on wooden material as a mathematical model (Hukka & Viitanen 1999)

An estimation of moisture production in the households was made using Equation 6.6 and considering the values for air leakage obtained with the air pressure tests as the only source of ventilation. Although the calculations did not consider any user related form of ventilation, they provided a valuable estimation of minimum levels of moisture production in the households.

$$MP = \left(\frac{\sum x_i V_i}{\sum V_i} - x_e\right)\rho n \sum V_i$$

Where	x_i	internal mixing ratio (kg vapour/kg dry air)
	x_e	external mixing ratio (kg vapour/kg dry air)
	ϱ	density of air at room temperature (kg/m^3)
	V_i	volume of room i (m^3)
	n	total air change rate (h^{-1})

Equation 6.6 Moisture production estimate (Jensen et al. 2011)

Monthly average values of external temperature and relative humidity recorded with the weather station are presented in Table 6-1. For the analysis, the data was sorted according to the results rather than to the calendar seasons. Thus, winter season - or heating period - was analysed using the measurements from the four coldest months (from December to March), while the summer season included the measurements from the four warmest months (June to September). Based on the measurement of temperature and relative humidity, the risk of mould growth and the internal moisture loads were calculated for both seasons.

Table 6-1 Monthly average outdoor temperature and relative humidity. Values in parentheses represent ± one standard deviation.

Month	2013		2014		2015	
	Temperature	**Relative Humidity**	**Temperature**	**Relative Humidity**	**Temperature**	**Relative Humidity**
January	-	-	3.8 (2.4)	91.1 (7.1)	4.4 (2.6)	79.7 (8.5)
February	-	-	6.8 (4.3)	82.7 (10.4)	4.9 (2.5)	81.7 (9.2)
March	-	-	7.6 (2.8)	75.8 (11.2)	6.4 (2.4)	77.8 (11.3)
April	-	-	8.7 (2.1)	81.2 (14.1)	8.2 (3.1)	76.1 (12.5)
May	-	-	10.8 (2.5)	82.3 (11.3)	8.8 (2.7)	74.7 (13.0)
June	-	-	13.7 (2.1)	79.8 (10.6)	-	-
July	17.4 (3.6)	77.4 (12.5)	15.5 (2.2)	81.6 (10.9)	-	-
August	15.3 (3.2)	76.8 (12.2)	13.8 (2.4)	81.4 (10.0)	-	-
September	12.5 (3.6)	79.2 (8.9)	13.7 (1.9)	84.8 (10.0)	-	-
October	9.9 (3.2)	86.1 (7.4)	11.4 (2.4)	83.0 (8.4)	-	-
November	5.0 (2.9)	85.5 (5.7)	9.3 (2.1)	88.3 (6.0)	-	-
December	6.0 (4.7)	85.5 (9.5)	4.5 (2.6)	81.2 (7.0)	-	-

A summary of the measurements of internal temperature and relative humidity, as well as the calculated values of moisture load, is presented in Table 6-2. When assessing the hygrothermal performance of building envelopes, critical moisture loads should be considered (Kalamees 2006). The International Energy Agency Annex 24 (IEA-EBC 2016) recommended using the 10 % critical level, that is, hygrothermal values that are not exceeded in more than 10 % of the cases. Therefore, besides the average values of moisture loads, the percentile 90 was also calculated.

The results are sorted according to room, season and whether or not the external wall was insulated. Table 6-2 also includes the results of the statistical analysis conducted to explore the influence of season and insulation on the internal temperature, relative humidity and moisture load. An independent two-sample t-test was performed to measure the differences between samples means. Due to the similarity of the results obtained in living rooms and bedrooms, the values of both rooms were averaged. The analysis presented below is primarily focused on the effect of seasonality and level of retrofit and the data from living rooms and bedrooms were analysed together in most of this study.

6.2 Results

6.2.1 Internal temperature

The average hourly values of internal temperature are plotted in Figure 6-3 as a function of the daily average external temperature for summer and winter. The values were calculated using a 0.5 °C step of outdoor temperature. The internal temperature of dwellings showed a strong dependence on the external temperature. Although the dependence was stronger in non-retrofitted dwellings, a positive relationship between internal and external temperature was evident in both samples.

Table 6-2 Average values of temperature, relative humidity and moisture loads measured in the analysed dwellings and t-test results comparing the effect of seasons and level of insulation. Values in parentheses represent ± one standard deviation.

	Insulation	Season	Room	Values per room		Values per household		2-sample t-test					
								Season		Retrofit (summer)		Retrofit (winter)	
				Mean	10%	Mean	10%	p-value	T-value	p-value	T-value	p-value	T-value
Temperature	Not Retrofitted	Summer	Livingroom	19.87 (2.69)	23.0	19.54 (2.52)	22.5	<0.001	309.7	< 0.001	29.0		
			Bedroom	19.21 (2.29)	22.0								
		Winter	Livingroom	14.80 (3.07)	19.0	14.47 (3.02)	18.5					< 0.001	-74.34
			Bedroom	14.12 (2.93)	18.0								
	Retrofitted	Summer	Livingroom	19.08 (2.26)	22.0	19.02 (2.20)	21.8	<0.001	127.9				
			Bedroom	18.97 (2.14)	21.5								
		Winter	Livingroom	17.09 (3.16)	21.1	16.10 (3.34)	20.1						
			Bedroom	15.11 (3.29)	18.9								
Relative Humidity	Not Retrofitted	Summer	Livingroom	67.41 (6.35)	76.0	68.01 (6.78)	77.0	<0.001	34.94	< 0.001	46.73		
			Bedroom	68.70 (7.16)	78.1								
		Winter	Livingroom	65.80 (10.80)	79.0	66.21 (9.44)	77.9					< 0.001	144.61
			Bedroom	66.00 (7.62)	76.4								
	Retrofitted	Summer	Livingroom	65.21 (7.41)	75.6	65.37 (7.55)	76.3	<0.001	127.44				
			Bedroom	65.52 (7.68)	77.0								
		Winter	Livingroom	51.54 (8.68)	64.0	55.74 (11.25)	71.4						
			Bedroom	59.70 (11.91)	75.7								
Moisture Load	Not Retrofitted	Summer	Livingroom	1.59 (1.54)	3.46	1.54 (1.61)	3.50	<0.001	-93.31	< 0.001	73.06		
			Bedroom	1.49 (1.67)	3.55								
		Winter	Livingroom	2.53 (1.33)	4.16	2.43 (1.33)	4.07					< 0.001	43.68
			Bedroom	2.32 (1.31)	3.98								
	Retrofitted	Summer	Livingroom	0.73 (1.29)	2.42	0.73 (1.33)	2.45	<0.001	-103.55				
			Bedroom	0.72 (1.37)	2.49								
		Winter	Livingroom	1.92 (1.57)	3.97	1.97 (1.56)	4.01						
			Bedroom	2.02 (1.55)	4.06								

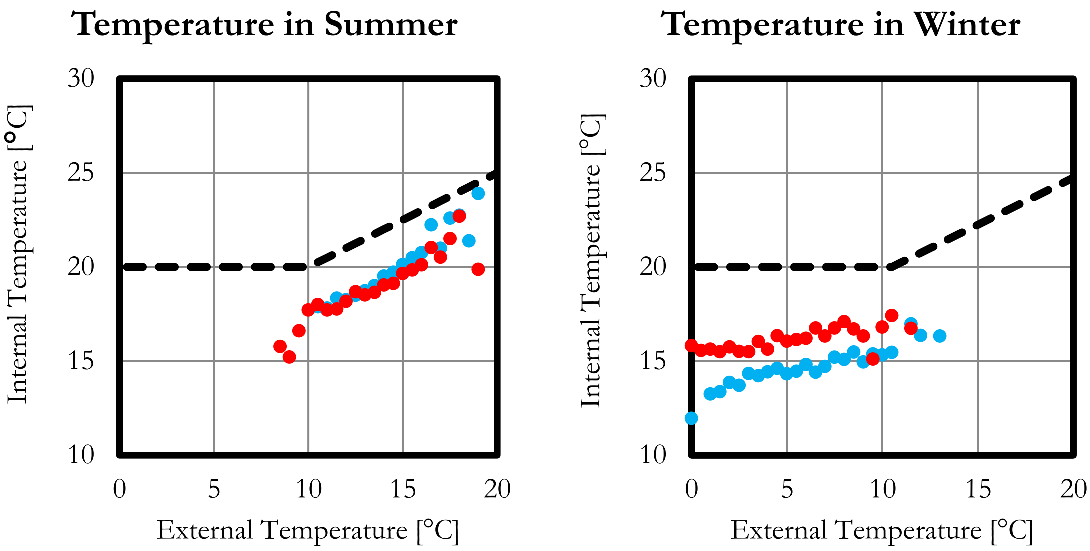


Figure 6-3 Internal temperature as a function of the external temperature for (a) summer and (b) winter. Blue dots represent the average hourly values of non-retrofitted dwellings, whereas red dots summarise the results for the retrofitted buildings. The dashed line represents the temperature design curve proposed in the standard EN 15026:2007.

In summer, the average internal temperature was 19.54 °C for non-treated houses, and 19.02 °C for retrofitted buildings. A one-way analysis of covariance (ANCOVA) was conducted to determine whether the internal temperature differed between non-retrofitted and retrofitted dwellings while adjusting the differences for the changes in the external temperature (covariate). In summer, the interaction between insulation and external temperature was not significant ($F_{1,35} = 2.73$, $p = 0.11$) indicating the similarities between the regression lines of both samples (non-retrofitted and retrofitted). The predicted main effect of insulation was also not significant ($F_{1,35} = 1.17$, $p = 0.28$), while the predicted main effect of external temperature proved to be significant ($F_{1,35} = 257.57$, $p < 0.001$).

The equations for the linear regressions, presented in Table 6-3, showed a strong positive linear dependence on the external conditions in both samples. The slope of the regression lines were similar to the design curve proposed in the standard Figure 6-3a. However, the average values found in the study are consistently lower than those suggested in the standard (around 3°C cooler).

Table 6-3 Equations for regression lines of internal temperature as a function of the external temperature.

	Equation	R-squared	P-value	Standard Error
Non-retrofitted (Summer)	10.6+0.645X	92.8%	< 0.001	0.556
Retrofitted (Summer)	11.6+0.537X	85.7%	< 0.001	0.706
Non-retrofitted (Winter)	12.9+0.279X	89.0%	< 0.001	0.392
Retrofitted (Winter)	15.4+0.132X	53.5%	< 0.001	0.455

In winter, the temperature in non-retrofitted buildings was significantly lower than in retrofitted buildings (Table 6-2). The average temperature for non-insulated houses was 14.47 °C while in insulated dwellings it reached 16.10 °C. Despite the higher temperature monitored in retrofitted buildings, both non-insulated and insulated dwellings were consistently colder than the temperature proposed in EN 15026:2007. An ANCOVA [factor: insulation; covariate: external temperature] revealed that the interaction between insulation and external temperature was significant ($F_{1,45} = 19.90$, $p < 0.001$) showing that the internal temperature in both samples in winter had different dependence on the external temperature. The effects of insulation ($F_{1,45} = 125.51$, $p < 0.001$) and external temperature ($F_{1,45} = 155.46$, $p < 0.001$) were also significant. In winter, the internal temperature in non-retrofitted dwellings was more dependent on the variation of the external temperature than in retrofitted buildings (as shown in the regression equations in Table 6-3). This dependency resulted in very low average values in non-retrofitted dwellings when the external temperatures dropped below 5 °C (Figure 6-3b).

Another aspect of the internal temperature worth noticing was the dispersion of the values. High values of standard deviation were found in both samples in winter (3.02 °C for non-retrofitted and 3.34 °C for retrofitted dwellings) indicating a wide range of internal temperatures during the heating season.

6.2.2 Internal relative humidity

The average values of relative humidity were consistently higher that the design curves proposed in EN 15026:2007 both for normal occupancy (50 %) and high occupancy (60 %). The average relative humidity in non-retrofitted dwellings was 66.5 %, (± 9.6 %), while in retrofitted dwellings the relative humidity decreased to 60.2 % (± 11.1 %).

The values of internal relative humidity are presented as a function of the external temperature in Figure 6-4. The internal climates in summer were similar in both samples with average values of 68.01 % for non-insulated and 65.37 % for insulated houses. In summer, the results of the ANCOVA test were analogous to those obtained for internal temperatures. The interaction between insulation and external temperature was not significant ($F_{1,35}$ = 1.09, p = 0.30). The predicted main effect of insulation in summer was not significant ($F_{1,35}$ = 1.78, p = 0.19) while the external temperature proved to have a significant effect on the predicted relative humidity ($F_{1,35}$ = 210.09, $p < 0.001$). There was a weak negative relationship between relative humidity and the external temperature (Table 6-4). The average values of humidity registered in the sample were mostly above the upper limit proposed in the standard for normal occupancy. For external temperatures under 15 °C, the values also exceeded the upper limit of the high occupancy curve (Figure 6-4a).

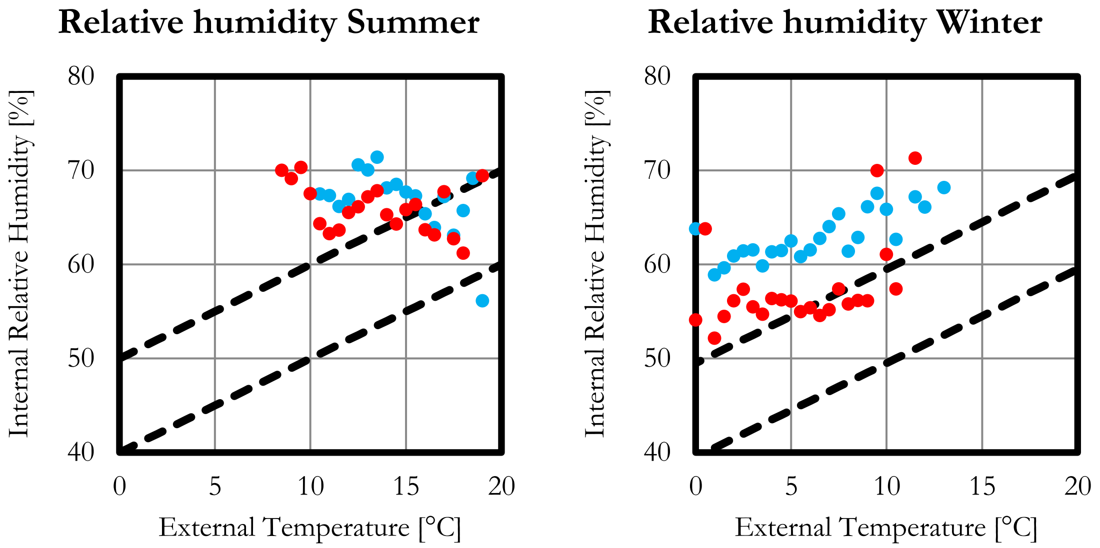


Figure 6-4 Internal relative humidity as a function of the daily average external temperature for (a) summer and (b) winter. Blue dots represent averaged hourly values in non-retrofitted dwellings, whereas the red dots stand for the retrofitted buildings. The dashed lines represent the upper limits of the boundary conditions proposed in the standard EN 15026:2007 for normal and high occupancy.

Table 6-4 Equations for regression lines of internal relative humidity as a function of the external temperature.

	Equation	R-squared	P-value	Standard Error
Non-retrofitted (Summer)	73.3-0.717X	36.6%	< 0.001	2.936
Retrofitted (Summer)	70.4-0.333X	16.5%	< 0.001	2.421
Non-retrofitted (Winter)	60.1+0.493X	55.1%	< 0.001	1.779
Retrofitted (Winter)	54.4+0.581X	20.3%	< 0.001	4.230

In winter (Figure 6-4b), the average levels of internal relative humidity were 66.21 % in non-retrofitted buildings and 55.74 % in retrofitted buildings. The relative humidity in buildings without insulation was always higher than the design curve proposed for buildings with high levels of occupancy. An ANCOVA [factor: insulation; covariate: external temperature] showed that the effect of the interaction between insulation and external temperature was not significant ($F_{1,45} = 0.12$, $p = 0.73$). The analysis revealed significant effects of insulation ($F_{1,45} = 11.30$, $p < 0.001$) and external temperature ($F_{1,45} = 18.20$, $p < 0.001$). The relationship with the external temperature during the cold season was positive for both non-retrofitted and retrofitted buildings and the slopes of the regression equations were similar (Table 6-4).

As observed for the internal temperature, the dispersion of internal relative humidity was greater in winter. The standard deviation values measured in winter (SD(non-retrofitted) = 9.44 °C, SD(retrofitted) = 11.25 °C) were higher than those measured in summer (SD(non-retrofitted) = 6.78 °C, SD(retrofitted) = 7.55 °C).

6.2.3 Mould growth risk

The internal conditions of dwellings were favourable for the initiation of mould growth in 5.86 % of the monitored time. As for the effect of the insulation, non-retrofitted buildings were at risk of mould growth in 7.37 % of the time while retrofitted dwellings were over the threshold only 2.97 % of the time. Regarding the seasonal effect, results for summer and winter were similar (4.27 % and 3.96 % respectively) whereas during the intermediate months (April, May, October and November) the time at risk was 9.63 %.

The frequency distribution shows that the time at risk of mould growth for non-retrofitted buildings was similar in living rooms and bedrooms (Figure 5). In retrofitted buildings this risk was mainly present in living rooms. The distribution also shows that the majority of the events (64.52 %) when the conditions were favourable for the initiation of mould growth were recorded when the external daily average temperature was between 9 and 14 °C.

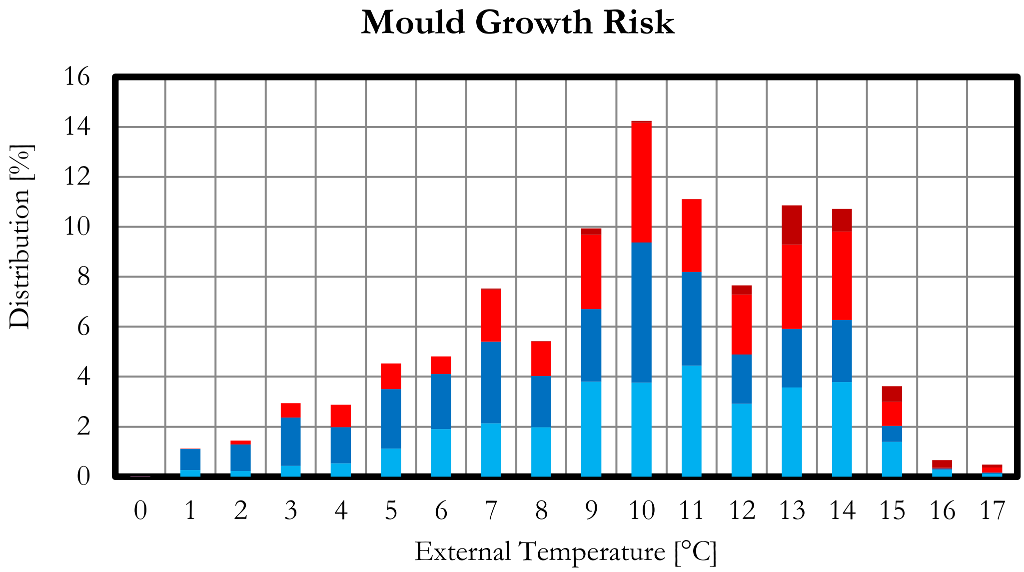


Figure 6-5 Frequency distribution of the time (in percentage) when RH > RH_{crit} as a function of the daily average external temperature. Blue stands for non-retrofitted buildings and red for retrofitted, while light and dark colours represent living rooms and bedrooms respectively.

6.2.4 Moisture load

The results of the t-test showed that the level of insulation had a significant effect on the moisture loads both in winter (T(63814) = 43.68, $p < 0.001$) and in summer (T(59895) = 73.06, $p < 0.001$). The average values of moisture load during the heating season were 2.43 g/m^3 (± 1.33 SD) in non-retrofitted dwellings and 1.97 g/m^3 (± 1.56 SD) in retrofitted. In summer, the values decreased to 1.54 g/m^3 (± 1.61 SD) in non-retrofitted and 0.73 g/m^3 (± 1.34) in retrofitted.

Average results of daily mean values showed a moisture load of less than 4 g/m^3 at an external temperature of 0 °C (Figure 6-6). This value was in agreement with the humidity class 2 (dwellings with normal occupancy and ventilation) of the standard 13788:2012. However, the 10 % critical level showed values that were higher than the upper limit established in the standard. The discrepancy with the standard was especially important in non-retrofitted buildings for external temperatures over 10 °C, as the dependence on the external temperature was much stronger in the retrofitted buildings than in those without insulation (Figure 6-6).

The 10 % critical values of moisture load in non-retrofitted dwellings were 3.2 g/m^3 in summer and 3.7 g/m^3 in winter. In retrofitted dwellings, the values decreased to 2.1 g/m^3 in summer and 3.6 g/m^3 in winter. The results of the ANCOVA [factor: insulation; covariate: external temperature] showed that the interaction between insulation and external temperature was significant ($F_{1,74} = 41.56$, $p < 0.001$), confirming the different dependency on the external temperature of non-retrofitted and retrofitted dwellings. The regression lines of the 10 % critical values, as well as the average values, are presented in Table 6-5. The predicted main effect of insulation was statistically significant ($F_{1,74} = 5.17$, $p = 0.03$) as well as the predicted main effect of external temperature ($F_{1,74} = 310.77$, $p < 0.001$).

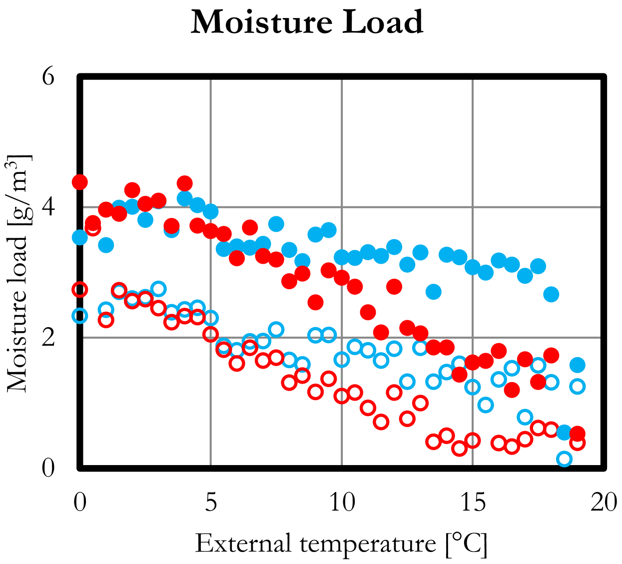


Figure 6-6 Calculated moisture loads as a function of external daily average temperature. Circles represent average values while dots show the percentile 90 for non-retrofitted (blue) and retrofitted (red) buildings.

Table 6-5 Equations for regression lines of moisture loads as a function of the external temperature.

	Equation	R-squared	P-value	Standard Error
Non-retrofitted (Average)	2.681-0.090X	78.7%	< 0.001	0.273
Retrofitted (Average)	2.82-0.154X	90.8%	< 0.001	0.284
Non-retrofitted (10% critical)	4.11-0.0843X	54.1%	< 0.001	0.454
Retrofitted (10% critical)	4.48-0.181X	93.3%	< 0.001	0.283

In Figure 6-7 the measured values of moisture load are compared with the values obtained using the design curve of the standard 13788:2012. Both retrofitted and non-retrofitted buildings obtained values of moisture load higher than those predicted by the standard. In non-retrofitted buildings, the differences were greater for high external temperatures when the standard anticipates low presence of vapour pressure excess (Figure 6-7a). The results from retrofitted buildings followed a trend almost parallel to the curve proposed in the standard although with values of moisture load between 10 % and 20 % higher than those predicted in 13788:2012 (Figure 6-7b).

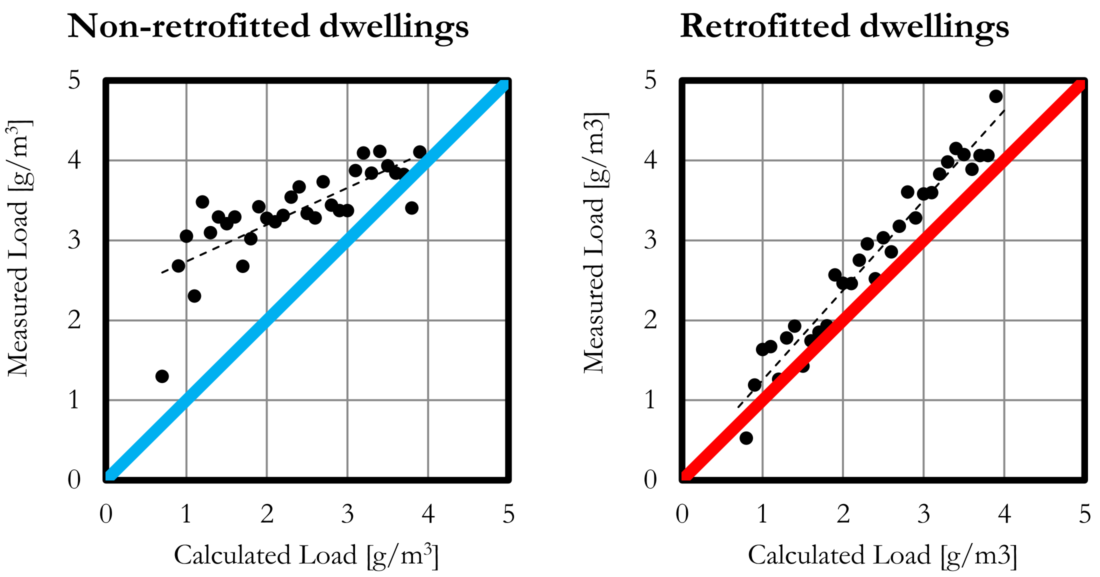


Figure 6-7 Calculated versus measured moisture loads in (a) non-retrofitted and (b) retrofitted buildings. Black dots represent average measured values while the thick lines show the theoretical expected result.

6.2.5 Air permeability and moisture production

The air pressure tests carried out in 10 of the properties revealed a great difference between retrofitted and non-retrofitted dwellings (Table 6-6). The average n50 values were 20.3 ach for non-insulated buildings and 10.7 ach for insulated buildings. The difference was even more important considering that all the non-retrofitted buildings analysed were tenements with less envelope area than the insulated houses in the sample. The results obtained in case 6 (n50 = 2.1 ach) differed greatly from the rest. The tenant of this rented property undertook a full draught proofing of the flat by sealing all the gaps between floorboards, around window and door frames and behind kitchen cabinets and bathroom units.

Table 6-6 Results of the air permeability tests and estimation of the moisture production values.

#	House Type	Insulation	Occupants	Floor area [m²]	Surface area [m²]	Volume [m³]	Air leakage [ach@50Pa]	Floor [m³/hm² @50pa]	Surface [m³/hm² @50pa]	Air leakage [ach]	Avg. Moisture load [g/m³]	Avg. Production [kg/day]
3	Flat	No	1	38.1	120.8	111	31.4	91.7	28.9	1.57	1.4	5.2
5	Flat	No	1	46.8	75.7	136	2.1	6.1	3.8	0.10	2.7	12.5
6	Flat	No	1	37.0	76.6	107	18.9	55.0	26.5	0.95	1.7	7.7
7	Flat	No	1	38.1	91.2	111	25.0	73.0	30.5	1.25	2.7	12.0
9	Flat	No	1	38.0	39.6	111	33.1	93.8	46.0	1.65	1.7	8.1
11	Semi-det	Yes	2	131.4	245.4	211	12.4	19.9	10.7	0.62	0.4	2.5
12	Detached	Yes	2	78.6	283.1	199	14.2	35.9	10.0	0.71	1.0	3.5
13	Detached	Yes	4	120.0	167.2	240	8.6	17.3	12.4	0.43	2.1	10.1
14(1)	Detached	No	3	136.0	332.0	329	11.0	26.6	10.9	0.55	-	-
	Detached	Yes	3	136.0	332.0	329	9.0	21.8	8.9	0.45	1.0	5.2
16(2)	Semi-det	Yes	2	141.0	400.0	410	9.0	26.2	9.2	0.45	2.3	5.0

(1) Measurements made by Farm Energy Consulting on behalf of Historic Environment Scotland as part of a refurbishment case study (Case Study 16 - To be published- http://www.historic-scotland.gov.uk/refurbcasestudies)

(2) Measurements provided by the house owners. A private consultancy firm was appointed to undertake the test.

The average daily moisture production rates oscillated between 2.5 kg/day and 12.5 kg/day (Table 6-6). The case with the lowest values of moisture production (case 11) was a deeply retrofitted house with automatic mechanical ventilation. Therefore, actual air change rates must be higher and moisture production is most likely underestimated. In any case, all the values calculated lie within the values proposed in the standard BS 5250:2011 (Table 6-7).

Table 6-7 Moisture production rates in housing according to BS 5250:2011.

Number of occupants	**Average moisture production rate, kg/day**		
	Low **One or two people, no children**	**Medium** **Average family with children**	**High** **Family with teenage children, indoor drying of laundry, etc.**
1	3 to 4	6	9
2	4	6	11
3	-	9	12
4	-	6	14
5	-	11	15
6	-	12	16

6.2.6 Daily oscillation

Besides the differences in the average values found between non-retrofitted and retrofitted dwellings, the measurements of the internal conditions also showed clear differences in the patterns of use of the rooms. Figure 6-8 and Figure 6-9 show the daily profiles of temperature and relative humidity in living rooms and bedrooms for both winter and summer seasons. Daily variation (δ) was defined as the difference between the maximum and minimum hourly values of the daily profile (Geving & Holme 2012).

Average hourly values of temperature in non-insulated dwellings produced almost flat curves with no variation during the day and no major changes in the patterns between summer (δT = 0.4 °C in the living room and bedroom) and winter (δT = 0.6 °C living room; δT = 0.5 °C bedroom).

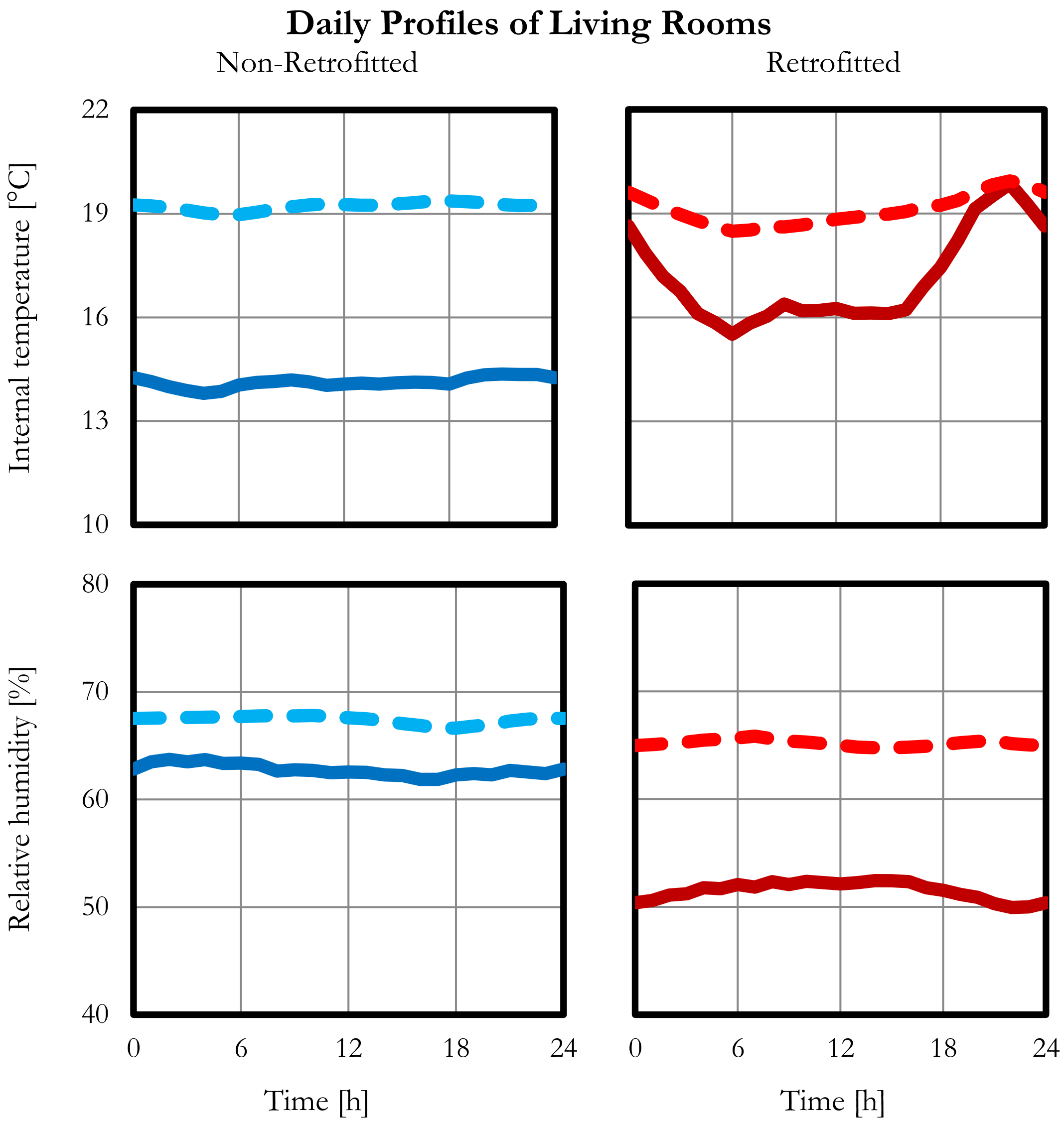


Figure 6-8 Average variations of internal temperature and relative humidity in non-retrofitted (blue) and retrofitted (red) living rooms throughout the day during summer (dashed lines) and winter (thick lines).

Relative humidity curves followed a similar trend with almost no oscillation during the day and parallel curves between summer (δRH = 1.2 % living room; δRH = 2.0 % bedroom) and winter (δRH = 1.9 % living room; δRH = 1.5 % bedroom). However, daily profiles of insulated properties changed considerably. Hourly average temperatures fluctuated during the day, especially in the cold season (δT = 4.3 °C living room; δT = 2.0 °C bedroom), with the highest temperatures recorded in the evening. Relative humidity, on the other hand, remained more constant during the day with variations similar to those found in the non-insulated dwellings (δRH = 2.5 % living room; δRH = 2.9 % bedroom).

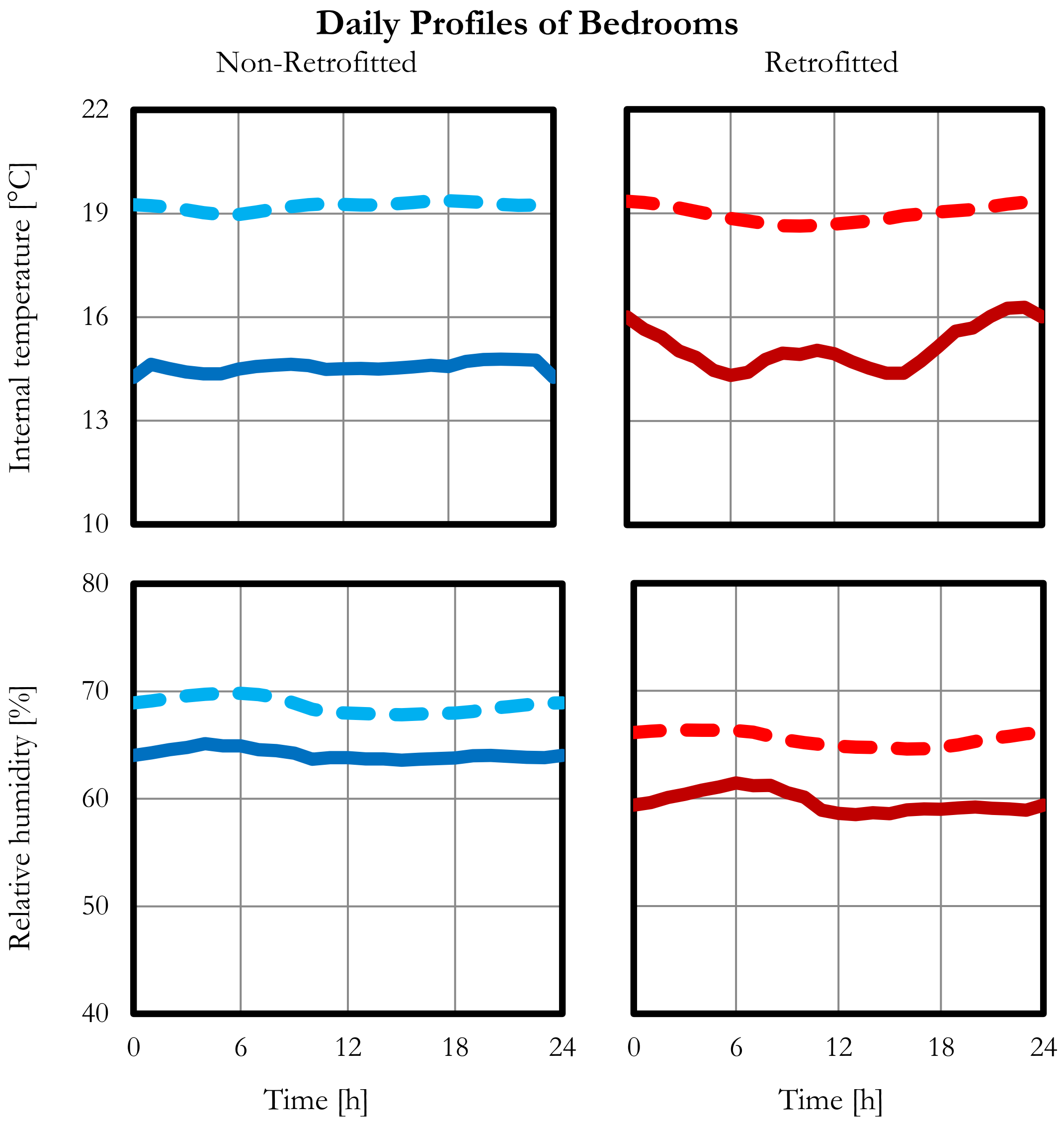


Figure 6-9 Average variations of internal temperature and relative humidity in non-retrofitted (blue) and retrofitted (red) bedrooms throughout the day during summer (dashed lines) and winter (thick lines).

The resulting daily profiles of moisture load (Figure 6-10) confirmed the differences between insulated and non-insulated buildings. Moisture loads in non-insulated properties were almost constant during the day and with minor differences between warm and cold conditions. The highest variation occurred in bedrooms during summer, where the daily variation reached 0.84 g/m^3, while the lowest variation was found in the living rooms in summer (0.44 g/m^3).

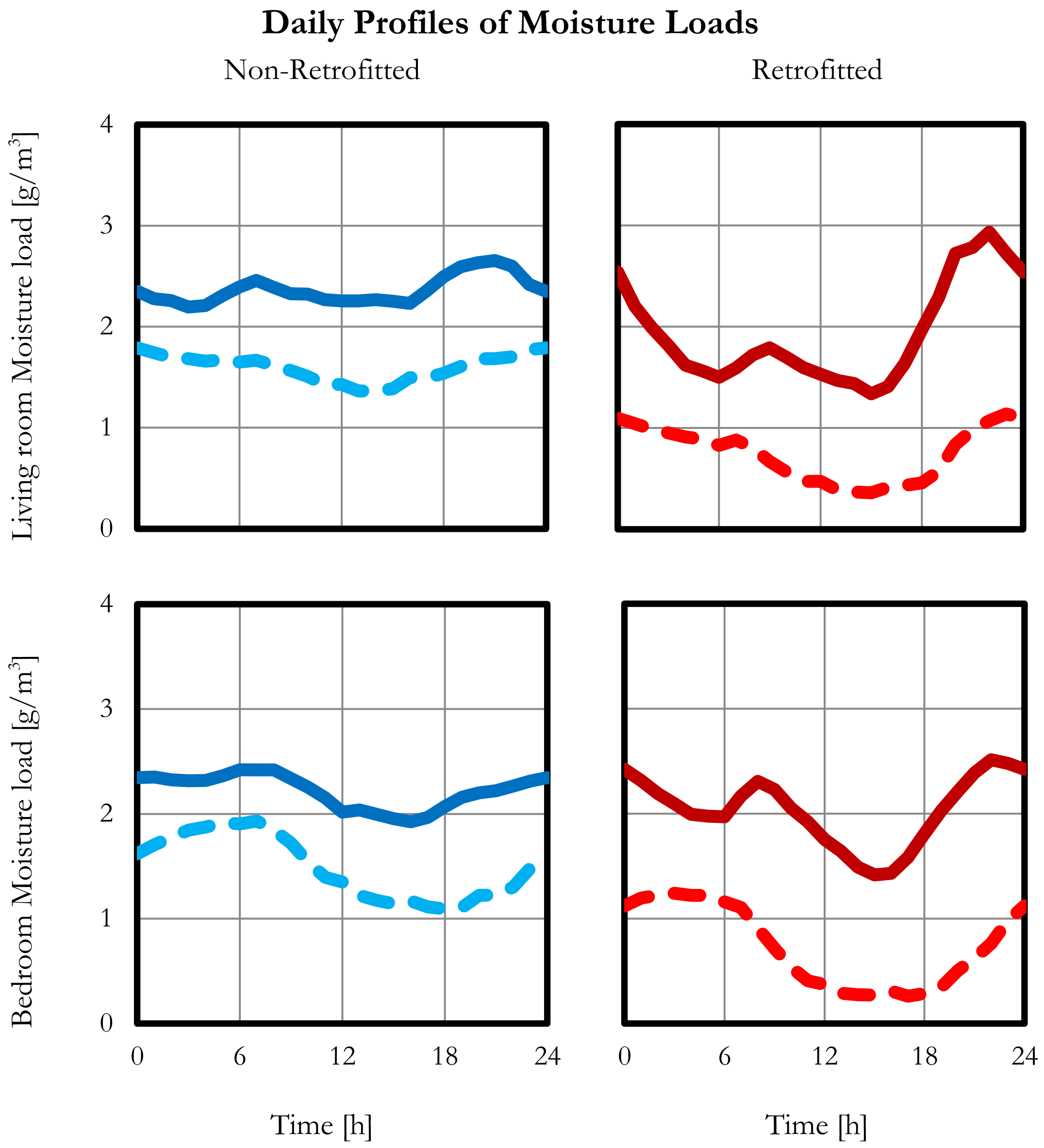


Figure 6-10 Average variations of moisture load in non-retrofitted (blue) and retrofitted (red) living rooms and bedrooms throughout the day during summer (dashed lines) and winter (thick lines).

In insulated properties, the variation during the day and the changes between warm and cold periods were much more significant. Daily variation in the living room in winter reached 1.60 g/m^3, while in summer it was 0.78 g/m^3. In the bedroom, the differences between seasons were smaller and the daily moisture load variation changed from 1.10 g/m^3 in winter to 0.98 g/m^3 in summer.

6.3 Discussion

6.3.1 Internal temperature

The recorded internal temperatures were consistently lower than the design curve proposed in 15026:2007 during the entire year, both in non-retrofitted and retrofitted buildings. Average temperature in non-retrofitted buildings was 17.01 °C, while in retrofitted properties temperature rose up to 17.56 °C. These measurements are far from the reference values in the European standard, that oscillate between 20 and 25 °C, and closer to the results obtained in previous monitoring studies carried out in the UK. As part of a post-refurbishment study, Bros-Williamson (2013) monitored an average internal temperature of 16 °C during the month of October in a traditional dwelling in North Lanarkshire (Scotland). Hong Hong et al. (2009), when looking at the thermal comfort in low-income dwellings in England before and after energy efficient refurbishment, recorded an average internal temperature of 16.42 °C. They found different levels of temperature increase depending on the nature of the improvement. If only insulation was applied, the temperature rose up to 17.61 °C, if the retrofit involved a new gas central heating system the temperature increased up to 18.30 °C and in cases of deep retrofit with new insulation and heating systems the final temperature reached 19.24 °C. Love (2014) documented a mean internal temperature of 15.9 °C in English dwellings and an increase of 1.1 °C after the insulation. Lomas & Kane (2013) also investigated the thermal comfort in English homes, but focused on summertime temperatures. They found an average temperature of 22.4 °C in homes built before 1919, significantly cooler than the rest of the house types in their study.

All these values are in agreement with the temperatures found in this research. The studies presented above covered all kind of dwellings from different ages and construction systems. Therefore, the discrepancies between the predictions made in the standards and the values measured in the dwellings cannot be exclusively explained by the physical characteristics of property. The users and their thermal comfort preferences also play a crucial role in the final temperature of the dwelling. Hong et al. (2009) found that the ideal temperature among the occupants in England was 18.9 °C, with a minor increase to 19.1 °C after the retrofit. These temperatures are far from the values presented in the standards.

Another important factor explaining the low average temperatures found in this sample could be a vertical temperature gradient inside the rooms, especially in non-retrofitted dwellings. A high temperature gradient will produce a strong convective movement in leaky houses, which will make the hot air reach ceiling level quickly and escape causing low temperatures at the monitored level (around 1.5 m). Alev et al. (2015) documented significant differences in the temperature between floor and ceiling level in historic buildings around the Baltic sea. The gradient was found to be dependent on the external temperature and the permeability of the envelope. In their study, the vertical temperature difference in houses with high levels of air permeability in winter was found to reach 12 °C. A similar vertical temperature gradient would explain the daily profiles of non-retrofitted dwellings found in this study (Figure 6-8 and Figure 6-9).

Although the internal temperatures were consistently low throughout the entire sample, there was an evident increase in the values monitored in retrofitted dwellings. One of the factors explaining the differences in the average temperatures between non-retrofitted and retrofitted dwellings was the permeability of the envelope. The results of the air pressure tests carried out in non-retrofitted properties showed high levels of air leakage (AVG = 20.3 ach @50Pa, SD = 4.93). The field measurements are in line with the results obtained by Snow (2012) in a traditional cottage in Cupar, Scotland, (21.5 ach@50Pa). The results, however, are higher than those reported by Hubbard (2011) in English traditional dwellings (permeability ranging from 7.2 to 20.1 ach). The results obtained in retrofitted buildings, on the other hand, presented a significant reduction of envelope air leakage (AVG = 10.7 ach @50Pa, SD = 1.12). The improvement of the permeability leads to significant reduction of heat losses and, as a result, an increase in the mean internal temperature. Although the results of this study should be considered cautiously, due to the small size and limitations of the sample, a similar reduction was also reported by Snow (2012) after the retrofit of the cottage (13.6 ach@50Pa). Air permeability testing of traditional buildings is an underdeveloped field in the Scottish context and the existing research is still very limited.

The relationship between the monitored internal and external temperatures has shown some discrepancies when compared with the design curves proposed in the standard. In addition to that, this relationship has confirmed to be different depending on the level of insulation of the envelope. The regression lines of retrofitted and non-retrofitted dwellings have a deflection or turning point at 10 °C (Figure 6-11a). This turning point is in agreement with 15026:2007. The standard presents a constant value of internal temperature of 20 °C when the external daily temperature is below 10 °C. The measurements, however, have shown that dependency on the external conditions continues beyond that point and the internal temperature decreases along with the external temperature. This relationship was also explored by Arumägi et al. (2014) as part of their investigation of the internal climate of traditional stone houses in Gotland (Sweden). In their study, different types of occupancy were compared: continuous, periodical and unheated. The average temperatures of continuously occupied houses followed a pattern similar to 15026:2007. The temperature in houses that were only periodically used decreased linearly towards 10 °C and the temperatures in unheated properties reached minimum temperatures of -5 °C.

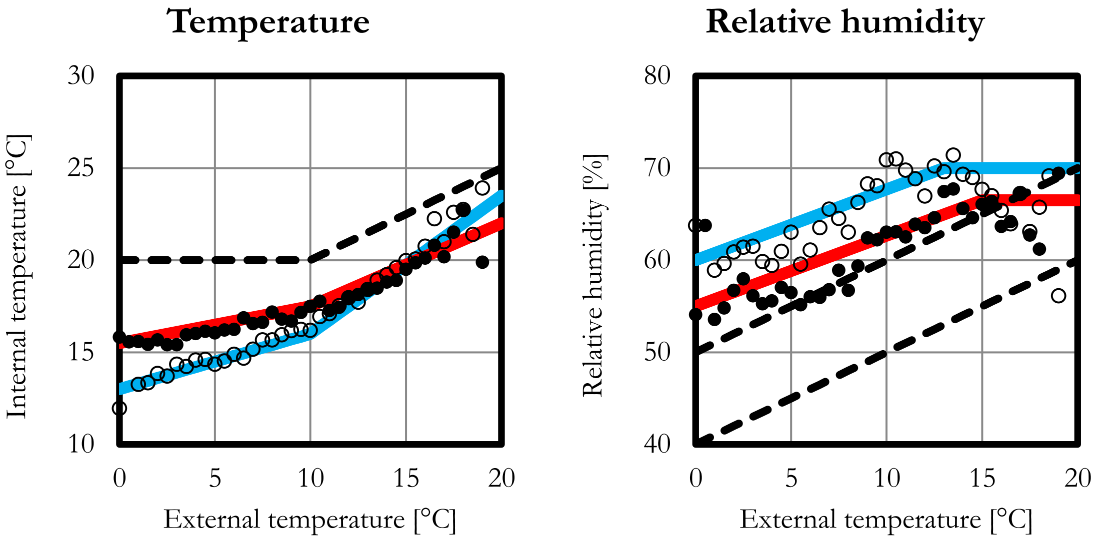


Figure 6-11 Proposed design curves for (a) internal temperature and (b) relative humidity as a function of the external temperature. Non-retrofitted buildings are represented by white dots and blue lines and retrofitted buildings are rendered as black dots and red lines. Dash lines represent the boundary conditions proposed in the standard 15026:2007.

Although the houses included in this research may have been vacant for some periods (such as holidays), all of them were meant to be continuously occupied. However, the discontinuous use of the heating systems (as presented in Chapter 5) together with the building performance resulted in a dependence on the outdoor temperature comparable to curve reported by Arümagi et al. for periodically used houses. Occupants of both non-retrofitted and retrofitted properties heated their dwellings for short periods of time. In non-retrofitted buildings, the poor insulation and high permeability of the envelope presumably made the temperature to drop during the non-heated periods, resulting in very low average internal temperatures when the external temperature decreased. Retrofitted buildings, on the other hand, suffered from the loss of thermal mass caused by the application of internal insulation. As a result, the internal temperature oscillated greatly between heated and non-heated periods (as can be seen in Figure 6-8 and Figure 6-9) and the average internal temperature, despite the significant increase during the heated periods, was still dependent on the external conditions.

6.3.2 Internal relative humidity

Besides the differences in internal temperature, important discrepancies in the levels of relative humidity were also found (Figure 6-11b). To a great extent, the high levels of relative humidity were due to the temperatures found in the dwellings (Korpi et al. 2008). Since the amount of water vapour that the air can contain depends on its temperature, the low average temperatures registered in dwellings (both non-retrofitted and retrofitted) resulted in high values of relative humidity. The temperature effect on the relative humidity levels can be observed in the daily profiles presented in Figure 6-8 to Figure 6-10. Mornings (around 8 am) and evenings (from 8 to 10 pm) were the periods of highest occupancy and moisture production rates (due to use of bathroom and kitchen). However, because of the temperature increase during those periods and consequently in the total amount of water vapour that the air could contain, relative humidity remained almost stable during the day. A similar effect has been found in previous research carried out by Geving & Holme (2012) and Ridley et al. (2007). In both cases, relative humidity remained constant during the day independent of the occupancy or moisture production levels. Only when the moisture loads (or vapour pressure excess values) were explored, the effect of occupancy and activity on the daily profiles became visible.

The regression lines for relative humidity as a function of the external temperature were slightly different from those proposed in the standard (Figure 6-11b). While in 15026:2007 the relative humidity increase is directly proportional to the external temperature increase (1 % increase per °C), in monitored dwellings 1 °C increase in the external temperature was translated into 0.7 % increase in the internal relative humidity. Besides the differences in the slopes, the different dependency on the exterior conditions was also manifested by the turning points. In the standard, relative humidity remains constant (at 60 % or 70 %, depending on the category) when the external temperature exceeds 20 °C. In monitored dwellings, the change to a constant relative humidity was found at lower temperatures, 13 °C in the case of non-retrofitted dwellings and 15 °C in retrofitted properties.

A similar discrepancy between the slopes of the standard and measured humidity curves has been found in Arümagi et al. work (2014). The curve resulting from the average values monitored by Arümagi in periodically used homes is, as seen for the temperature, very similar to the relative humidity values found for non-retrofitted buildings in this study. Retrofitted buildings perform more similarly to the continuously used houses in Arümagi's work (or high occupancy humidity levels in EN 15026:2007) showing a change in the building response to occupants' behaviour. As explained above, although the discontinuous use of heating systems did not change after the retrofit, the insulation of the envelope caused an increase in the internal temperature and that resulted in a decrease in the relative humidity levels.

The reduction in the levels of relative humidity found in retrofitted dwellings resulted in internal environments with less time over the threshold of mould growth risk (2.97 % of the time versus 7.37 % in non-retrofitted dwellings). Therefore, besides comfort improvement, the envelope retrofit resulted in healthier environments for the occupants. This finding is in agreement with the results obtained by Hall et al. (2013) who analysed different scenarios of retrofit of dwellings in the UK. In their study, the simulation of scenarios where the envelope was insulated also resulted in a significant decrease in the risk mould growth when compared to the base case. The only scenario where the retrofit increased the risk was the "Passivhaus" configuration where the air infiltration was reduced to 0.1 ach, a level of air tightness that was not found in this sample.

6.3.3 Moisture load

Moisture load, or the difference in water vapour mass content between the inside and outside air, has confirmed to be an effective variable to compare the internal climate of dwellings. In contrast to relative humidity, the moisture loads allow weighting the effect of temperature and make the comparison between households easier. Hence, this has been a key value when comparing the humidity loads of non-retrofitted and retrofitted dwellings.

Table 6-8 Review of moisture load results in previous research. Values in parentheses represent ± one standard deviation.

Author	Year	Country	Sample	N	Winter (ExtT ≈ 0°c)			Summer (ExtT ≈ 15°c)		
					Average moisture load g/m^3	**10% critical load g/m^3**	**Turning point °C**	**Average moisture load g/m^3**	**10% critical load g/m^3**	**Turning point °C**
			Non-retrofitted	16	2.43 (1.33)	4.13	5	1.54 (1.61)	3.50	15
			Retrofitted	10	1.97 (1.56)	4.01	5	0.73 (1.33)	2.45	20
EN 13788:2012	2012	-	Office and dwellings	-	-	4	0	-	0.75	20
EN 13788:2002	2002	-	Low occupancy	-	-	6	0	-	0	20
			High occupancy	-	-	8	0	-	0	20
Hens (Kalamees 2006)	1992	Belgium	Social housing	50	5.0	-	-	-	-	-
Tolstoy (Kalamees)	1993	Sweden	Mixed	1500	3.6	-	-	-	-	-
Rodriguez (Kalamees)	2000	Spain	Mixed	18	1.8 [yearly]	-	-	-	-	-
Gustavsson (Kalamees)	2004	Sweden	Mixed	390	2.3	-	-	-	-	-
Rose (Kalamees)	2004	USA	Mixed	31	2.2	-	-	-	-	-
Kalamees	2005	Finland	Detached timber frame	107	-	4 [T<5°C]	5	-	1.5 [T>15°C]	15
Kalamees	2006	Estonia	Timber-frame	101	2.0	4 [T<5°C]	5	-	1.5 [T>15°C]	15
Kalamees	2006	Estonia	High occupancy	13	-	6.4	-	-	-	-
Mihalka	2006	Slovakia	Flats	3	2.93	4.2	-	-	-	-
Janssens	2006	Belgium	Mixed	39	2.3 (0.9)	3.7 (95%)	-	0.5 (0.7)	1.7 (95%)	15
Rosseau	2007	Canada	Detached timber frame	8	-	-	-	2.17	-	-
				8	7.89 [T≈-15°C]	-	-	-	-	-
Ridley	2007	England	Mixed	1600	2.2 [T=5°C]	3.8 [T=5°C]	0	0.7	≈2.0	-
Antretter	2010	USA Zone4	Detached	10	1.9 (2.1)	-	-	-5.5(3.4)	-	-
		USA Zone6	Detached	11	2.7 (1.8)	-	-	-1.4(3.0)	-	-
Geving	2011	Norway	Mixed	117	2.2 (0.9)	3.2	5	1.6 (1.0)	3.0	15
Alev	2011	Estonia	Old rural houses	29	≈2.5	≈4.5	-	1.0	≈3.0	-
Kalamees	2012	Estonia	Multi-storey wooden	41	3.0 (1.1)	6.0	5	0.7 (0.7)	2.0	20
Alev	2016	Baltic sea	Historic houses	67	≈2.0	≈4.0	-	≈0.0	≈2.0	-

The results of both samples (non-retrofitted and retrofitted) in winter were in line with most of the results obtained in different research studies carried out in the US, Spain, Sweden, Estonia, Belgium, England or Norway (Table 6-8). In summer, however, this agreement was only found in retrofitted dwellings and average values monitored in non-retrofitted dwellings are higher than the majority of the values reported in previous publications. Comparable results were only found in two studies conducted by Geving & Holme (2012) and Rousseau et al. (2007) in Norway and Canada respectively. None of these studies found any clear relationship between the high values monitored in summer and the number of occupants, or user behaviour. The only evident similarity between those studies and this research is that all of them were carried out in coastal locations with warm summers (Peel et al. 2006).

The regression lines of the 10 % critical level (Table 6-5) have shown that the moisture load dependency on the external temperature is much stronger in renovated dwellings than in non-retrofitted buildings. Moisture load in insulated properties decreased towards 1 g/m^3 when approaching an external temperature of 20 °C (similar to the standard). On the other hand, the non-insulated sample remained above 3 g/m^3 independent of the external conditions. A similar trend was also reported by Geving & Holme (2012) who found a difference in living rooms between cold ($T < 5$ °C) and warm periods ($5 < T < 15$ °C) of only 0.2 g/m^3.

The moisture load dependency on the external conditions is normally explained as a consequence of occupants' behaviour. When the external temperature rises, there is an increase in air change rates due to more frequent ventilation and a reduction in moisture production rates as a result of less time spent indoors (Janssens & Hens (2003), British Standards Institution (2011)). This rationale is compatible with the curves proposed in the standard and the results obtained in retrofitted properties, as they all tend to 1 g/m^3 for external temperatures around 20 °C. However, the results obtained in non-retrofitted dwellings did not match that line of argumentation. The narratives analysis presented in the previous chapter has shown that the seasonality effect on ventilation and moisture production patterns in non-retrofitted dwellings varied greatly among different occupants and in some cases it was fairly limited. As a result, the moisture load in summer of those buildings that have not been upgraded was higher than that forecast in the standard.

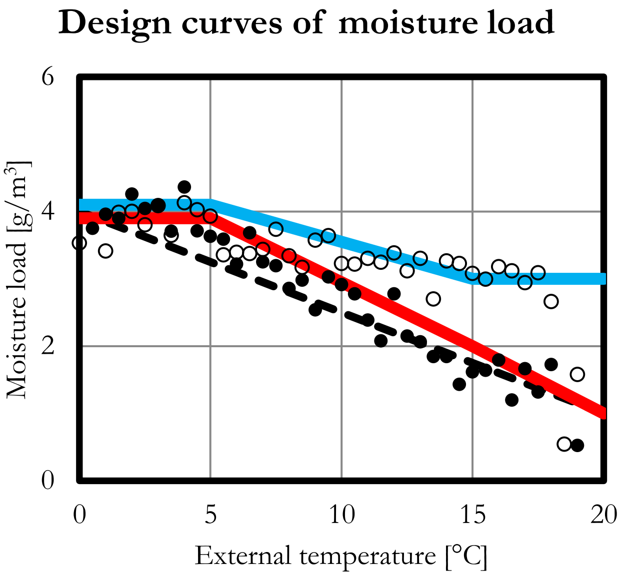


Figure 6-12 Proposed design curves for moisture load as a function of the external temperature. Non-retrofitted buildings are represented by white dots and blue lines and retrofitted buildings are rendered as black dots and red lines. Dash lines represent the boundary conditions proposed in the Annex A of EN 13788:2012.

The discrepancies in the results of critical values of moisture load revealed the need of new and more accurate design curves for the context of traditional buildings in the North-East of Scotland. Based on the daily average values of moisture load, *"simplified and stylised curves"* (Kalamees et al. 2012) of 10 % critical levels are proposed (Figure 6-12). The resulting curves have a first turning point, for both non-retrofitted and retrofitted dwellings, at 5 °C external temperature. This change, compared to the standard 13788:2012, is in agreement with previous work from Kalamees et al. (2005, 2006) and Geving et al. (2008) developed in Finland, Estonia and Norway. As mentioned before, moisture load in retrofitted houses decreased linearly to 1 g/m^3 after the turning point (at a rate of 0.2 g/m^3 per degree Celsius), following a trend similar to the design curve in the standard. In non-retrofitted dwellings, instead, moisture load decreased at a lower rate (0.1 g/m^3 per degree) and remained stable around 3 g/m^3 for external temperatures above 15 °C. Therefore, and despite the limited amount of data gathered at high external temperatures, a second turning point was proposed. This is in line with the results obtained by Janssens & Vandepitte (2006), Kalamees et al. (2005, 2006) or Geving et al. (2008). They all proposed design curves with a second turning point at 15 °C.

As for the discrepancy in moisture loads at high temperatures, it is interesting to highlight that the latest 13788 standard (ISO 2012) already corrected the humidity loads proposed in the previous version (ISO 2002). While in 13788:2002 the humidity load at 20 °C was 0 g/m^3, in the newest version the internal load was updated to 100 Pa ($\approx$ 0.75 g/m^3). This change, however, is still not sufficient to represent the high loads found in non-retrofitted dwellings during the warm periods.

It is clear that, contrary to what Alev et al. (2015) found in historic houses around the Baltic sea, the internal loads in Scottish traditional structures differ greatly from those found in modern houses or recommended in the international standards. However, the humidity loads in traditional buildings after the retrofit of the envelope are comparable to modern houses. In fact, the discrepancy in the first turning point was already reported in previous research focused on modern domestic buildings (Kalamees et al. 2005; Kalamees 2006; Geving & Holme 2012).

The two turning points found in non-retrofitted buildings, 5 and 15 °C, correspond almost exactly with the average external temperatures monitored in winter (5.3 °C) and summer (14.2 °C) respectively. That suggests that the moisture loads during the cold and warm season are fairly stable whereas the effect of the external temperature on the internal moisture load is more immediate in autumn and spring. This effect, however, is not necessarily identical in both seasons. Janssens & Hens (2003) simulated a single bedroom under different occupancy scenarios and found that the moisture load presented hysteresis over a year. The vapour pressure calculated by Janssen & Hens was higher in autumn than in spring despite having similar external conditions. The difference was explained as a consequence of the moisture sorption and desorption potential of the materials.

Moisture buffering potential of a room is determined by the materials. Substitution of the original internal finishes of traditional buildings (made of lath and plaster) by gypsum boards, or the superposition of synthetic insulating materials, is therefore most likely limiting the ability of the walls to moderate the humidity levels (Ge et al. 2014). The profiles presented in Figure 6-10 show important differences in the daily variation of moisture load between non-retrofitted and retrofitted properties. The variation in non-retrofitted dwellings oscillated between 0.44 and 0.84 g/m^3, while in retrofitted dwellings the moisture load ranged from 0.78 to 1.60 g/m^3. The internal renovation of the envelopes in traditional buildings, besides the changes in the thermal mass, might therefore affect the moisture buffering potential of the dwellings.

6.3.4 Indoor climate classes for hygrothermal assessment

The results of this investigation have shown several discrepancies between international standards and the actual conditions of the internal climate in traditional buildings. Since the last step of this thesis consisted of the hygrothermal simulation of envelopes under different scenarios of occupant behaviour, new internal climatic classes based on the monitoring campaign results were proposed in order to obtain more accurate scenarios.

Results obtained by Arumägi et al. (2015) indicated that moisture loads have a stronger effect on the probability of failure of internally insulated walls than indoor temperature. Therefore, and following Kalamees' (2006) recommendations, a moisture load approach was used to define the new climatic classes.

Two different strategies have been found in the literature when designing new humidity design curves. On the one hand, Geving & Holme (2012) proposed three categories (low, medium and high) based on levels of occupancy (< 0.02 person/m^2 and > 0.02 person/m^2) and room use (cellar, living room, bathroom, etc.). All the three curves were based exclusively on the 10 % critical level. Ridley et al. (2007), on the other hand, followed a statistical approach and proposed three categories (named dry, average and wet) that represented different fractions of their sample. Their dry class represented the lowest 15 % of the sample, wet represented the top 15 % and the average stood for the intermediate 70 % of the results.

In this thesis, the second approach was chosen and the internal climatic classes proposed in Figure 6-13 were based on different percentiles of the sample. The values of these percentiles, however, differed slightly from those used by Ridley et al. In order to have more homogeneously distributed groups, Class I (or low or dry) represented the lowest 30 % results of the sample, instead of 15 %. The upper limit of the intermediate Class II was calculated to represent another 40 % of the sample. To eliminate abnormally high values, Class III was based on the percentile 95 instead of using the maximum values. The same distribution was used for both non-retrofitted and retrofitted samples. The regression lines of these three percentiles (30, 70 and 95) were used to create the design curves. It can be noted that the three classes proposed for non-retrofitted dwellings respect the turning points described previously (5 and 15 °C). In retrofitted dwellings, however, the curve proposed for Class I did not follow the same trend described above for insulated properties and had the turning points at 0 and 15 °C.

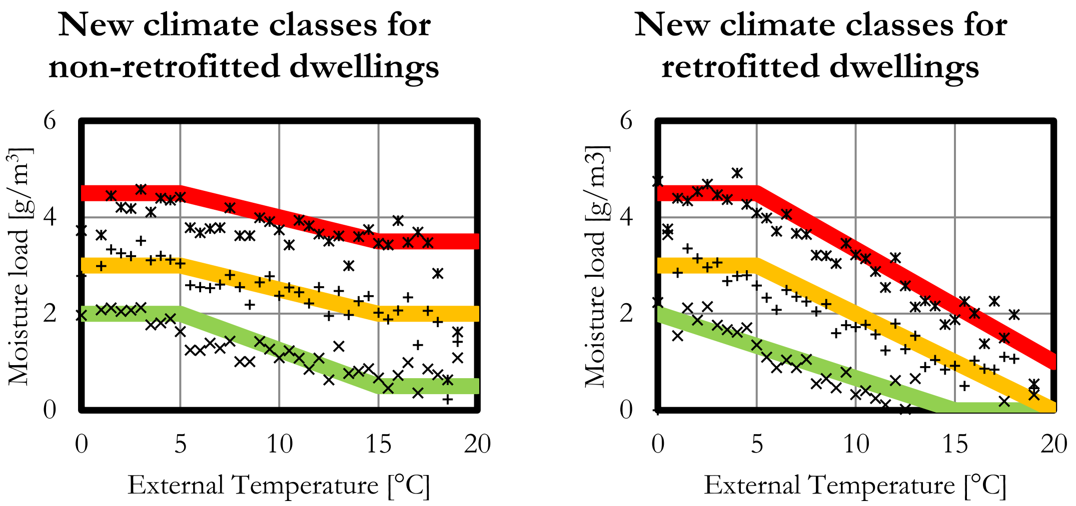


Figure 6-13 Proposed indoor climate classes for hygrothermal assessment of (a) non-retrofitted and (b) retrofitted traditional Sottish dwellings. Moisture load (in g/m^3) as a function of the external temperature (°C)

Due to the limited size of the sample, no relationship between the humidity loads and the household demographics or building characteristics has been established. Further research is therefore needed to explore these relationships. Moreover, the design curves proposed here may not be representative of other type of buildings nor similar buildings located in different climates.

6.4 Conclusions

The hypothesis presented at the beginning of this research claimed that:

> *"Internal climates of residential buildings presented in the international standards are not representative of the traditional Scottish building stock"*

Analysis of the monitoring campaign measurements has provided evidence to validate the original hypothesis. The boundary conditions proposed in BS EN 15026:2007 and BS EN ISO 13788:2012 for hygrothermal calculations are not representative of the internal climate of Scottish traditional dwellings. The internal temperature is clearly overestimated in 15026:2007 and the design curve proposed in 13788:2012 does not represent the high values of moisture load measured in some dwellings.

Indoor climate of retrofitted buildings is more similar to the boundary conditions proposed in the standards. However, although traditional buildings are supposed to perform in the manner of modern construction after the retrofit of the envelope, there are still some important discrepancies in the values of internal temperature and humidity between the standards and the buildings included in this sample.

Considering the importance of internal climate for the accurate assessment of building enclosures performance, new classes of internal climate were proposed for both non-retrofitted and retrofitted dwellings based on the monitored results.

6.5 Summary

This chapter presented the second part of the multi-case study analysis. In this case, the focus was on the quantitative data collected during the monitoring campaign.

The purpose of this analysis was the characterisation of the internal climate of this particular type of constructions before and after the envelope thermal improvement. A second objective of this chapter was the comparison of the results with the values proposed in the international standards used for hygrothermal assessment of buildings.

The values of temperature and relative humidity monitored in the dwellings were sorted according to seasons and used to calculate internal moisture load, mould growth risk and moisture production rates. An ANCOVA analysis was performed to investigate the effect of insulation and external temperature on the internal climate characteristics. The effect of insulation was proven be significant on both temperature and relative humidity during the cold season. Envelope insulation also showed an improvement in indoor environmental quality as the time over the threshold of mould growth risk decreased considerably when compared with non-retrofitted dwellings.

The characteristics of the internal climate were further investigated by exploring the daily profiles of temperature and humidity. Notable differences between non-retrofitted and retrofitted dwellings were found, showing the effect of internal insulation on the thermal mass and moisture buffering capacity of traditional buildings.

Finally, and due to the discrepancies found between measurements and standards, new internal climatic classes were proposed for traditional buildings in the North-East of Scotland before and after the envelope retrofit. These new classes were one of the key parameters explored in the hygrothermal assessment of envelopes presented in the next chapter. This chapter concluded with the revision and validation of the hypothesis proposed at the beginning of this research.

7 NUMERICAL SIMULATION. QUANTIFYING THE EFFECT OF THE INTERNAL CLIMATE

The environmental monitoring results presented in the previous chapter showed important discrepancies between the boundary conditions proposed in the international standards and the internal climates of traditional Scottish dwellings. In addition to that, a wide range of different internal climates was found, from cool households with very low moisture loads of around 1 g/m^3 to hot and humid dwellings with loads over 5 g/m^3.

Hence, the next step of this research was the analysis of the hygrothermal performance of the envelope "*with respect to the uncertainties in the internal boundary conditions*" (Antretter et al. 2010) in order to complete Objective III, 'To explore the effect of the internal boundary conditions on the performance of internally insulated solid granite walls'. The use of numerical simulation allowed for the quantification of the impact that a range of different climatic scenarios had on the moisture dynamics of walls. Thus, numerical simulation was especially appropriate in this research as it helped to explore the effect of climates in different wall assemblies and with different insulating materials simultaneously.

7.1 Model configuration. Input parameters

Modelling of the moisture dynamics in envelopes requires several steps and different data inputs. The steps, summarised in Figure 7-1, are discussed below.

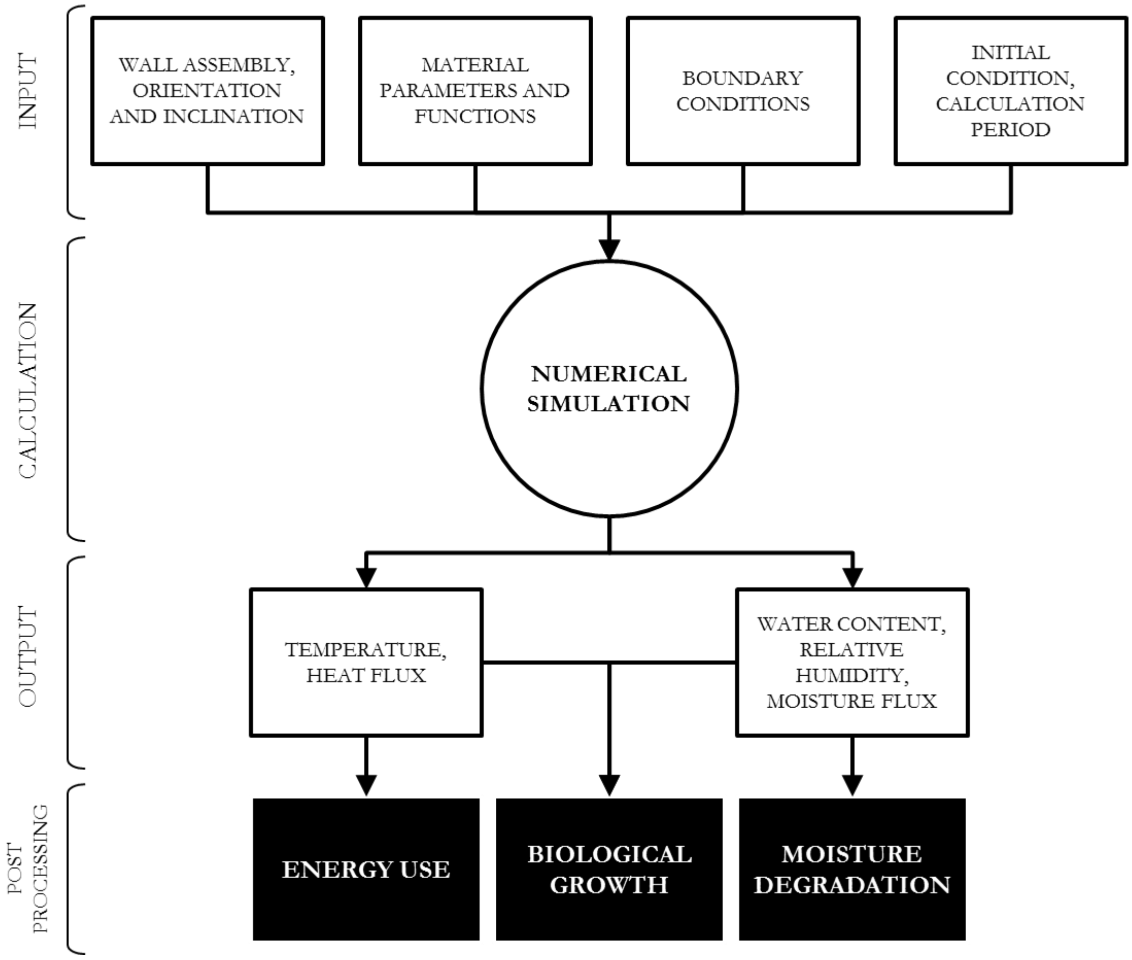


Figure 7-1 Flow chart for hygrothermal simulation proposed in prEN 15026. The chart was eventually removed from the final version of the standard, only because of difficulties in the translation. Adapted from Künzel & Holm (2009)

7.1.1 Wall geometry

The first step prior to the hygrothermal evaluation of the envelope was the geometric definition of the wall itself. The software chosen (DELPHIN 5.8.1) allowed modelling in one or two dimensions. Two-dimensional simulations required higher computer processing power and involved much longer periods for the calculation. Although according to the standard EN 15026:2007 (CEN 2007) one-dimensional simulation is acceptable in the majority of scenarios, in this case (due to the materials nature) both options were explored before deciding which one offered the most suitable results.

Modelling of mortar in granite walls is very important when it comes to hygrothermal performance (Ruisinger 2014). Besides the difference in thermal conductivity between mortar and granite (Browne 2012), there are important differences in the vapour diffusivity properties of both materials. Since granite has a very low porosity and is virtually impervious to water vapour (Urquhart & Young 1998), moisture migration can only take place in the mortar layers. Thus, modelling a wall where the mortar network is connecting the internal and external boundaries was crucial to obtain reliable results and that could only be done in two-dimensional models. Both one and two-dimensional models were simulated, resulting in six different wall assemblies. The characteristics of the models are fully described in the Appendix 7.

Following the advice of the software developers, not every layer was modelled in the definition of the geometry of the walls. The complexity of the wall construction was simplified trying not to exceed the 10,000 elements after the discretization of the model (Ruisinger 2014) (Figure 7-2).

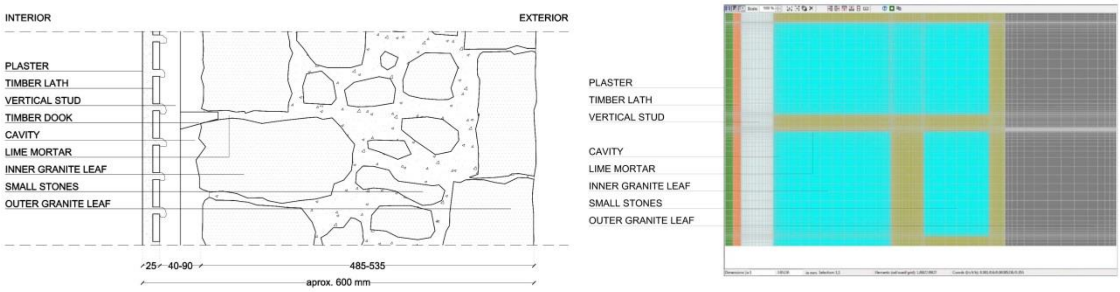


Figure 7-2 Wall section (left) and simplified model assembly in DELPHIN 5.8.1 (right)

7.1.2 Material properties

After the wall geometry was defined, it was necessary to define the materials. Data needed for the definition can be obtained from the software in-built libraries, previous studies characterising thermophysical properties of construction materials (Hens 1991; Kumaran n.d.) or laboratory experiments. Unfortunately, laboratory testing of hygrothermal properties was not feasible for this research and published studies did not include all material properties necessary for this study. Therefore, the use of material libraries was selected in this study. Characteristics of every material used in this research are summarised in Table 7-1. DELPHIN characterises the materials as functions (Figure 7-3), based on laboratory measurements of the physical properties (Bishara et al. 2015).

Table 7-1 Material characteristics

Material	**Library**	**Source**	**Density**	**Porosity**	**Effective saturation moisture content**	**Hygroscopic moisture content at RH=80%**	**Water uptake coefficient**	**Vapour diffusion resistance factor**	**Heat Capacity**	**Thermal conductivity (dry)**
			(ϱ)	(θPOR)	(θEFF)	(θ80)	**(A_w)**	**(μ)**	**(CE)**	**(λ)**
			$[kg/m^3]$	**$[m^3/m^3]$**	**$[m^3/m^3]$**	**$[m^3/m^3]$**	**$[kg/m^2\sqrt{s}]$**	**[-]**	**[J/kgK]**	**[W/mK]**
Air gap 50mm (vertical)	Delphin 5.8.1	Literature	1.3	1	1	1E-5	1E-7	0.2	1050	0.278
Blow-in Cellulose	Delphin 5.8.1	TU-Dresden, MaterialGenerator v.1.0.3.9	55.2162	0.926378	0.78	0.00636248	0.562862	2.0487	2544.42	0.0482
Clay mortar (Historical)	Delphin 5.8.1	TU-Dresden, MaterialGenerator v.1.0.3.9	1567.77	0.408387	0.405	-	0.175662	11.3684	488.389	0.5815
Granite (Weathered)	Delphin 5.8.1	IBK-Laboratory	2450	0.09	0.05	-	0.086	54	700	1.7
Granite Boulder	Delphin 5.8.1	TU-Dresden, MaterialGenerator v.1.0.3.9	2452.91	0.094867	0.054052	-	0.085974	53.798	702.156	1.7175
Lime/Cement Mortar	Delphin 5.8.1	IBK-Laboratory	1570	0.408	0.25	-	0.176	11	1000	0.7
Lime Plaster (Historical)	Delphin 5.8.1	IBK-Laboratory	1800	0.3017	0.285	-	0.127	12	850	0.82
Polyurethane Foam	Delphin 5.8.1	Literature	45	0.92	0.92	0.001	-	104	1500	0.029
Polyurethane (Open Cell)	WUFI 5.3	North America Database, ASHRAE 1018-RP	7.5	0.99	0.92	0.00021	-	2.38	1470	0.037
Spruce-SW Longitudinal	Delphin 5.8.1	TU-Dresden, MaterialGenerator v.1.0.3.9	519.919	0.695	0.69197	0.0679547	0.0432112	4.44281	1946.25	0.193833

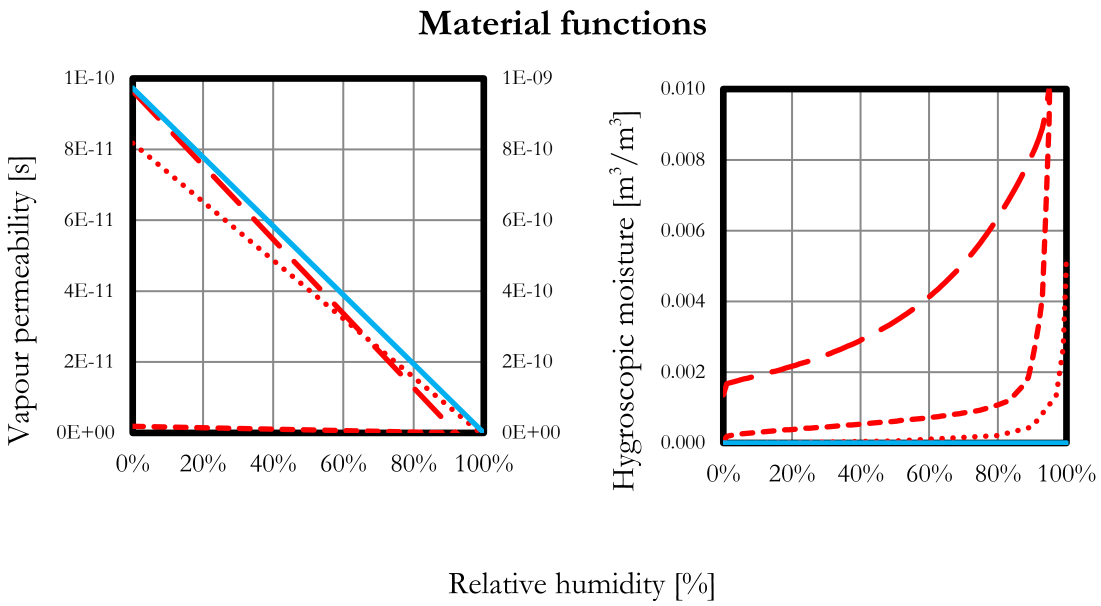


Figure 7-3 Materials functions as described in DELPHIN 5.8.1 (a) Vapour permeability as a function of the relative humidity and (b) sorption curve of the materials simulated in the cavity: Air Gap (blue line), Cellulose (red long dash line), PURopen (dashed line) and PURclosed (dotted line). Vapour permeability of Air Gap to be read on the right y-axis.

As discussed above, characterisation of granite stones and mortar layers was crucial for the accuracy of the results and special attention was paid to the selection of these materials. As for the granite stones two different materials from the DELPHIN library were used: Granite (weathered) and Granite boulder. Weathered granite was applied in the outer leaf of the envelope imitating a wall that had been exposed to the external conditions for a long period of time, as it would be the case of any traditional structure (Urquhart & Young 1998). The core and inner parts of the model are built with Granite boulder. According to the description included in DELPHIN, the samples used for granite characterisation came from a farm stable built in 1857 near Dresden, Germany.

A similar approach was followed for the mortar selection. The external joint of the masonry was modelled with a lime/cement mortar while the rest of the wall was modelled using a 'historical' clay mortar. The reason for this differentiation can be found in the traditional construction methods. External finish of walls was usually pointed using a rich lime mortar that prevented water ingress in the wall. The core of walls, on the other hand, was normally built using a lean mortar or even clay or mud as a mortar (Figure 7-4) (Snow & Torney 2014, p.5).

Figure 7-4 Kincardine O'Neill. Example of granite wall built using (a) rich mortar on the exterior and (b) a lean mortar in the core of the wall.

7.1.3 Initial conditions

Configuration of the initial conditions of materials was the next input needed for the envelope definition. This refers to the elements temperature and relative humidity at the start of the simulation.

Temperature is usually not a cause of concern since building components adapt quickly to the boundary conditions and therefore a uniform temperature close to the expected mean temperature could be used as a start value (Künzel & Holm 2009). In this case, 20 °C was adopted as the initial temperature of the materials. Moisture transport processes, on the other hand, are comparatively slow and the initial scenario could have an important effect on the outcome of the simulation. A common practice is to start with an equilibrium moisture content (EMC) corresponding to RH=80% (Peuhkuri et al. 2010).

7.1.4 External boundary

Two different sources of data can be used when defining the external boundary: synthetic averaged data (from databases such as TMY and WYEC or generated with tools like Meteonorm) or monitored data. Use of hourly site data is recommended for forensic studies, while averaged data can be suitable for design analysis (TenWolde & D Colliver 2001). In this research, both approaches were used. Firstly, the averaged weather data file for Aberdeen Dyce (N 57°12''; W 2°13''; 65 metres above sea level) from the International

Weather for Energy Calculations (IWEC) database was used to perform long term simulations (10 years). Secondly, hourly data recorded with the weather station was used to perform short and more detailed simulation.

The simulated walls had North orientation. This orientation was chosen as this is where the impact of solar radiation and wind driven rain is least important and therefore where the internal climate effect can be observed more easily. The effect of different external boundaries on the wall moisture dynamics, and the interaction between internal and external boundaries, was also explored before defining the final simulation settings. The results of these preliminary investigations are presented in the Appendix 8.

7.1.5 Internal boundary

Internal climate classes resulting from the environmental data analysis presented in the previous chapter were used for the internal boundary definition (Classes I, II and III for both non-retrofitted and retrofitted dwellings). Besides these bespoke climates, a static indoor climate was also simulated. In that case, the conditions were constantly set at 20°C and 50% relative humidity. This is the most common internal boundary found in the literature (Mukhopadhyaya et al. 2006; Abuku et al. 2009; Morelli & Svendsen 2012; Hendrickx et al. 2013) and it was used as a benchmark for the analysis (the results of this scenario are not discussed here, but are also included in the Appendix 8).

7.1.6 Outputs

The last step was the definition of the calculation outputs, that is, the parameters that were going to be calculated. It was necessary to define the variable that was calculated (temperature, humidity, moisture content, etc.), the position in the wall where the output was calculated and the frequency of the calculations (hourly, daily, etc.). In this case, the following parameters were calculated:

i. Temperature. Measured in °C.
ii. Relative humidity. Measured in %.
iii. Moisture content. Water mass density in liquid, vapour or ice form. Measured in kg.
iv. Overhygroscopic moisture content. That is, condensate water. Measured in kg.
v. Moisture saturation. Moisture volume divided by pore volume. Measured in %.

The variables presented above were calculated at the following positions (Figure 7-5):

i. At the interface between the lath and the cavity (or the insulation, if filled)
ii. In the middle of the cavity (or the insulation layer)
iii. At the interface between the cavity (or insulation) and the mortar joint of the masonry
iv. At the interface between the cavity (or insulation) and a granite stone of the masonry
v. At the corner of the timber joist embedded in the wall
vi. As an integrated value for the entire cavity (or insulation)
vii. As an integrated value for the joist end embedded in the wall

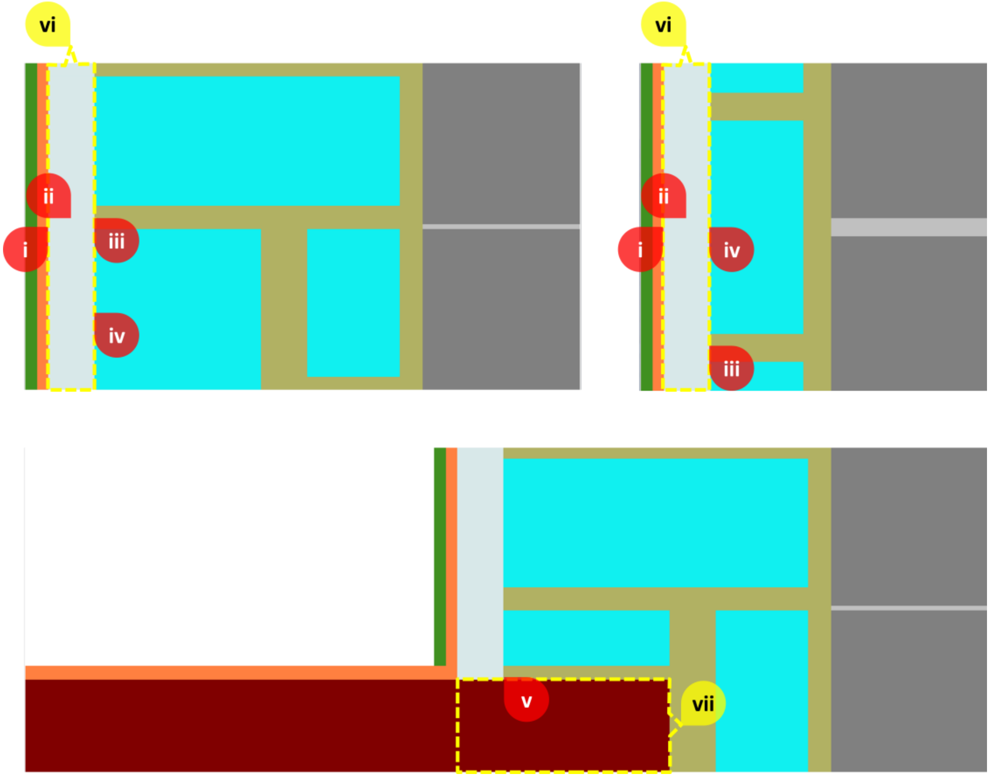


Figure 7-5 Modelled walls assemblies: (a) front wall, (b) gable wall and (c) wall junction. Red arrows show the main monitoring positions and yellow arrows show the integrated areas.

7.2 Performance criteria

Post-processing of results (Figure 7-1) required defining the performance criteria that were going to be used for the wall assessment. Below, the criteria adopted in this research for the performance assessment are described, as well as the 'failure' thresholds established.

7.2.1 Moisture content

First aspect considered in the assessment was the wall moisture content. Moisture content results were used to predict different aspects of the wall long term performance, from the annual moisture balance variation to the impact of internal climate on the insulation properties.

7.2.1.1 Moisture balance

Simulation results were used to calculate the annual increase (or decrease) of moisture content in the insulation layer. In addition to that, the joist end moisture content and saturation degree was explored. Moisture balance was calculated for three different periods. First, water vapour content increase or decrease was measured six months after the insulation to compare the evaporation rates of initial moisture. After that, two complete annual cycles were measured, that is 1.5 and 2.5 years post-insulation.

7.2.1.2 Condensation

A hygroscopic moisture range between 1 and 95 % was defined, following the guidelines proposed by the developers of DELPHIN (Bishara et al. 2015). Condensation was therefore considered to start at humidity levels above 95%. Two separate values were calculated, time (in hours per year) above the condensation threshold at the interface between the granite masonry and the insulation (Figure 7-5) and total amount of condensate accumulated in the insulation over a year (in kg/m^2). German standard DIN 4108-3 *("Thermal protection and energy economy in buildings - Part 3: Protection against moisture subject to climate conditions - Requirements and directions for design and construction")* limits the condensate in a wall to a maximum of 0.5 kg/m^2 to prevent any moisture related damage (Künzel 2000). This limit was adopted in this research as a failure threshold for the assessment of the envelope.

7.2.1.3 Thermal conductivity

Use of numerical simulation allows for a transient calculation of thermal conductivity. In this work, moisture values were used to calculate the maximum increase of thermal conductivity (in W/mK) of the insulation when compared to nominal values. In addition to that, thermal conductivity variation was studied as a function of the external temperature.

7.2.2 Time of wetness

TOW was defined as the interval of time when both relative humidity and temperature were above their respective critical values (RH_{crit} and T_{crit}). The critical values of temperature and humidity varied depending on the mechanism studied. In this case, two different processes of biological damage were considered: mould growth and wood decay.

7.2.2.1 Mould growth

The mould growth prediction function presented in Chapter 6 (Equation 6.5) was used again in the assessment of the simulations results. Here, risk of mould growth was calculated at the masonry-insulation interface. Hukka and Viitanen's mould growth model was used as a threshold for initial organism colonisation. Although mould does not cause a structural damage, it indicates the presence of favourable conditions for other organisms like bacteria and actinomycetes. These organisms destroy pit membranes in the timber increasing its porosity and moisture uptake leading to conditions that are even more favourable for the growth of rotting fungi like dry rot (Coggins C. R. 1980) (Figure 7-6).

Figure 7-6 Dry rot growth on a party granite wall behind the lath and plaster. The wall had been exposed for treatment and all the affected timber removed.

In the cases where conditions were found to be prone to mould growth, its evolution was also calculated to identify whether mould was accumulating or declining over time. In this research, the evolution of mould growth was evaluated using the concept of 'Mould Index'

(MI) developed by Viitanen. 'MI' evolution during the last year of the simulation was calculated using the VTT model built in DELPHIN 5.8.1. This model is based on the equations of mould growth and decline presented by Hukka & Viitanen (1999) and Viitanen (2011) respectively. Characteristics of the element upon which mould was simulated were defined by the following parameters: material, surface and decline. Model options, as well as the chosen configuration, are presented in Table 7-2. MI at the masonry interface was calculated as average values as well as a time dependent curve.

Table 7-2 Mould Index parameters of the VTT model as implemented in DELPHIN 5.8.1. Shaded cells indicate the settings adopted in this research.

Parameter	
Material	Very sensitive (pine sapwood)
	Sensitive (spruce, wooden board)
	Medium resistant (concrete, mineral wool)
	Resistant (EPS)
Surface	Very sensitive
	Sensitive
	Medium resistant
	Resistant
Decline	Short periods (pine)
	Significant relevant decline
	Relatively low decline
	Almost no decline

7.2.2.2 Wood decay

The model proposed by Kehl et al. (2013) to predict the decay of wooden elements, as described in Chapter 2 (Equation 2.2), was adopted in this research for the assessment of the envelope. Time over the threshold (in hours per year) was calculated, again, at the interface between the granite masonry and the insulation.

7.3 Results

Numerous simulations were carried out prior to the definition of the final configurations presented here. These preliminary studies explored the length of the simulation, the feasibility of one or two-dimensional models and the characteristics of the external boundary. The results of these simulations are presented in the Appendix 8. The conclusions of the exploratory study led to a compromise solution with short-term simulations (2.5 years) of two-dimensional models with a detailed calculation of the outputs during the last year of the simulation. The external boundary included the effect of temperature, relative humidity and solar radiation. The impact of wind driven rain was also explored in preliminary assessments but it was discarded for the final simulations in order to optimise the computational resources while ensuring accurate results. The results presented below correspond to the simulation of three different two-dimensional models:

- Front wall. Total thickness 600 mm. External joint width 5 mm.
- Gable wall. Total thickness 375 mm. External joint width 20 mm.
- Joist end. Junction between a front wall and an intermediate floor.

The results of the simulation of a non-retrofitted wall are also included in this chapter. The results of this scenario must be considered carefully since the ventilation of the cavity was not considered. Despite the limitations, the results provided a good reference for the comparison with the retrofitted walls. The different scenarios were named as follows:

- Cavity. Non-retrofitted wall. Space between masonry and lath and plaster was simulated as a vertical air gap of 50 mm.
- Cellulose. Retrofitted wall. Cavity filled with blown-in-cellulose.
- PURclosed. Retrofitted wall. Cavity filled with closed-cell polyurethane foam.
- PURopen. Retrofitted wall. Cavity filled with open-cell polyurethane foam.

A summary of the results obtained in the different scenarios is presented in Table 7-3.

Table 7-3 Summary of simulation results for the last year of the simulation

		Front wall				Gable wall				Floor junction			
		Cavity	**Cellulose**	**PURclosed**	**PURopen**	**Cavity**	**Cellulose**	**PURclosed**	**PURopen**	**Cavity**	**Cellulose**	**PURclosed**	**PURopen**
Moisture Balance [g/m^2]	Class I	0.1	-1.7	0.0	1.4	0.1	-11.5	-0.8	-1.2	2.9	3.0	2.9	3.2
	Class II	0.1	-4.9	0.4	2.2	0.1	-13.7	-0.7	-2.8	4.9	5.2	3.6	5.5
	ClassIII	0.1	-0.8	1.6	11.0	0.2	-7.7	0.0	4.8	7.1	9.4	4.3	9.6
Average Saturation [%]	Class I	-	-	-	-	-	-	-	-	7.57	7.70	7.20	7.80
	Class II	-	-	-	-	-	-	-	-	9.45	9.50	7.80	9.64
	ClassIII	-	-	-	-	-	-	-	-	10.89	11.50	8.40	11.67
Time Above RH=95% [h/y]	Class I	0	0	0	0	0	0	0	0	0	0	0	0
	Class II	0	1592	0	2805	0	2763	0	3165	0	0	0	0
	ClassIII	180	4349	0	5330	2564	4729	0	5736	0	0	0	0
Maximum Condensate [g/m^{2}y]	Class I	0.6	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Class II	0.7	10.6	0.0	56.2	0.7	42.1	0.0	134.6	0.0	0.0	0.0	0.0
	ClassIII	0.7	144.4	0.0	728.5	0.8	145.5	0.0	928.8	0.0	0.0	0.0	0.0
Maximum λ [W/mK]	Class I	0.2780	0.0512	0.0295	0.0376	0.2780	0.0513	0.0295	0.0376	0.1310	0.1310	0.1310	0.1310
	Class II	0.2780	0.0518	0.0295	0.0387	0.2780	0.0522	0.0295	0.0397	0.1310	0.1310	0.1310	0.1310
	ClassIII	0.2780	0.0540	0.0297	0.0470	0.2780	0.0540	0.0297	0.0492	0.1310	0.1310	0.1310	0.1310
Time at Risk of Mould Growth [h/y]	Class I	0	1836	0	2478	0	2845	0	3333	0	0	0	0
	Class II	3866	5102	4099	5313	5076	5428	3530	5709	2917	3185	0	3507
	ClassIII	6310	7447	8760	7894	7468	7874	7899	8181	5859	7340	0	7760
Average Mould Index [-]	Class I	0.00	0.05	0.00	0.19	0.00	0.26	0.00	0.43	0.00	0.00	0.00	0.00
	Class II	0.28	2.44	0.23	3.35	1.00	3.72	0.14	4.09	0.08	0.14	0.00	0.18
	ClassIII	2.34	4.97	2.37	4.99	4.29	5.05	2.10	5.06	1.23	1.86	0.00	2.11
Time at Risk of Wood Decay [h/y]	Class I	0	0	0	0	0	0	0	383	0	0	0	0
	Class II	0	2655	0	3050	441	3213	0	3950	0	0	0	0
	ClassIII	1885	5266	223	6037	3929	5686	171	6525	0	0	0	0

7.3.1 The effect of the internal climate on the moisture content

7.3.1.1 Effect on the moisture balance

Moisture content of the insulation, in both front and gable walls, decreased after half year in all the scenarios simulated with humidity classes I and II (Figure7-7a to f). The reduction in the moisture content ranged from 6.8 % (gable wall insulated with PURopen under Class II, (Figure7-7f) to 29.3 % (front wall insulated with PURopen under Class I, Figure7-7c). In scenarios simulated under humidity class III the results varied depending on the insulating material. Moisture content decreased in walls insulated with PURclosed (7.8 % in the front wall and 5.1 % in the gable wall, Figure7-7b-c) and increased in walls insulated with Cellulose (4.4 %; 8.2 %, Figure7-7a/d) or PURopen (9.7 %; 29.2 %, Figure7-7c/f). The following annual balances were always close to the equilibrium (max = 4.9 %; min = -5.6 %) with the only exception of walls simulated with PURopen and high moisture loads (Class III). In that case, the equilibrium was still not reached after 1.5 years and the annual moisture content increased (18.6 % in front walls and 6.9 % in the gable walls, Figure7-7c/f). Equilibrium was reached after 2.5 years in all the cases, even in those with higher increase in moisture content after the retrofit (Figure 7-8).

In the charts plotted in Figure7-7 two different patterns can be noted in the case of the joist end. Moisture balance of joists ends was positive in all the simulated scenarios (Figure7-7g-i), independent of material or humidity class. However, only in walls insulated with PURclosed (Figure7-7h) the moisture increase was similar under the three different climates. After an average increase of 7.5 % in the first half year, the wall tended to approach the equilibrium and the moisture increase in the last year oscillated between 2.0 % (Class I) and 3.9 % (Class III). The effect of internal climate was more evident in walls insulated with Cellulose (Figure7-7f) and PURopen (Figure7-7i). Moisture increase in the first half year post-insulation was again very similar in all the cases, with an average increase of 8.1 %. In the last year, however, the difference between scenarios with humidity class I and III was noticeable. Thus, while the wall simulated with Class I was close to the equilibrium (2.1 % increase with Cellulose and 2.5 % with PURopen), in the scenarios simulated with Class III the annual moisture increase was between 8.9 % (Cellulose) and 9.1 % (PURopen).

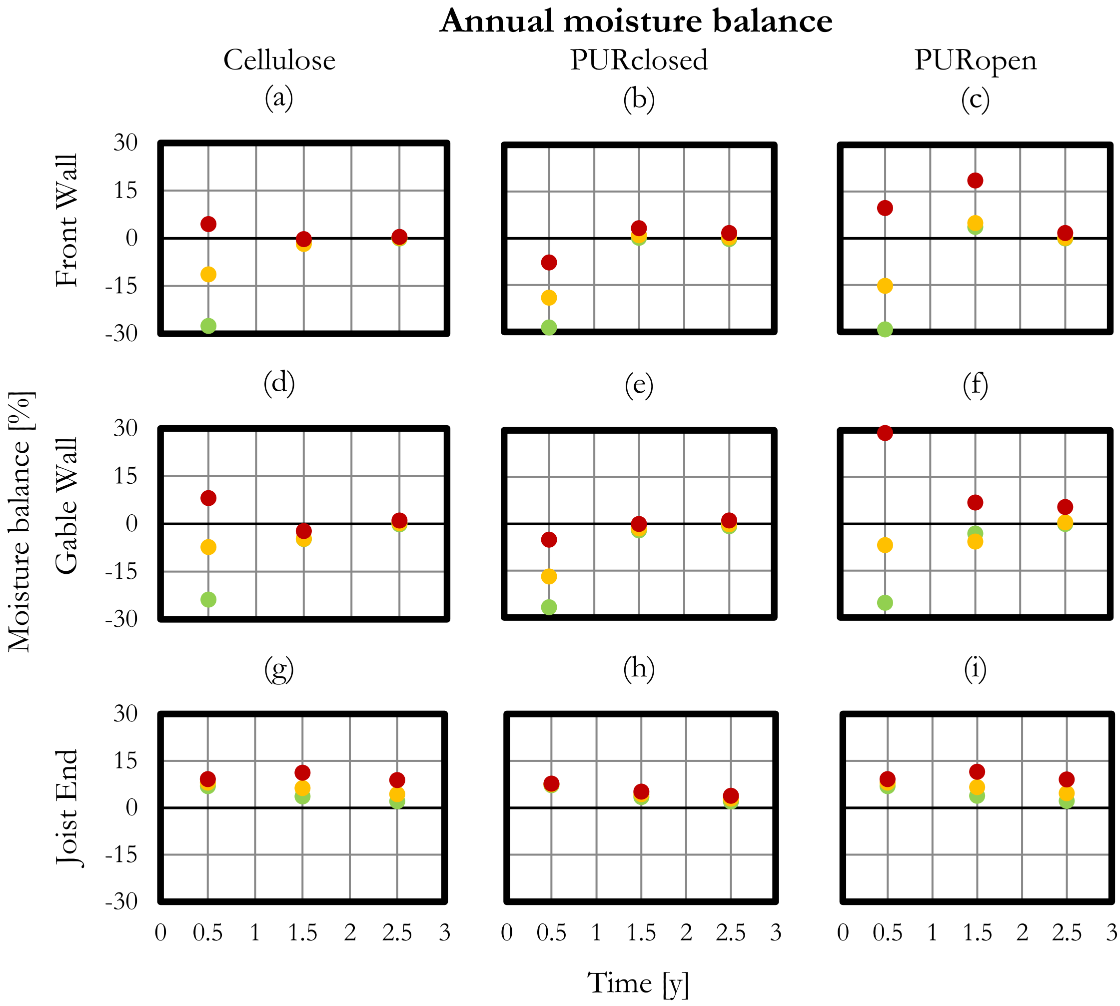


Figure 7-7 Annual moisture balance (%) of all retrofitted scenarios. Green dots represent results for Class I, yellow dots stand for Class II and red dots represent Class III.

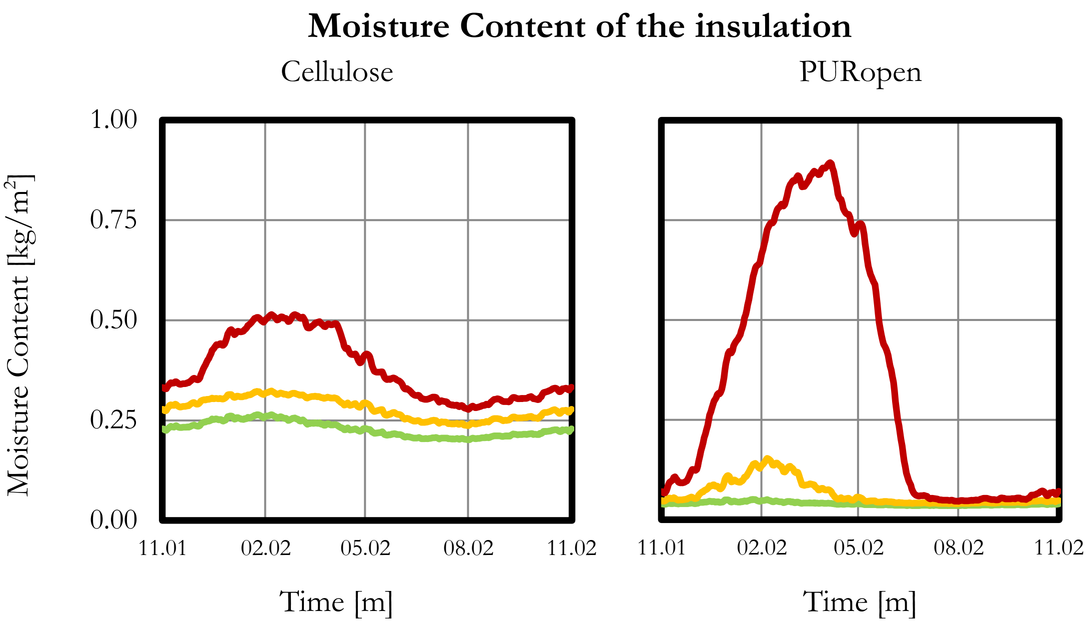


Figure 7-8 Integrated values of moisture content in the insulation (kg/m^2) for the last year of the simulation. The green line represents the results for Class I, yellow stands for Class II and red represents Class III.

7.3.1.2 Effect on the moisture saturation in the joist end

Average values of saturation calculated in the joist end (Table 7-3) were consistently lower than the thresholds found in the literature, 18 % (Browne 2012) and 20 % (Morelli & Svendsen 2012). Even in the most critical point, the junction between the insulation, the masonry and the timber joist (Figure 7-9), the moisture content never exceeded 14 % of effective saturation limit of the material.

As for the evolution of the saturation levels during the last year of the simulation (Figure 7-10), the results showed that the saturation of the joist in walls insulated with Cellulose (Figure 7-10b) and PURopen (Figure 7-10d) is almost identical to the results found before the insulation (Figure 7-10a). Only the results of simulations with Class I changed after the insulation. The yearly variation in non-insulated walls was of only 0.2 % while in insulated walls it increased to 3.2 % (Cellulose) and 3.4 % (PURopen). In the cases where the wall was insulated with PURclosed (Figure 7-10c) the moisture saturation pattern changed and the values remained almost constant independent of the humidity class. The yearly variation of saturation ranged from 0.3 % with Class I to 0.6 % with Class III. The highest values of moisture content were recorded between December and May, with a delay of around one month in walls insulated with PURclosed.

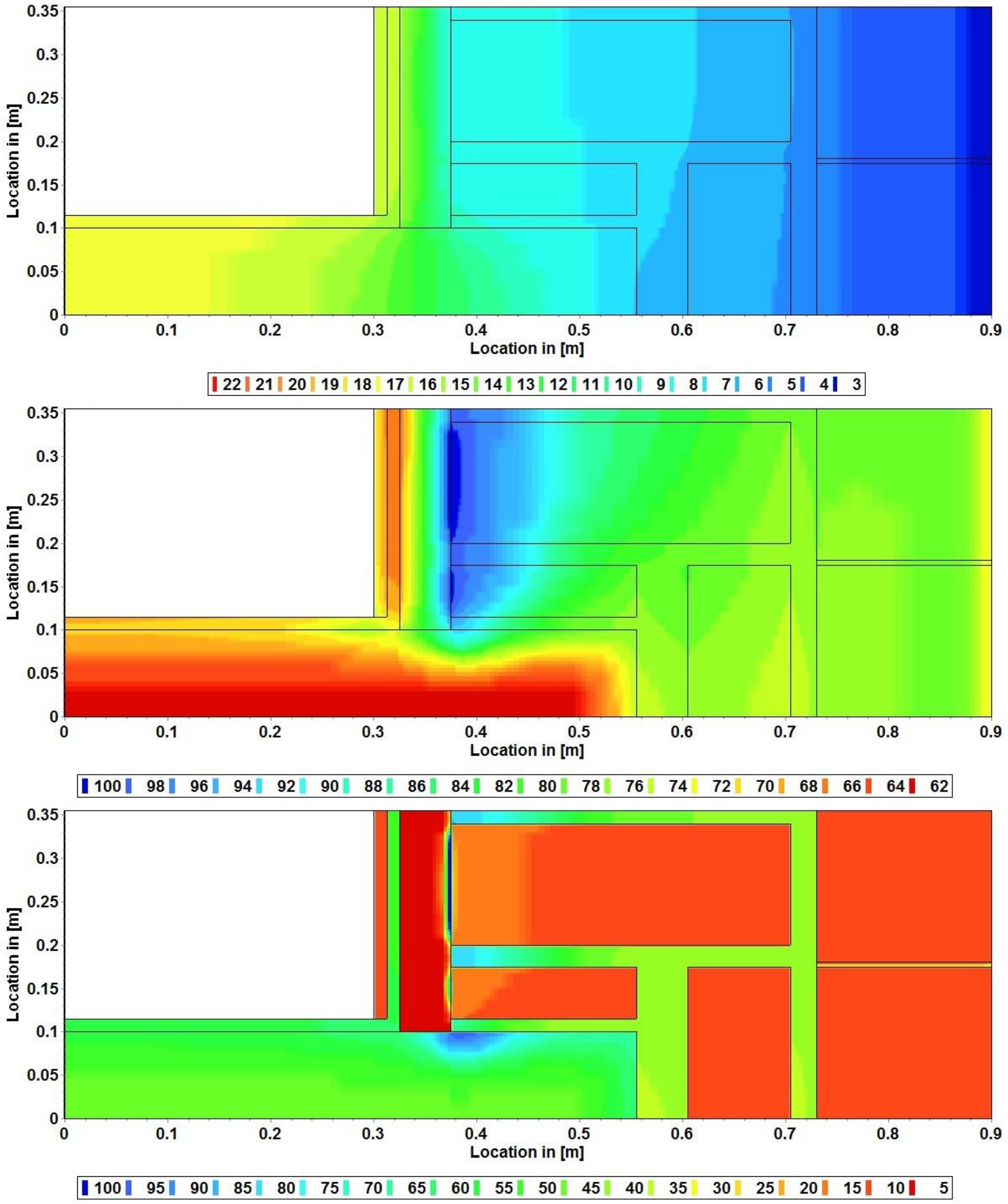


Figure 7-9 Temperature (°C), Relative Humidity (%) and Moisture Content (kg/m^3) profiles of a wall junction insulated with PURopen and simulated under Class III on the 1st of February of the last year of the simulation.

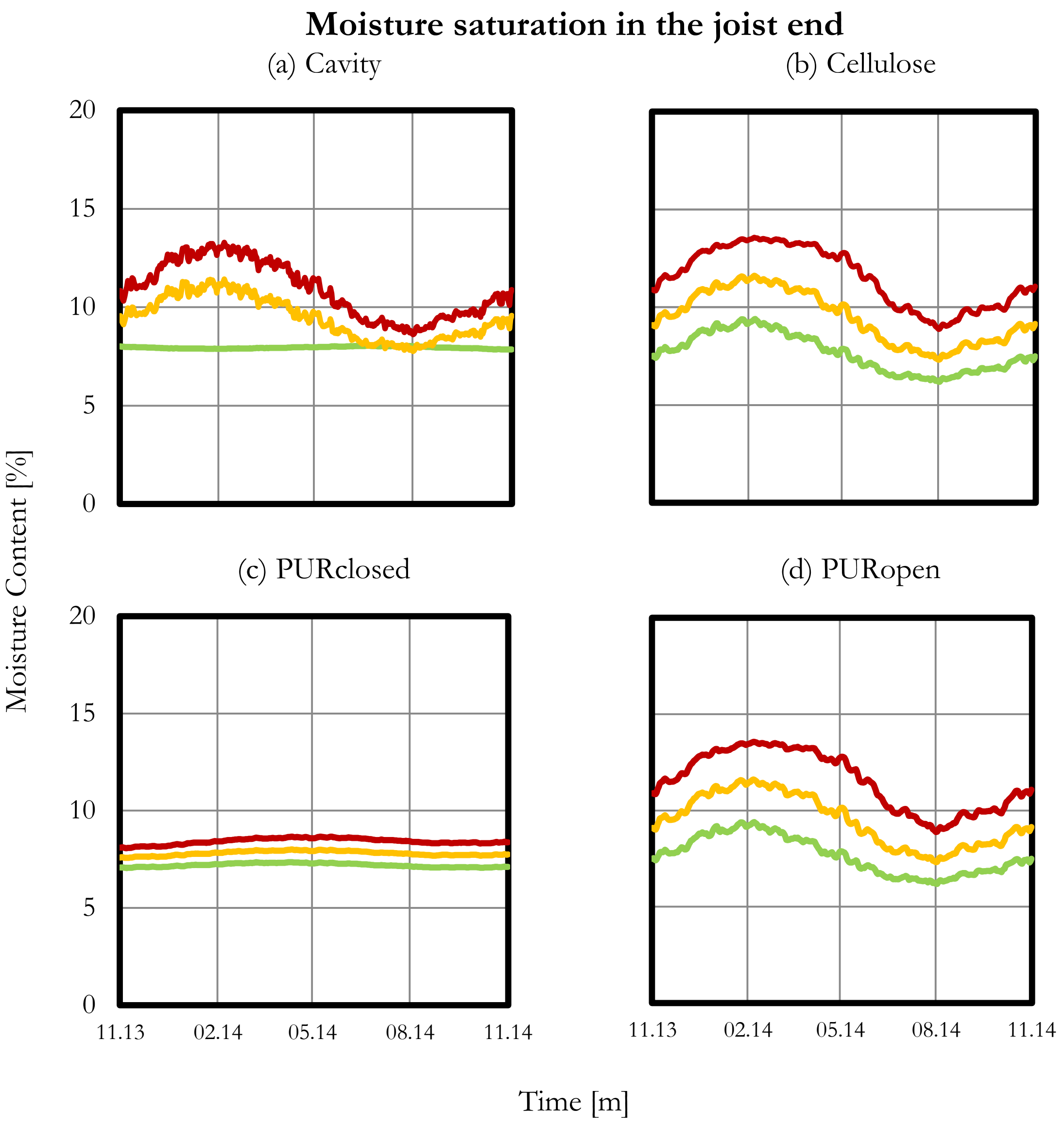


Figure 7-10 Moisture saturation (%) of the joist end during the last year of the simulation. The green line represents the results for Class I, yellow stands for Class II and red represents Class III.

7.3.1.3 Effect on the risk of interstitial condensation

The results of time over the condensation threshold (RH = 95 %) during the last year presented two very different scenarios (Table 7-3). The simulation of the wall junction did not produce any value above 95 % in the joist end for any insulating material tested. Measurements at the masonry-insulation interface in front and gable walls showed a significant increase when walls were insulated with Cellulose or PURopen.

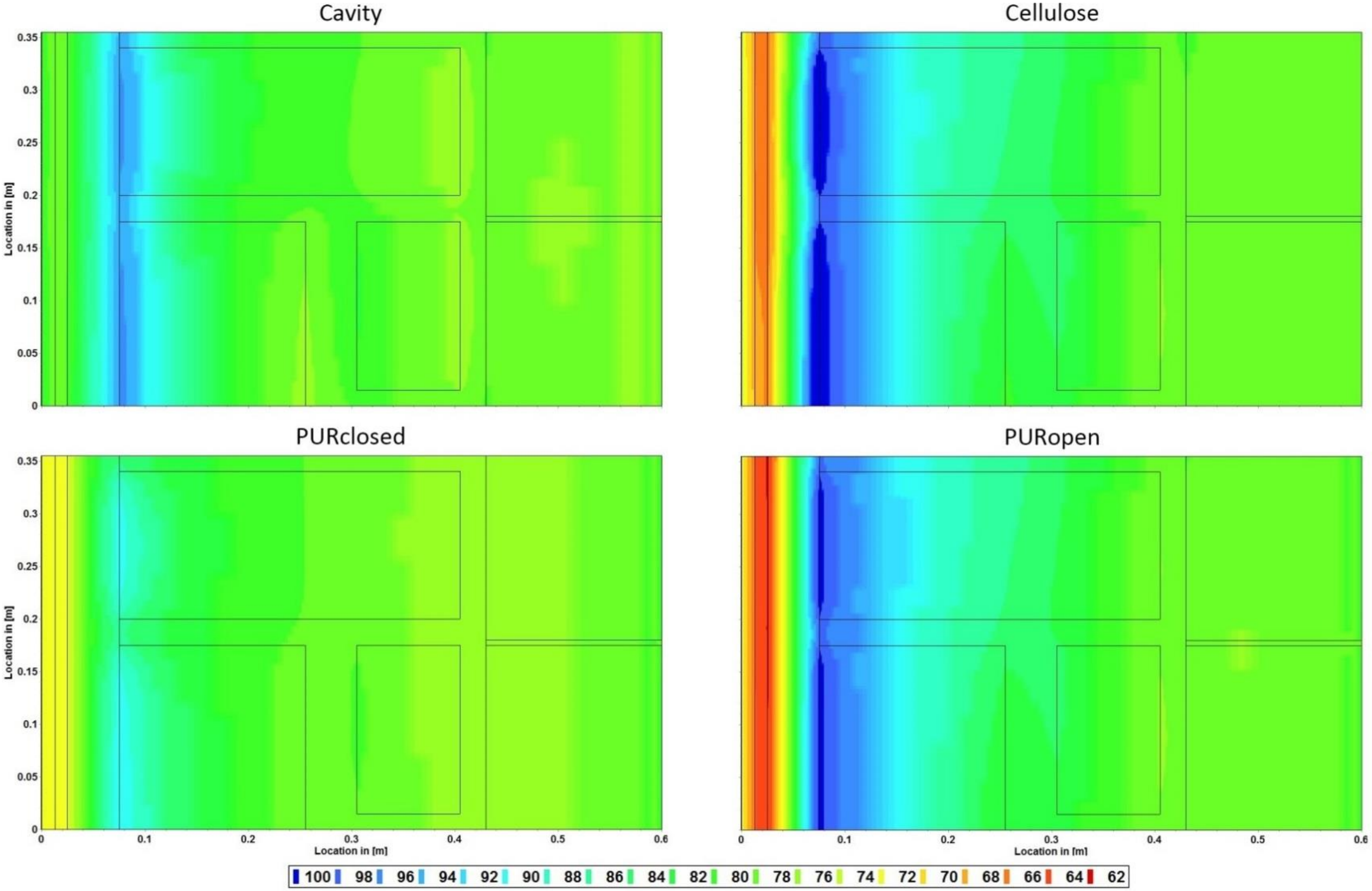


Figure 7-11 Relative Humidity (%) profiles of the front wall under Class III on the 1st of January of the last year of the simulation. The wall assemblies represent the cavity as (a) an air gap or a layer of (b) blow-in-cellulose, (c) PURclosed and (d) PURopen.

In the case of front walls insulated with Cellulose, the yearly time above 95% RH increased from 0 % in Class I to 18.17 % in Class II to 49.65 % in Class III. The gable wall showed a similar trend increasing from 0 % to 31.54 % to 53.98 %. Walls insulated with PURopen increased from 0 % to 32.02 % to 60.84 % in the front wall and from 0 % to 36.13 % to 65.48 % in the case of the gable wall. When the cavity was filled with PURclosed, no conditions for interstitial condensation at the interface occurred at any time. The risk of condensation in non-insulated walls was only visible under the humidity class III. The effect differed greatly from the front wall (180 h, 2.05 % of the time) to the gable wall (2564 h, 29.27 %). A snapshot of the relative humidity distribution in winter of the four different configurations of the front wall is presented in Figure 7-11.

The evolution of the relative humidity at the masonry-insulation interface of the front wall is shown in Figure 7-12. Relative humidity remained more stable in cases without any insulation (annual variation ranged from 13.7 % in Class I to 19.3 % in Class II to 20.7 % in Class III) or insulated with PURclosed (5.9 %, 5.8 %, 5.2 %) than in those insulated with Cellulose (30.9 %, 32.7 %, 27.1 %) or PURopen (33.7 %, 32.9 %, 26.7 %).

Although the recorded time above the condensation threshold was similar in walls insulated with Cellulose and PURopen, the maximum amount of condensate accumulated varied between the two scenarios. In front walls insulated with Cellulose (Figure 7-13a), the maximum condensate increased from 0.00 kg/m^2 (Class I) to 0.01 kg/m^2 (Class II) to 0.15 kg/m^2 (Class III). The amount of condensate was larger in the gable wall and the maximum values rose from 0.00 kg/m^2 to 0.04 kg/m^2 to 0.15 kg/m^2. If the cavity was filled with PURopen (Figure 7-13b), the condensate increased from 0.00 kg/m^2 to 0.05 kg/m^2 to 0.73 kg/m^2 in the front wall and from 0.00 kg/m^2 to 0.14 kg/m^2 to 0.93 kg/m^2 in the gable wall.

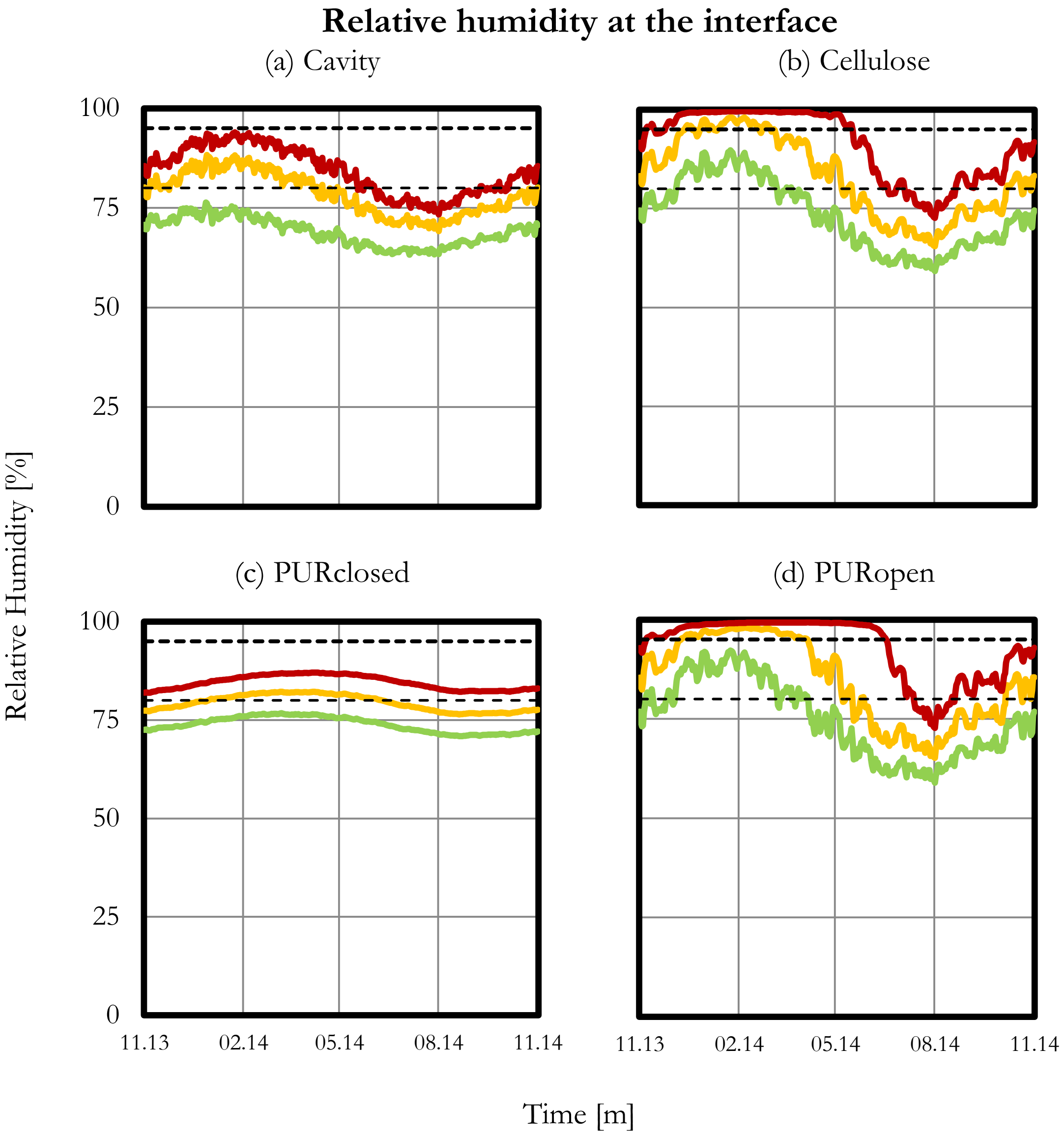


Figure 7-12 Relative Humidity (%) at the interface between the cavity and the masonry in the front walls during the last year of the simulation. The wall assemblies represent the cavity as an air gap, insulated with blow-in-cellulose, insulated with PURclosed and insulated with PURopen. The green line represents the results for Class I, yellow stands for Class II and red represents Class III.

The walls insulated with PURclosed did not accumulate any condensate since the relative humidity never reached 95 %. The water accumulated in the cavity of non-insulated walls was negligible (0.8 g/m^2). Therefore, the only scenario where the DIN 4108-3 limit of 0.5 kg/m^2 was exceeded was that with walls insulated with PURopen and high moisture loads (Class III). As can be seen in Figure 7-13b, the threshold was exceeded continuously for more than three months, from late January to the beginning of May.

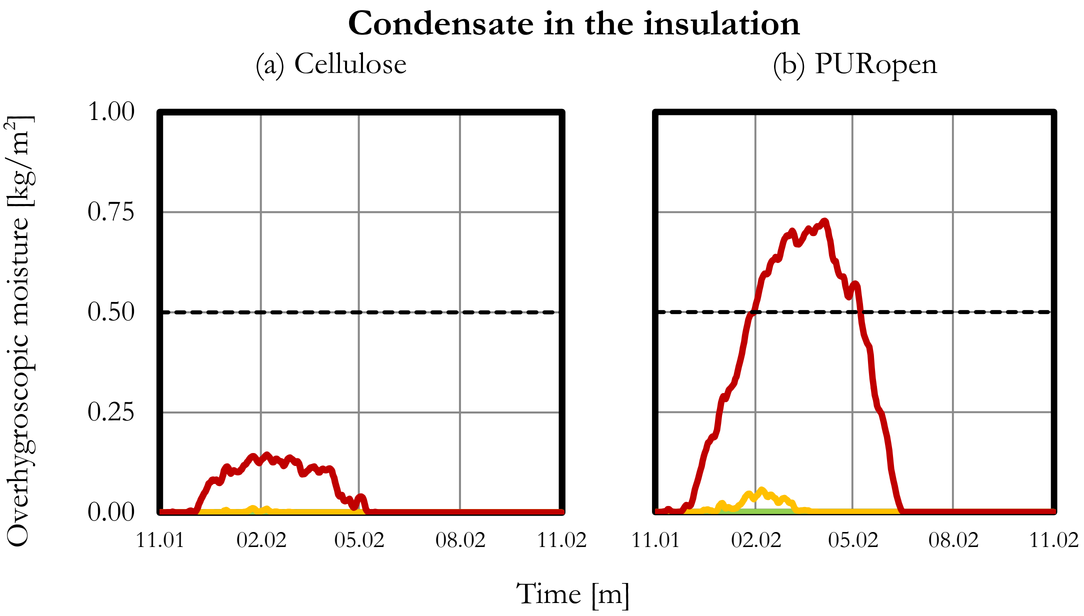


Figure 7-13 Amount of overhygroscopic moisture (condensate) in kg/m^2 accumulated in the insulation of front walls during the last year of the simulation. The wall assemblies represent the cavity as (a) insulated with blown-in-cellulose and (b) insulated with PURopen. The green line represents the results for Class I, yellow stands for Class II and red represents Class III.

7.3.1.4 Effect on the heat losses

The last aspect of moisture content evaluated in this study was the effect of internal climate on the thermal conductivity (λ) of the insulation. Based on moisture content results, the final thermal conductivity of the insulating layer was calculated. The effect of the different humidity classes varied greatly between materials (Table 7-3). PURclosed was the material least affected by the internal climate and the relative increase ranged from 1.6 % to 2.6 %. The thermal conductivity increase of cellulose was higher and the humidity class effect was evident. Thus, cellulose pumped in front and gable walls increased its thermal conductivity by around 6 % under Class I, 8 % under Class II and 12 % under Class III. In walls with PURopen, thermal conductivity increase was lower than in the case of Cellulose for humidity classes I (1.5 % front wall; 1.7 % gable wall) and II (4.6 %; 7.2 %) and much higher for the humidity class III (27.1 %; 33.0 %). The thermal conductivity increase of the air gap and timber joist were negligible, ranging from 0.002 % to 0.9 % across classes.

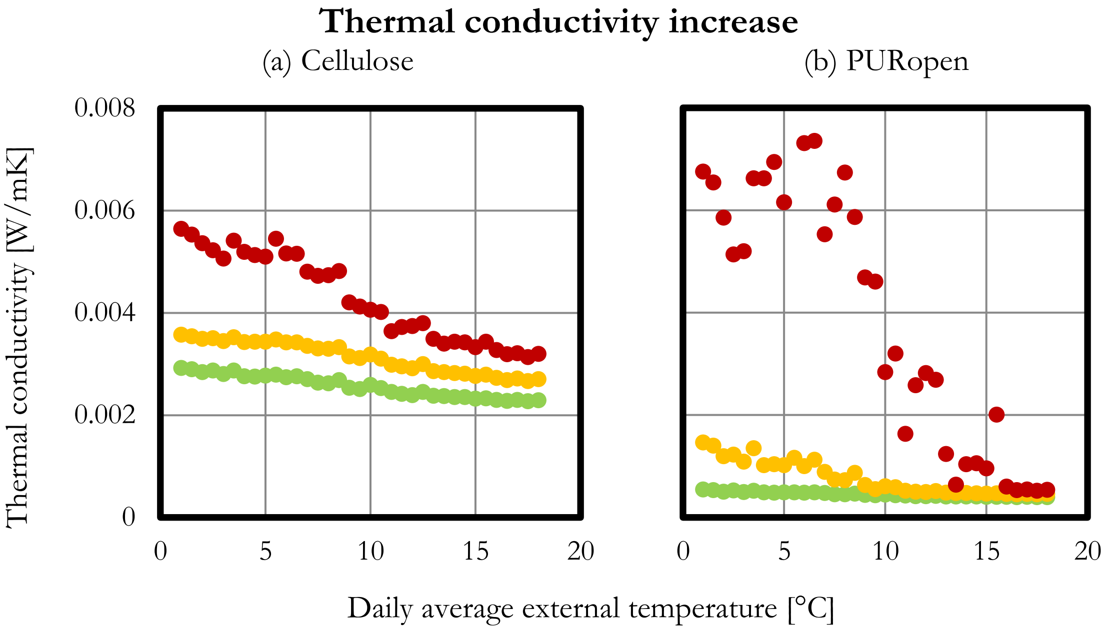


Figure 7-14 Thermal conductivity increase (W/mK) of the insulation in the front wall as a function of the daily average external temperature (°C). Green dots represent results for Class I, yellow dots stand for Class II and red dots represent Class III.

In Figure 7-14, the thermal conductivity increase of Cellulose and PURopen was plotted as function of the external temperature. The relationship between the conductivity of cellulose and the temperature was linear and negative under the three internal climates. The dependence on the external conditions became stronger as the moisture load (i.e. humidity classes) increased. In walls insulated with PURopen (Figure 7-14b), the pattern of the results changed entirely from Classes I and II to Class III. The dependence on the exterior was very weak for the first two classes while in scenarios with high moisture loads the relationship was very strong and the conductivity increased rapidly as the temperature decreased, especially for external temperatures below 10 °C.

7.3.2 The effect of the internal climate on the time of wetness

7.3.2.1 Effect on the risk of mould growth

The values obtained for mould growth risk differed from those for the risk of condensation presented above. In the case of mould growth, a similar outcome was found in all the models (Table 7-3) and the main differences found between the results of the joist end and the insulation-masonry interface occurred under Class I conditions. When low moisture loads were simulated (Class I), no favourable conditions for mould growth were found in the joist end with any of the materials simulated. Meanwhile, in external walls, the risk threshold was exceeded at the masonry interface in the cases insulated with Cellulose (21.0 % of the time in the front wall and 32.5 % in the gable wall) and PURopen (28.3 %, 38.1 %). When PURclosed was simulated in the cavity, no conditions for mould growth were found in the joist end with any internal climate.

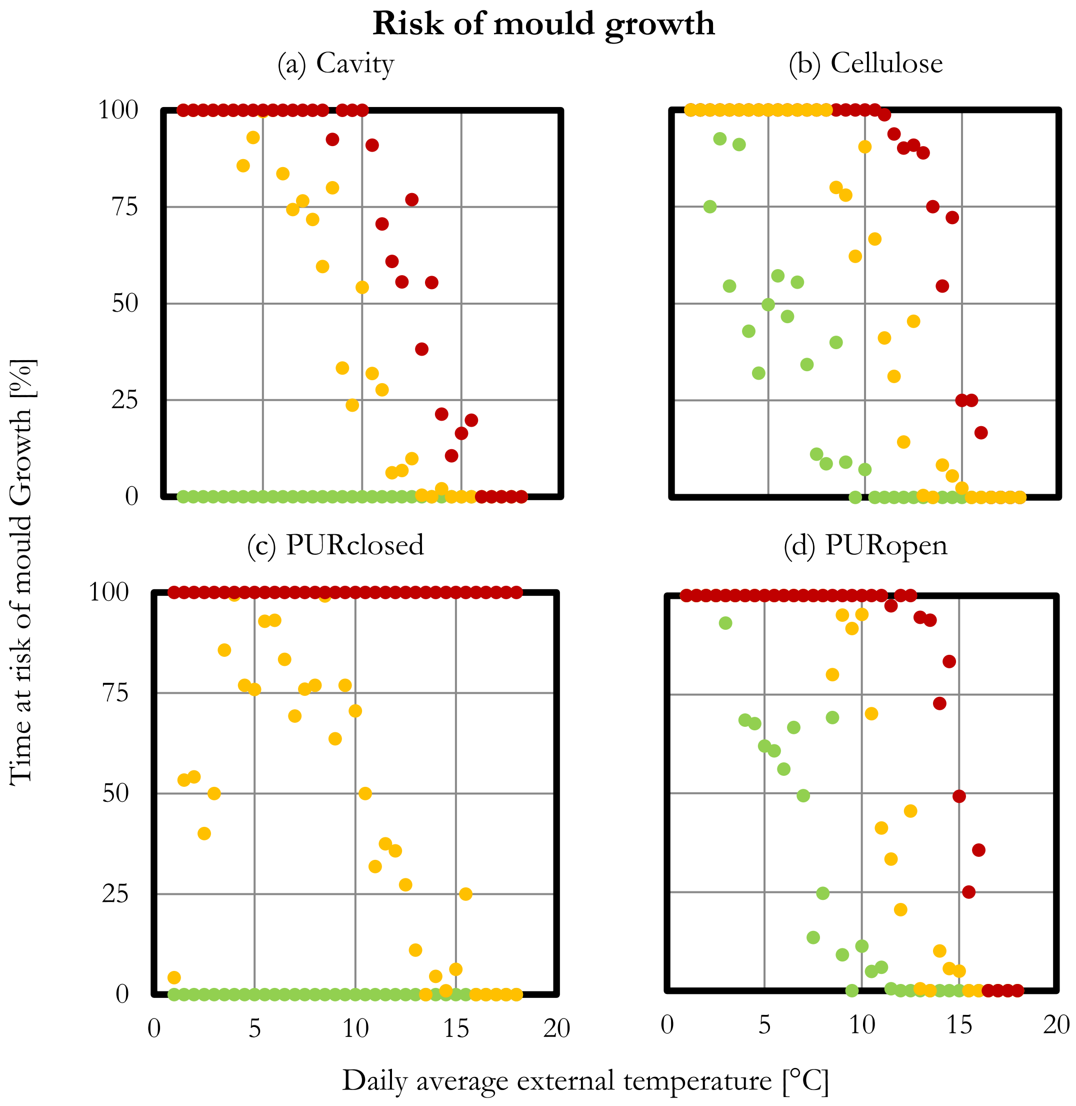


Figure 7-15 Time at risk of mould growth (h) at the interface between the cavity and the masonry in the front wall as a function of the daily average external temperature (°C). Green dots represent results for Class I, yellow dots stand for Class II and red dots represent Class III.

Under medium moisture loads (Class II), the results of the three models were comparable, independent of the material simulated in the cavity. The time at risk of mould growth oscillated between 33.3 % (in non-insulated joist end) to 65.2 % (gable walls insulated with

PURopen). When the scenarios were simulated under Class III, the results oscillated between 66.9 % (non-insulated joist end) and 100 % (front wall insulated with PURopen).

When looking at the risk of mould growth as dependent on the external temperature in the front wall (Figure 7-15), different relationships were found depending on the material simulated in the cavity. In non-insulated walls (Figure 7-15a), no dependency was found under Class I, as no conditions for mould growth were identified. Under the other two classes, the dependence was similar and the risk decreased linearly as the temperature increased. The walls insulated with PURclosed (Figure 7-15c) showed different relationships depending on the climate class. Classes I and III showed no dependence on the external weather while the risk of mould growth in Class II decreased linearly from 100 % to 0 % for temperatures ranging between 5 °C and 15 °C. At lower temperatures, no clear relationship was observed. Walls insulated with Cellulose and PURopen (Figure 7-15b-d) presented similar patterns. The dependence on the external temperature was visible under the three climatic classes. In both cases, the dependence became more important for higher humidity classes. In scenarios simulated under Class I the risk of mould growth decreased from 100 % to 0 % as the temperature increased from 0 °C to 10 °C. Under higher humidity classes the range of external temperatures affecting the risk of mould growth decreased to 7 °C for Class I (from 8 °C to 15 °C) and 5 °C for Class III (from 12 °C to 17 °C).

7.3.2.2 Effect on the Mould Index

The average values of MI obtained during the last year of the simulation are presented in Table 7-3. Two differentiated patterns were observed. MI in the joist end only exceeded the threshold value of 1 under Class III. In the other two walls, front and gable wall, the MI threshold was exceeded at the masonry-insulation interface under Class II and it reached values close to 5 under Class III. MI under Class I remained below 1 in all the simulated scenarios.

Different patterns were also found when comparing the results obtained by different materials. Thus, for walls insulated with PURclosed the effect of internal climate was mainly evident with Class III as the MI increased from 0.00 (Class I) to 0.23 (Class II) to 2.37 (Class III) in the front wall and from 0.00 to 0.14 to 2.10 in the gable wall. In walls insulated with Cellulose or PURopen, the effect of the internal climate was already visible under Class II. Average MI in front walls insulated with Cellulose increase from 0.05 to 2.44 to 4.97 and MI increased from 0.19 to 3.35 to 4.99 in walls insulated with PURopen.

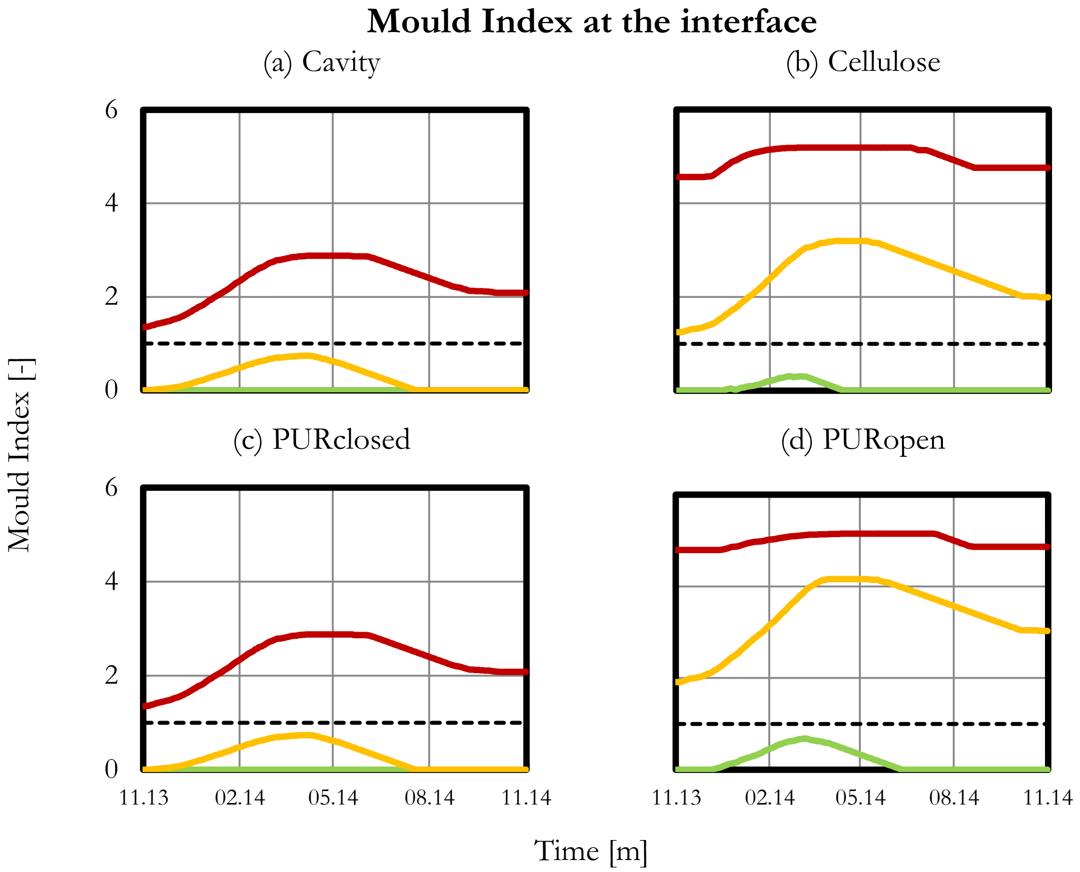


Figure 7-16 Mould Index at the interface between the cavity and the masonry in the front walls during the last year of the simulation. The wall assemblies represent the cavity as (a) an air gap, (b) insulated with blown-in-cellulose, (c) insulated with PURclosed and (d) insulated with PURopen. The green line represents the results for Class I, yellow stands for Class II and red represents Class III.

The interaction between materials and internal climate was also evident when looking at the evolution of the MI in the front wall during the last year of the simulation (Figure 7-16). In the wall insulated with PURclosed (Figure 7-16c), there was no increase of MI at the end of the year when the scenario was simulated with the Class II. If the Class III was used instead, the simulation resulted in a MI increase of 1.05. The simulation of walls insulated with Cellulose (Figure 7-16b) and PURopen (Figure 7-16c) showed a different result. While the MI increase at the end of the year ranged between 0.74 and 1.12 with Class II, in scenarios with Class III the MI only increased 0.20 and 0.07.

7.3.2.3 Effect on the risk of wood decay

Wood decay risk analysis showed differences between wall junctions and external walls (Table 7-3). No risk of wood decay was found in the joist end under any scenario, independent of the material or internal climate tested. In the external walls, front and gable walls, the results were affected by both factors. Walls insulated with PURclosed were only at risk of wood decay under Class III conditions and for very short periods, 2.6 % of the time in the front wall and 1.9 % in the gable wall. Wood decay risk increased in scenarios with Cellulose or PURopen. Time at risk in the front wall oscillated from 30.3 % (Class II) to 60.1 % (Class III) if the cavity was filled with Cellulose and from 34.8 % to 68.9 % if PURopen was used. Similar results were obtained in the gable wall with values oscillating from 36.7 % to 64.9 % in the case of Cellulose and from 45.1 % to 74.5 % with PURopen. Gable walls insulated with PURopen were the only assembly under Class I with risk of wood decay, with 4.4 % of the time exceeding the threshold.

7.4 Discussion

According to the results, there was no risk of moisture accumulation in any of the simulated walls and moisture balance stabilised rapidly in all the scenarios, especially when compared to other studies that reported much longer periods of time before reaching an equilibrium (Browne 2012; Little et al. 2015). However, those studies considered large amounts of water ingress from the external boundary and this research was exclusively focused on the impact of the internal boundary. Besides, and as described above, annual moisture balance is not the only criterion affecting wall durability and the final performance was dependent on many other factors. Internal climate was found to have an effect on most of those factors. Its impact, nevertheless, varied greatly between cases.

Vapour diffusion and capillary suction are the main mechanisms of moisture migration affected by internal climate (Lstiburek & Carmody 1991). Therefore, the envelope final performance is a consequence of the interaction between internal climate and the materials properties that regulated those mechanisms: thermal conductivity, vapour permeability and moisture capacity (Ge et al. 2014). The insulating materials properties (Table 7-1) were very different and so was the interaction of different materials with the internal climates. Therefore, the differences in physical properties of the materials should be taken into account in the discussion. Moreover, comparison with previous studies should also be considered carefully as often the walls configurations differed.

7.4.1 Thermal conductivity and the temperature gradient across the wall

Pre-retrofit scenarios were modelled to simulate a non-ventilated cavity between the lath and plaster and the masonry wall. This configuration neglected the effect of ventilation and therefore the results might have overestimated the moisture accumulation in the cavity. In any case, recent research on modelling of ventilated cavities (Vanpachtenbeke et al. 2015) has concluded, based on the comparison between in-situ measurements and simulation, that the current models are not fully reliable and further research is needed to predict the moisture conditions in the cavity accurately. In addition to that, it is worth noting that the ventilation of these cavities is often compromised as debris from old mortar may fall and clog the cavity stopping any possible circulation of air (Young 2007).

In this research, the air in the cavity was still and therefore acted as a thermal barrier (Lorente & Bejan 2002; Baker 2011). However, due to the high thermal conductivity of the air in the gap (0.278 W/mK), the temperature gradient between the inner face of the masonry and the room was rather low and the risk of condensation and mould growth on the masonry was found only under very adverse conditions (Class III). In walls simulated under Class III, there was almost no decline of the mould growth over summer. This can be explained as a direct effect of the internal climate since the humidity class III of non-retrofitted dwellings, as designed in the previous chapter, maintained high levels of moisture throughout the year. Moisture load ranged from 4.5 g/m^3 in winter to 3.5 g/m^3 in summer and no period of low moisture was considered, resulting in an increase of the mould growth intensity over time. Time above the mould growth threshold in non-retrofitted walls was also conditioned by the masonry thermal resistance. Temperature on the inner side of gable walls, that were thinner and therefore had lower resistance, was lower than on front walls. This affected the temperature gradient between room and wall surface, increasing the relative humidity levels and the risk of condensation and mould growth.

Cavity insulation, with any of the proposed materials, amplified the temperature difference between the room and the inner side of the masonry. The temperature decrease on the masonry surface limited the amount of water vapour that air could contain. This increased the risk of condensation and mould growth and made assemblies more sensitive to the internal climate changes.

In the junctions between the external wall and the intermediate floor, the joist end embedded in the wall acted as a thermal bridge connecting both sides of the cavity (Figure 7-9). The resulting temperature gradient was, as for non-insulated walls, more homogeneous and therefore the effect of the internal climate was less important.

7.4.2 Vapour permeability and where the moisture was accumulated

At the beginning of this chapter, it was argued that the granite masonry wall would act as a barrier to water vapour diffusion to the exterior due to its low vapour permeability. Depending on the permeability of the insulation (Figure 7-3), masonry remained as the only vapour diffusion obstruction or a new one was added to the envelope. If materials with high vapour permeability like Cellulose (μ = 2.05) or PURopen (μ = 2.38) were added, no major changes to the diffusion profile were made and moisture travelled 'freely' up to the masonry-insulation interface. In those scenarios, condensation risk increased along with humidity classes. Higher moisture loads resulted in higher amount of moisture accumulated at the interface and longer time above the condensation threshold. On the other hand, when the cavity was filled with PURclosed (μ = 104), the insulation layer acted as a first barrier to the vapour diffusion and no condensation occurred at the masonry interface. Different profiles of vapour diffusion can be observed in Figure 7-11. In walls insulated with Cellulose (Figure 7-11b) and PURopen (Figure 7-11d), the insulation-masonry interface showed the highest levels of RH (around 100 %) whereas the lath and plaster registered low values (64 %). At the same time, in cases insulated with PURclosed (Figure 7-11c) relative humidity was lower at the masonry interface (90%) and considerably higher in the lath and plater (72 %).

The results, therefore, did not find any effect of internal climate on the risk of condensation in walls insulated with PURclosed. However, lower values of relative humidity are needed for the development of mould and favourable conditions for mould growth were found in scenarios with medium (Class II) and high (Class III) humidity loads. In fact, the time at risk of mould growth under Class III was higher in walls insulated with PURclosed than in the other two assemblies, reaching 100 % of the time above the threshold. Most probably, this was also due to the low permeability of the material. The insulation blocked the vapour diffusion in both directions and impeded the wall to dry towards the interior in summer resulting in an accumulation of the MI over time. This result is in agreement with the findings of previous research carried out by Klõšeiko et al. (2014) in a historical school building. They found that the high vapour resistance of polyisocyanurate limited the indoor drying capacity of the wall and as a result the most adverse period for walls insulated with this material was between late summer and early winter. The average values of mould growth risk (around 55 % of the time for Class II and above 90 % for Class III), as well as the MI dependence on the internal climate, are also in line with previous studies. Alev et al. (2015) compared the performance of mineral wool, cellulose and reed mat as interior insulation materials for log walls and found an important dependence on the internal climate, especially for reed mat, the material with the highest value of vapour diffusion resistance factor.

Despite the high levels of moisture accumulated in the lath and plaster of walls insulated with PURclosed (Figure 7-11c), no conditions of condensation or mould growth were found on the inner part of the wall. Since the temperature on the warm side of the insulation was higher, the air could contain more humidity and the thresholds were never reached.

7.4.3 Hygroscopic capacity and how the moisture was accumulated

If the vapour diffusion resistance factor of the insulation determined where the moisture was accumulated, it was found that the hygroscopic capacity of materials defined how the moisture was accumulated (Holm et al. 2008). When looking at the sorption isotherm curves of Cellulose and PURopen (Figure 7-3) it is clear that the properties of both materials were very different. At a relative humidity of 80 %, Cellulose contains 6.36 kg of moisture per cubic metre of insulation whereas PURopen can only contain 0.21 kg/m^3.

In the cases where the condensation threshold was exceeded (Classes II and III), the different hygroscopic moisture content capacity of both materials played a crucial role in defining whether the moisture was accumulated as water vapour or condensate, especially if high levels of relative humidity occurred. The effect becomes evident when looking at the superposition of overhygroscopic (condensate) and total moisture content results of walls insulated with Cellulose and PURopen under Class III (Figure 7-17).

In walls insulated with PURopen (Figure 7-17b), due to the low hygroscopic moisture capacity of the material, the great majority of the humidity was accumulated in liquid form. The high moisture capacity of cellulose, on the other hand, allowed for the storage of moisture as vapour, reducing the final amount of condensate accumulated at the interface. Besides the total amount of condensate found in the wall, the different hygroscopic properties of materials determined the effect of internal climate on the thermal conductivity of insulation. These results are analogous to the findings reported by Ramos et al. (2010) after the simulation of the thermal conductivity increase in mineral wool when used as an internal insulating layer. Bishara et al. (2015), in the final report of the 3enCult project (http://www.3encult.eu/), also reported differences of up to 7 % between 'theoretical' steady U-values and unsteady simulations of refurbished historic buildings.

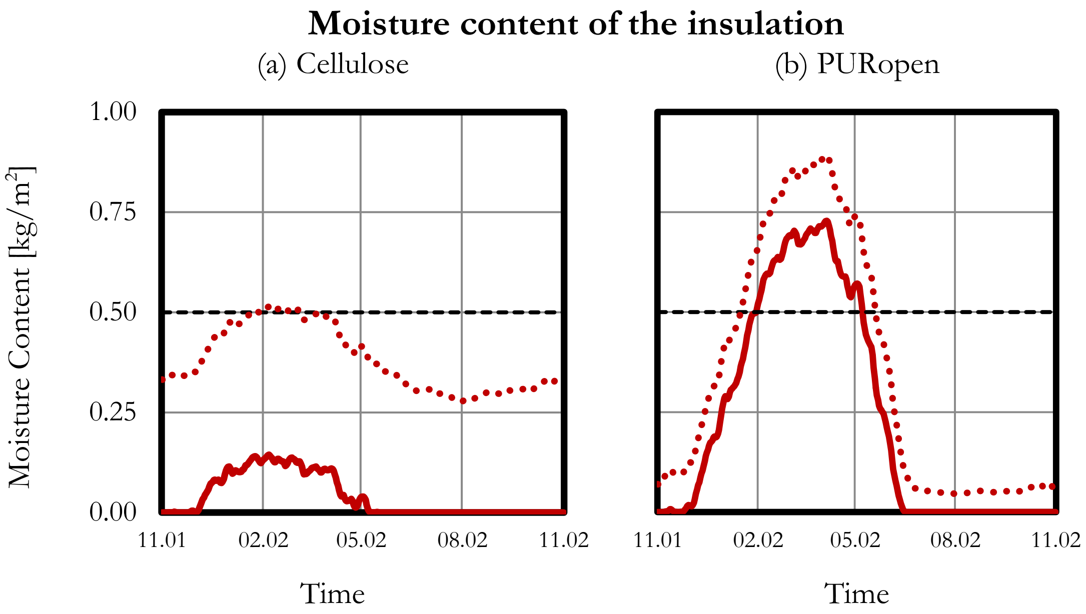


Figure 7-17 Evolution of the moisture content (kg/m^2) of the insulation in front walls under Class III during the last year of the simulation. The dotted lines represent the total moisture content and the thick lines stand for the overhygroscopic (condensate) moisture content.

Moisture storage capacity also played an important role in the effect of the internal climate on wall junctions, especially on the risk of wood decay in the joist ends. Wood has a high hygroscopic moisture capacity (69.3 kg/m^3 at 80 %) as well as high effective saturation moisture content (692 kg/m^3) and therefore large amounts of moisture are needed to reach the failure thresholds. Thus, internal climate was not sufficient to reach those levels and the joist remained safe in all the scenarios, even at the most critical locations (Figure 7-9) and under the most adverse conditions (Class III). Analogously, Häupl (2004) found that the joists of refurbished historic half-timbered houses in Germany were below any critical threshold despite the relatively high moisture content found in the junction between the insulation and the framework infill. Only in cases where a convective gap between the internal environment and the space around the joist end exists, the risk of wood decay due to the internal climate might exist (Kehl et al. 2013). Otherwise, the main cause of concern regarding the deterioration of joist ends would come from the external boundary. Previous research has concluded that the implementation of internal insulation does not present any risk for the durability of the structure if the wall is conveniently protected from the WDR (Morelli & Svendsen 2012).

The results of this research suggested that the use of VCL on the inner side of the envelope should be explored in further research as a measure to limit the risk of interstitial condensation in internally insulated walls. VCL, however, should allow the transfer of vapour to the interior of the building to ensure the wall indoor drying potential. Otherwise moisture would accumulate between barriers in case of any water ingress caused by the wind driven rain, rising damp or an accident (Browne 2012). In addition to that, and due to the important role played by the buffering potential of the materials in managing condensation in high moisture load scenarios, highly hygroscopic materials like calcium silicate (Roels et al. 2004), wood (Padfield & Jensen 2011) or hemp-lime (Evrard 2006) should be investigated. Häupl (2004) explored the use of capillary active materials (such as Calcium Silicate) as internal insulation materials. His work, that included the measurement and modelling of the moisture storage and transport functions of the material, showed that the wall assembly was very sensitive to the internal climate and up to 0.29 kg/m^2 of condensate were accumulated in scenarios with 70 % interior relative humidity. Nevertheless, the capillary active material allowed for a fast drying process towards the interior and no accumulation over time was found. Besides the buffering effect of the insulating material, Kalamees et al. (2009) stressed the role that furniture, textiles or books could play in the hygroscopic potential of a room. Currently, the simulation of such elements with the available tools is still very problematic.

Another aspect that needs to be further investigated is the effect of the initial moisture content on the performance of the wall and its interaction with the internal climate. In this research, all the insulating materials were modelled with the same initial conditions (20 °C and 80 %). However, previous studies (Alev, et al. 2015; Klõšeiko et al. 2014) have shown that the moisture added to some materials in their application (such as sprayed Cellulose) can cause long periods of high humidity inside the wall depending on the time of the year they were installed and the use of VCL in the wall. Internal climates with high humidity loads would also limit the drying potential of the wall and therefore determine its final performance.

7.5 Conclusions

The last of the hypotheses proposed at the beginning of this research stated that:

> *"The hygrothermal performance of internally insulated solid granite walls is greatly dependent on the characteristics of the internal climate"*

Simulation of several configurations of solid walls and internal boundaries has shown that the internal climate can have a crucial effect on the final performance of walls. The proposed hypothesis can therefore be validated.

The results have shown that the assessment of the performance of a retrofitted wall may change from 'safe' to 'not feasible' according exclusively to the internal climate. Thus, for instance, the risk of mould growth at the interface between insulation and masonry was strongly dependent on the internal climate and increased from 0 to 100 % when the humidity classes changed from Class I to Class III.

The effect of the internal climate, however, was not equally evident for all the performance criteria evaluated in this research and its impact was very much dependent on the material properties. Therefore, two additional findings, drawn from the discussion of the results, can be highlighted: the importance of the criteria chosen for the assessment and the interaction between internal climate and material properties. Hygrothermal assessment of retrofitted solid walls should not be limited to the analysis of the risk of condensation, as other criteria (such as mould growth risk or thermal conductivity) have been found to play a crucial role in the final performance of the wall. Besides, the impact of internal climate should be carefully considered if solid granite walls are to be insulated with vapour permeable materials, especially if the materials have limited moisture buffering potential.

Despite the impact of internal climate on the performance of the wall, the scenarios simulated in this research did not show the same effect on the junction between the wall and internal floors. Thus, according to the results of the simulations carried out in this research, if the wall is protected from external water ingress, the internal climate does not represent any risk for the durability of timber joists in internally insulated walls.

7.6 Summary

This chapter presented the results of the numerical simulation of the hygrothermal performance of internally insulated solid granite walls. This research made use of DELPHIN, a Heat, Air and Moisture (HAM) software, for the evaluation of moisture dynamics in solid walls before and after the insulation.

The hygrothermal assessment was carried out using the three indoor climate classes presented in the previous chapter. These classes were developed based on the environmental data gathered during the multi-case study and represented the 30 %, 70 %

and 95 % values of moisture load monitored in the sample. Besides the three different classes, simulations considered three different wall configurations (front wall, gable wall and a junction between the front wall and an internal floor) and three different insulation materials (blown-in-cellulose, closed cell polyurethane foam and open cell polyurethane foam).

The performance criteria adopted for the wall assessment were discussed at the beginning of the chapter. The parameters eventually considered were annual moisture balance, moisture content, time above the condensation threshold, overhygroscopic moisture content, thermal conductivity increase, risk of mould growth, MI and risk of wood decay.

The discussion of the results is focused on the interaction between the internal climate and the physical properties of the insulating materials. More specifically, thermal conductivity, vapour diffusion resistance factor and hygroscopic moisture capacity of the materials. The findings of this chapter allowed for the validation of the hypothesis presented at the beginning of this research.

8 GENERAL DISCUSSION AND CONCLUSIONS

This research was originally set up to answer the following question:

In the context of Scottish traditionally constructed dwellings,

> *What role does user behaviour play in the hygrothermal performance of internally insulated solid granite walls?*

In order to facilitate the approach to the subject, the research question was subdivided in three intermediate objectives and seven sub-questions (Figure 1-1). The objectives were defined to look at the connections between (i) decision makers and the effect of user behaviour, (ii) user behaviour and internal climate and (iii) internal climate and the performance of solid granite walls. The three corresponding research stages were designed to link as a chain, so the findings from each stage fed into the initial observation phase of the next stage (Figure 3-2). In this final chapter, the findings from the different research stages are discussed in inverse order to form a response to the original research question. Thus, the discussion of findings begins looking at the effect of internal climate on wall's performance and ends exploring the potential implications of hygrothermal performance results on the decision making process. Prior to this discussion, a reflection on the limitations of the research is presented.

8.1 Limitations: A reflection on the research scope, design and development.

One of the key challenges of this work was present since the formulation of the research question itself. A combined approach that included insights from both social sciences and building physics was going to be needed in order to understand user behaviour as well as its effect on the hygrothermal performance of the wall. A broad definition of social science proposed by the Economic and Social Research Council referred to it as "*the study of society and the manner in which people behave and influence the world around us*" (ESRC 2016). On the other hand, building physics have been defined as "*the phenomena of heat (energy), moisture, air, acoustics, fire and daylight which may occur in the interior of rooms, in building and structure components*" (Verhoeven 1983). The answer to the research question, therefore, could only be found by looking at the entire qualitative-quantitative continuum that connected the study of people behaviour with the physical phenomena occurring in the wall.

Previous research in this field focused on one end of this qualitative-quantitative continuum (Strachan 2013; Ingram 2013). In the cases where the aim of the research was wider (Love 2014), the studies generally covered the relationship between the physical characteristics of the buildings, the occupants' behaviour and the resulting internal climate. In this case, however, a more comprehensive approach to the problem was adopted. Thus, this research addressed the problem by covering a whole chain of events, from the exploration of the rationales behind the adoption of retrofit measures to the quantification of the hygrothermal performance of insulated walls.

The focus of the research was considered a strength of this work, as it represented a novel approach to the topic, but it also imposed some practical limitations to the design and development of the study. The research required several steps of collection and analysis of data of very different nature and from different samples. As a result, and due to the constraints in terms of time and resources, the final samples were relatively small (12 interviews with decision makers, a multi-case study formed by 24 households and 52 two-dimensional simulations). Therefore, the findings and conclusions of this research should be considered carefully. The size and characteristics of all samples were, however, in line with the studies found in the literature (Townsend 2010; Love 2014; Morelli 2013; Little et al. 2015).

Besides the samples size, the design of a transversal study added a caveat to the results due to the differences across samples. Thus, for instance, the multi-case study sample of non-retrofitted buildings was formed to a large extent by tenants of social housing with low incomes, whereas an substantial number of retired professionals owned and occupied the retrofitted dwellings. The different demographics might have had an effect on both quantitative and qualitative information, that is, on the internal climate characteristics and on how freely they discussed their routine habits. Nevertheless, the comparison of both sources of data (environmental monitoring and interviews) complemented the information and therefore helped minimising that effect.

The development of the multi-case study, as it was designed, did not present any major problem. However, the use of two different types of monitoring devices required very different practical approaches. While LASCAR EL-USB-2 are stand-alone loggers powered with batteries and their configuration was relatively straight forward, the use of Aeotec MultiSensors involved a significant effort for their configuration and installation in the dwellings. The final performance of both devices was rather satisfactory and only a minimal proportion of data was lost due to issues with batteries or configuration of the equipment. The equipment characteristics meant that several visits to the dwellings were essential in order to collect data and replace batteries. Despite the time consuming nature of the task and the practical difficulties of arranging visits with tenants, this approach allowed for a more frequent contact with the occupants and helped to build a closer relationship. Frequent visits and contact with occupants resulted de facto in a detailed post-occupancy evaluation and led to a deeper understanding of their comfort practices and the reasons behind them.

8.2 Discussion of findings: Why things done for social reasons have physical effects and the implications for the retrofit of traditional buildings

8.2.1 The internal climate and its effect on the hygrothermal performance of the wall

Use of numerical simulation allowed for the quantification of the effect that different internal climates had on the hygrothermal performance of solid granite walls. Whereas the impact of the internal boundary on non-retrofitted walls was fairly limited, the three different internal climates simulated produced very different outcomes in the case of retrofitted walls. It was found that the wall performance declined considerably as the moisture loads increased. The results clearly showed that internal insulation made solid walls more sensitive to changes in the internal climate. The impact was especially important on gable walls. That was explained as a consequence of the construction characteristics of the wall (Figure 7-5). Gable walls were thinner than front walls and therefore the final thermal resistance of the masonry was lower resulting in lower temperatures on the cold side of the insulation. Final performance of walls was therefore dependent on the internal moisture load but also on the temperature gradient across the wall.

The interaction between climate and materials' properties was found to be an important factor for the final wall performance. Effect of internal climate depended, primarily, on two parameters of the insulation material: vapour permeability and hygroscopic moisture capacity. The different performance criteria evaluated in this research helped to identify the effects that internal climate had on different configurations of the wall.

Materials with low permeability acted as vapour barriers separating internal and external boundaries and therefore walls insulated with this material were the least affected by the changes in the internal climate. However, a material acting as a barrier would potentially block any moisture transfer in both directions, limiting also the drying potential towards the interior. In walls insulated with vapour permeable materials, the hygroscopic capacity of the material to buffer moisture was found to be a determinant factor. Materials with high moisture capacity can store more water vapour and therefore minimise the amount of water condensed in the wall. Thus, in walls with hygroscopic materials, thermal conductivity and risk of decay was not as dependent on the internal climate as in walls with low moisture capacity materials.

This research has shown that the internal climate has an important effect on the final performance of solid masonry walls with internal insulation. Even more, from the results of the exploratory studies carried out to define the configuration of the model, it can be assumed than in some cases (mainly depending on orientation) internal climate was more determining for the final performance of the wall than the external boundary. The results of the simulations also showed the importance of the drying potential of walls towards the interior and how this mechanism was heavily affected by the internal climate. The internal climate will therefore play a significant role in cases with high water ingress (from WDR, rising damp or accidental) and should be considered carefully in any assessment. However, most of the studies focused on the impact of WDR (Morelli 2013; Johansson et al. 2014;

Abuku et al. 2009) neglected the internal climate and were usually simplified using constant values of internal temperature and humidity throughout the year.

The internal boundary modification, as an input of the model, in the software version used in this research (DELPHIN 5.8.1) was laborious, although it allowed a full climate customization. Newer software versions (5.8.3) (Institute for Building Climatology 2016) include a generator of indoor climates according to the standard BS EN ISO 13788:2012. The implementation of such tools would facilitate the exploration of internal climate effect and lead to more accurate assessments. However, it should be noted the discrepancies found in this research between the internal climates proposed in 13788 and values monitored in the dwellings. The use of non-representative data could also favour 'misinformed decisions' and lead to an unexpected performance of the wall after the insulation.

8.2.2 The users' interaction with the building and its effect of the internal climate

The internal climates used as boundaries of the hygrothermal simulation were based on the results of the measurements carried out during the multi-case study. The results of this monitoring campaign exposed important differences between the internal climates depicted in the international standards (13788 and 15026) and the reality of Scottish households. Although there was an increase in the temperatures measured in retrofitted dwellings, internal temperatures throughout the entire sample were consistently lower than the values proposed in the standards, independent of the level of insulation. This difference was explained as a consequence of the envelope air permeability, a vertical temperature gradient in the rooms and the effect of user' behaviour. Discontinuous use of space heating resulted in low average internal temperatures and strong dependence on the external weather, almost comparable to periodically occupied homes (Arumägi et al. 2014). The intermittent use of the heating sometimes responded to the need to save money or energy, but often it was a consequence of the comfort preferences of occupants. In many cases, occupants felt comfortable with temperatures that were considerably lower than those proposed in the standards.

The differences between non-retrofitted and retrofitted traditional buildings became more evident when looking at the moisture loads. Moisture loads of retrofitted dwellings decreased when the external temperatures increased, whereas the moisture loads of non-retrofitted dwellings were almost constant throughout the year, independent of the external weather. Accordingly, the average moisture loads of non-treated buildings were significantly higher than those found in renovated dwellings. Besides, the difference between the households with the lowest moisture loads (Class I) and those with the highest (Class III) was much larger in non-retrofitted dwellings than in retrofitted buildings. In conclusion, while insulated buildings performed similarly to the models proposed in the standards (i.e. to modern construction), non-retrofitted properties followed a different pattern and the variation between households was more important.

The concept of 'Indoor Climate Classes', developed in the Netherlands in 1970, was introduced to overcome the uncertainties regarding the numerous factors shaping the indoor environment during the design phase (Janssens & Hens 2003). However, the classes proposed in the standards are based on studies carried out in Scandinavia (in the case of 13788) or Germany (in the case of 15026) (Holm et al. 2008) and therefore are not necessarily representative of the Scottish context, and particularly not of traditional buildings. The design curves resulting from this research are therefore a more accurate representation of the internal climate in Scottish traditional buildings. These results are derived from context specific field measurements and embrace the particularities of this type of buildings and the people that inhabit them.

Despite the benefits that 'Indoor Climate Classes' offer for the assessment of the moisture performance of buildings and components, a strong criticism regarding the role of climate classes and standards can be found in the literature. Nicol et al. (2012) argued that these documents were produced by bodies (academic or institutional) that were interested in providing the industry with specifications of 'comfort' that did not vary in time or space. Comfort had to be clearly defined as it was ultimately likened to a 'product'. Moreover, the occupant was depicted as the 'customer' that would purchase it (Fanger 1970). However, the environments that occupants consider comfortable are, as the results of this research have showed, *"far less closely defined than the standards would predict"* (Humphreys et al. 2011).

The current challenge is therefore to adapt the existing norms of comfort to models of 'Adaptive Thermal Comfort' that consider differences between individuals and dynamic environmental conditions (Fabbri 2015). Use of adaptive models would eventually lead to more realistic scenarios for building assessment and also encourage designers to perceive comfort not as a product ('attribute') that can be taken for granted but as an 'achievement' that the occupant should be enabled to seek (Shove 2003).

8.2.3 The practice of comfort and its effect on the users' interaction with the building

While the aim of the standards was to produce a set of conditions that would help designers to meet users' requirements, field studies demonstrate the effects of cultural variation in the meaning, experience and expectation of users on the internal environment of buildings (Shove 2003). As Shove explains, there are two approaches to tackle the discrepancies between the models proposed in the standards and the results of field studies: to refine the prediction of the internal climate by extending the studies or to explore how people behave in order to understand what makes them comfortable. In this case, the research took both directions.

On one hand, a set of internal climates exclusively designed to describe the internal environment of traditional buildings in North-East of Scotland was proposed. On the other hand, an investigation of the *"social, technical and economic dynamics of comfort"* (Shove 2003) was carried out to understand the reasons behind these discrepancies. The interpretation of the results suggested that the final internal climates were the outcomes of dispersed practices of seeking comfort at home (heating, ventilation, laundering, cooking, etc.). Moreover, comfort is, as Shove states, "*an acquired habit laden with meaning*". The analysis of these dispersed practices has shown that being comfortable at home had very different meanings for different people. Furthermore, the meaning of comfort was far more determining in shaping the internal climate than the physical structure. As a result of that, the hypothesis presented at the beginning of this research connecting the users' interaction with the building and the level of insulation of the envelope could not be validated.

Previous research showed that comfort definition changed depending on the nature of the building (DeDear et al. 1998). In this case, however, the meaning of comfort was generally independent of the material structure. Just a few older occupants of non-retrofitted properties that had lived in traditional buildings for long periods of time presented an exception to this rule. Those occupants had accepted that *"old is cold"* and adapted their expectations of comfort to what they thought it was achievable in that specific context.

The importance of the meaning of comfort for the hygrothermal performance was linked to one of the main ideas behind adaptive comfort: "*people react to the changes in the environment that cause discomfort in order to restore their comfort"* (Nicol et al. 2012). The results of this research revealed that the reaction to discomfort was a major factor determining how occupants interacted with the building. Moreover, coping with discomfort was the main reason behind the high loads of moisture found in some households. Those users that were not able to restore their comfort quickly engaged in practices that resulted in negative lasting effects. Besides, the effects of their behaviour, even if known and understood, were ignored when coping with recurrent causes of discomfort.

The current standards of comfort present the occupants as *"passive recipients of given conditions"* (Brager & DeDear 1998), while the reality has shown that occupants actively engage in whatever practices are needed to achieve 'their idea of comfort', regardless of the secondary effects that they might have on the internal environment. The interaction between occupants and buildings can only be explained as the combination of the occupants' meaning of comfort, the material structure and their competences to operate it. The original hypothesis can therefore be reformulated as follows:

> *"People living in traditional properties interact with the building in a different manner depending on the meaning that comfort has for them and their ability to achieve it"*

8.2.4 The decision making process and its effect on the practices of comfort

Vlasova & Gram-Hanssen (2014) argued that both daily life activities and energy retrofits are practices that can be understood as a function of 'meanings, materials and competences'. By contrast, Haines et al. (2010) made a distinction between these two processes and considered that everyday practices are routine aspects of a household while energy retrofits are often a one off action and therefore cannot be studied using the same practice theory principles. Daily practices, as presented by Darnton et al. (2011), are the outcome of complex networks of existing elements in our social world and cannot be shaped unless the links between those elements are broken and rearranged differently. On the other hand, energy retrofits are shaped by a range of factors that can be classified as 'drivers' or 'barriers' (Wilson & Dowlatabadi 2011) and a specific outcome can be achieved changing drivers and removing barriers. In this research, Haines' view was preferred and the energy retrofits were not explored as practices but as individual units of analysis (Judson 2013) trying to identify the drivers and barriers that configured the renovations of traditional buildings in Scotland.

The results of this analysis showed that occupants were considered either passive (with small differences between beneficiaries and customers) or active agents (that is, operators) of the buildings functioning depending on how the DM looked at their comfort practices.

The DMs that depicted occupants as beneficiaries of the retrofit or potential customers tried to create an environment that was appealing to the user. In those cases, the decisions were made with a limited vision of the users' effect on the building. The DMs that considered occupants as active agents, on the contrary, directed their choices to avoid future problems caused by the users' practices when trying to achieve comfort. The reflections were usually based on previous experiences of occupants' interaction with the same or similar buildings.

The differences between both approaches were in some aspects similar to those found between the current standards of comfort and the new models of adaptive comfort. For the DMs that looked at the users as passive occupants, the internal environment was a final 'product' offered to match what the DMs thought that they ('customers') were expecting. Whereas, in the cases where the DMs presented the occupants as active parties in the operation of the building, the internal environment was not presented as a finished product but as a consequence of occupants' interaction with the building. The interaction with the building was understood to seek occupants' comfort and therefore DMs tried to facilitate the achievement of a comfortable environment while limiting the risks of undesired consequences.

8.2.5 The hygrothermal performance of the wall and its effect on the decision making process

Focusing on how people behave and the impact that it has on the performance of the buildings in which they live has come to validate, and quantify, an idea that was present since the beginning of this work:

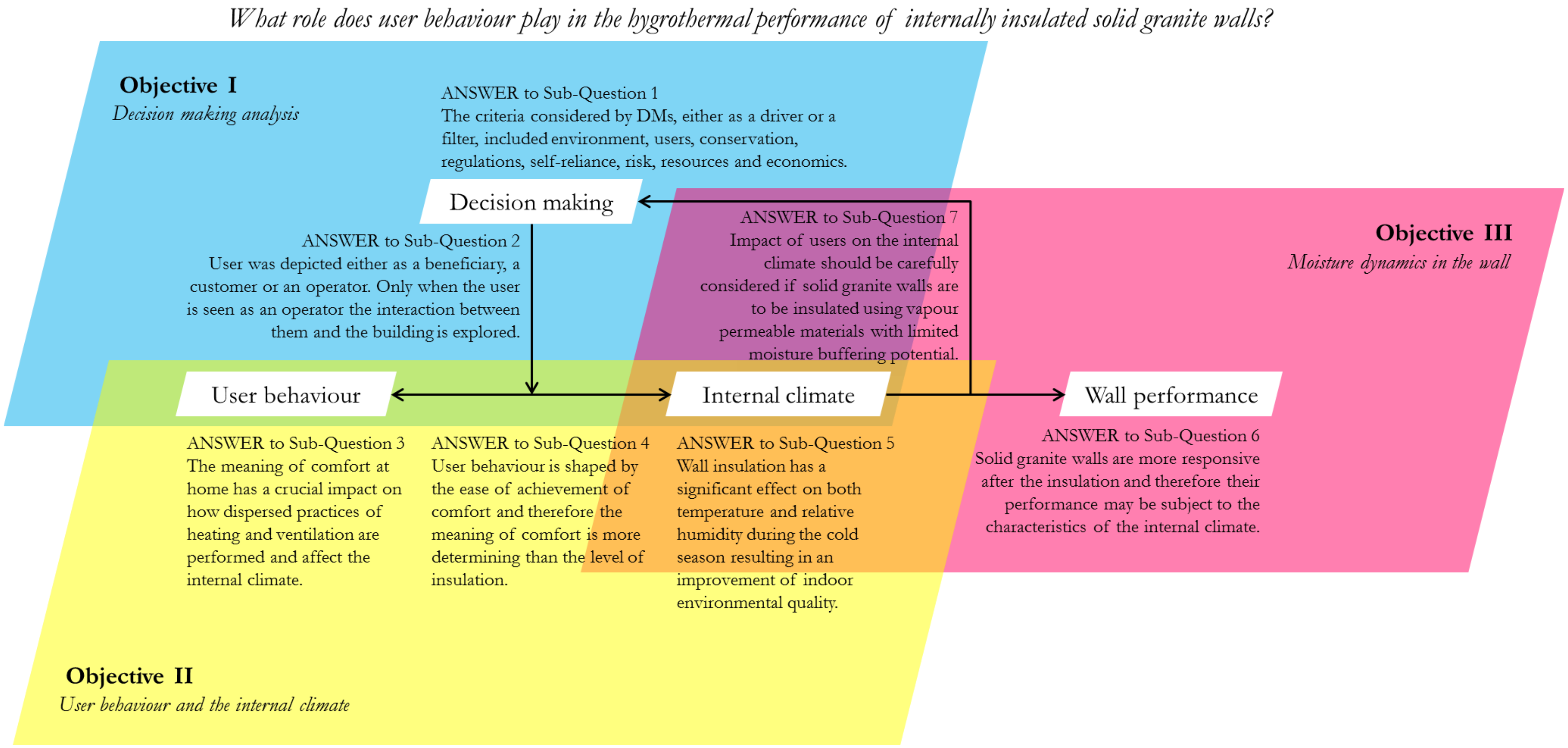
> *"Things done for social reasons have physical effects" (Nicol et al. 2012)*

This statement was proposed by Nicol, Humphreys and Roaf in their work on adaptive thermal comfort to illustrate how culture and social norms affect clothing in the indoor environment and therefore the thermal comfort of the occupants. In this case, the results of the research have shown the connection between the practices of comfort at home, as a social concept (Madsen 2014), and the hygrothermal performance of solid walls, the physical phenomenon. The results presented the effect of occupants' practices on the internal climate and the impact that different internal climates had on the long term performance of walls. Decision making processes of energy retrofit of traditional buildings should therefore consider the connection between occupants and building fabric in order to assess the feasibility of the interventions. According to the results of the numerical simulations carried out in this research, the interaction between internal climate and the material chosen to insulate the wall should be carefully considered. Additionally, the adoption of retrofit technologies should evaluate occupants' mechanisms of coping with discomfort and provide systems that minimise the risk of high moisture loads.

Nevertheless, the analysis of retrofit processes revealed that most of DMs did not consider any aspect of the users' interaction with the building when choosing the measures to implement. Furthermore, the few DMs that took occupants into account based their decision on previous experiences exclusively and therefore their awareness of potential consequences of the implementation of inadequate solutions was fairly limited.

8.3 Conclusions

The key findings of the research are presented in this section according to the sub-questions formulated at the beginning of this work (Figure 8-1). The findings demonstrate that user behaviour is a determining factor for the internal climate and walls' performance of retrofitted buildings. The results, however, have also revealed that user behaviour plays a secondary role in the decision making process and, furthermore, that existing design tools for internal climate design are not representative of traditional Scottish dwellings.



ANSWER to Sub-Question 1
The criteria considered by DMs, either as a driver or a filter, included environment, users, conservation, regulations, self-reliance, risk, resources and economics.

ANSWER to Sub-Question 7
Impact of users on the internal climate should be carefully considered if solid granite walls are to be insulated using vapour permeable materials with limited moisture buffering potential.

ANSWER to Sub-Question 2
User was depicted either as a beneficiary, a customer or an operator. Only when the user is seen as an operator the interaction between them and the building is explored.

ANSWER to Sub-Question 3
The meaning of comfort at home has a crucial impact on how dispersed practices of heating and ventilation are performed and affect the internal climate.

ANSWER to Sub-Question 4
User behaviour is shaped by the ease of achievement of comfort and therefore the meaning of comfort is more determining than the level of insulation.

ANSWER to Sub-Question 5
Wall insulation has a significant effect on both temperature and relative humidity during the cold season resulting in an improvement of indoor environmental quality.

ANSWER to Sub-Question 6
Solid granite walls are more responsive after the insulation and therefore their performance may be subject to the characteristics of the internal climate.

Figure 8-1 Research conclusions. The interconnection between research objectives and answers to sub-questions.

- Sub-Question 1. What are the driving factors for decision makers when adopting energy efficient technologies in traditional buildings?

The decision making analysis presented in Chapter 4 allowed for the identification of two essential dimensions in the adoption of low carbon technologies in traditional buildings: drivers for improvement and filters for purchase. The drivers or motivations for retrofitting an old property included an environmental awareness, the improvement of occupants' comfort, obligations set by regulations, an interest in becoming more self-sufficient or the reduction of the running costs. Limitations for the implementation of specific measures were related to their environmental impact, the disruption caused to the user or the system controllability, compatibility with the building original features, risk for the property, the resources necessary for the implementation and the cost and funding of the technologies.

- Sub-Question 2. How are user behaviour and comfort needs considered when adopting energy efficient technologies in traditional buildings?

The way in which user behaviour was evaluated as part of a decision making process was determined by whether DMs considered them active or passive agents in the interaction with the building and its services. Interviews analysis revealed that if users were considered passive agents, their behaviour was often ignored and the internal environment was designed as a finished product. If the users were presented as active agents, their behaviour occupied a prominent position in the decision making process and the measures implemented were chosen to be compatible with their use of the building.

- Sub-Question 3. What are the interactions between users, systems and fabric in traditional dwellings?

Analysis of qualitative data from the multi-case study presented in Chapter 5 showed that the interaction with the building was aimed at achieving occupants' comfort. However, the different activities carried out in the building (heating, ventilating, laundering, cooking, etc.) were not seen as an integrated practice of comfort that shaped the internal climate but as a combination of single practices that were part of their daily routines. Therefore, each practice was dominated by its own meaning. Thus, heating was usually associated with warmth and cosiness but also with economics, pollution or convenience, the practice of ventilation had to balance opposite images of freshness and wastefulness and drying clothes combined meanings of cleanliness and convenience. In addition to the meaning, the infrastructure, as well as the competence of the users, shaped how they interacted with the building and its services.

- Sub-Question 4. Does user behaviour change after the improvement of the envelope?

Analysis of the users' narratives (Chapter 5) did not find a correlation between the level of insulation and the users' daily practices of comfort. Interaction between users and buildings was dominated by the meaning associated to the practice and therefore a change in the material structure did not produce any major alteration in their behaviour. A relationship between material and meaning was only found among some occupants of non-retrofitted traditional buildings who shared the perception that "old is cold" and accommodated their expectations of comfort to this pre-established image.

- Sub-Question 5. What is the internal temperature and relative humidity of traditional dwellings before and after retrofitting the building fabric?

As described in Chapter 6, internal temperature of non-retrofitted buildings was very dependent on the external temperature and consistently lower than the values proposed in the standard BS EN 15026:2007. Internal temperature ranged from 12 °C (when the external daily temperature was 0 °C) to 23 °C (ExtT = 19 °C). After retrofit, the average values increased and they were less dependent on the external temperature. Internal temperatures ranged from 16 °C (ExtT = 0 °C) to 22 °C (ExtT = 19 °C). The relative humidity in non-retrofitted buildings was considerably higher than the values proposed in the standard for high levels of occupancy, although the dependence on the external temperature was comparable. Relative humidity values ranged from 60 % (ExtT = 0 °C) to 70 % (ExtT = 19 °C). In retrofitted buildings, relative humidity followed a similar pattern but the values were lower, comparable to the values proposed in the standard for high levels of occupancy. The results ranged from 55 % (ExtT = 0 °C) to 66.5 % (ExtT = 19 °C).

- Sub-Question 6. To what extent are indoor climate conditions affecting the moisture dynamics of internally insulated solid granite walls?

Numerical simulation of internally insulated walls presented in Chapter 7 has demonstrated the change in the moisture dynamics of retrofitted envelopes. Internal insulation made walls more sensitive to the characteristics of the internal environment. Thus, the final performance of insulated walls was very dependent on the internal humidity loads. No moisture related risks were identified in the walls simulated in scenarios with low moisture loads and the thermal performance of the insulation was not affected. Walls under scenarios of medium moisture loads presented long periods at risk of condensation, mould growth and in some cases wood decay. Besides, thermal performance of the insulation was slightly worse than the nominal values. When a scenario with high moisture loads was used to simulate the internal boundary, the risk of condensation and mould growth was almost permanent and the thermal performance decreased by up to 30 % when compared to the nominal values.

- Sub-Question 7. Must energy behaviour of users be considered during the decision making process when retrofitting solid granite walls?

Considering the dependence of the hygrothermal performance of insulated walls on the internal climate shown in Chapter 7 and the importance of users' interaction with the building in shaping the internal climate of the dwellings presented in Chapter 5 and 6, it can be concluded that users' energy behaviour must be explored as one of the main criteria for the adoption of retrofit measures. Assessment of intervention feasibility should consider users' comfort requirements and their compatibility with the renovation. Besides, the decision making process should facilitate different mechanisms to limit the negative effect that users' behaviour might have on the internal climate and, ultimately, on the performance of the wall.

8.4 Research contribution to knowledge

This research has approached the connection between users and buildings from a new angle looking at the effect that the user behaviour has on the hygrothermal performance of the buildings' envelope after the retrofit. Despite the limitations stated above, the novel approach chosen in this research, covering the entire qualitative-quantitative continuum, has contributed to a deeper understanding of the following aspects:

- The understanding of the decision making process in energy retrofits.

The rationale behind the energy retrofit of buildings, and particularly those of traditional construction, has not been fully explored yet. The findings of this work revealed the disconnection existing between the criteria used by DMs and the effect of user behaviour on buildings performance. This research provides new insights into how the user is considered in the adoption of low carbon technologies.

- The understanding of how users behave in traditionally constructed dwellings.

The final performance of a building can only be predicted accurately if the behaviour of its users can also be anticipated. That relies on understanding the reasons behind their behaviour. The results of this research have shown that user behaviour is not conditioned exclusively by the physical properties of the building. The meaning of comfort plays an important role in how the users interact with the building.

- The characterisation of traditional buildings internal climate.

Environmental monitoring has revealed and quantified the differences in the internal climate of traditional buildings before and after their renovation. More importantly, the climate characterisation has highlighted considerable discrepancies when compared with the boundaries proposed in the international standards that serve as guidelines for the hygrothermal assessment of buildings.

- The understanding of the moisture dynamics of insulated solid walls.

The use of numerical simulation of moisture dynamics in building envelopes is a relatively new body of research that has grown rapidly. However, no investigation on the effect of the internal boundary on insulated solid granite walls has been carried out before. Focusing on vapour diffusion, this work has shown the effect of the interaction between the internal climate and the properties of the materials on the final performance of insulated walls.

- The study of the energy related behaviour of users and decision makers

In addition to the original contributions to the understanding of user behaviour and its effect on buildings performance, this work also contributes to the research design itself. First, an adapted ‘purchase process model’ was used as an instrument for decision making analysis. Template analysis has proven to be very effective in the analysis of recent retrofits as it unveiled both drivers and filters used by decision makers. Furthermore, this research has successfully combined the use of narratives and social practice theory in the exploration of user behaviour effect on the internal climate.

8.4.1 Recommendations to decision makers

This work was ultimately aimed at helping policy makers, practitioners, developers and home owners to make better informed decisions when improving the efficiency of traditionally constructed dwellings. The final goal was to enable DMs to identify 'safe' options of retrofit that can achieve a reduction in energy consumption and provide comfort to users while limiting the risk of undesired consequences.

The findings of this research have highlighted the need for a change in the approach of DMs. The decision making process should consider the effects of users' interaction with the building as one of the strong filters for the adoption of retrofit measures. DMs should, therefore, be encouraged to perceive the user not as a passive agent but as the operator of the building. DMs must consider the compatibility between the type of system and the occupants' meaning of comfort. Thus, passive systems would only be suitable for users that are willing to engage actively in their operation. Active systems, on the other hand, would not require users' engagement and could be operated autonomously. In addition to the change in DMs' approach to the user, an increase in the awareness of the potential impact of user behaviour is needed. The dissemination of successful - and unsuccessful - case studies would help to illustrate the connections between user behaviour and building performance. DMs should be approached universally as a change is needed for both DMs that occupy the building and those that are not the final users. This research has showed that DMs' approach to the retrofit does not depend on the type of ownership.

As for the insulation of solid walls, the research results have shown that moisture loads in residential buildings must be controlled in order to avoid problems caused related to vapour diffusion through the envelope. Vapour pressure difference can be regulated by mechanical, physical or social means. The use of mechanical systems, such as demand-controlled ventilation, is probably the safest option as it would maintain optimum conditions for the internal environment. However, use of mechanical ventilation would involve higher energy consumption and higher upfront costs. Energy consumption can be improved using mechanical ventilation with heat recovery, although it would increase the implementation cost even more.

Humidity levels can also be controlled with passive systems like stack ventilation. These systems, however, can be overruled by the users if they are perceived as a cause of discomfort. Alternatively, the effect of vapour pressure on the wall can be mitigated using VCL. However, the feasibility of these barriers should be carefully assessed as secondary risks could be even greater than the original. An internal VCL in combination with a poorly maintained wall or an accidental ingress of water could result in high levels of moisture trapped in the wall. The use of hygroscopic materials that buffer the internal humidity peaks and control the environment of the buildings can also be explored as part of the retrofit.

Considering the limitations of physical and mechanical means, the social aspects of humidity control can be fundamental in ensuring an optimal wall performance. Making users aware of their effect on the internal environment, and ultimately on the performance of the building, could minimise the risk of adverse internal conditions. Helping users to connect their dispersed practices of comfort at home (heating, ventilating, cooking, laundering, etc.) into one integrated practice could also improve their understanding of the effect of their actions and enable a change in their behaviour.

Lastly, the results of this research revealed the importance of using accurate data to represent the internal boundary in order to achieve a reliable assessment of the retrofit options. In the absence of measured or reliable data, the worst case scenario should be considered for the hygrothermal assessment of the envelope.

8.5 Further Research

The findings emerged from this work could serve as a foundation for further lines of investigation. Thus, a deeper analysis of the role of users in the decision making process should be carried out involving a larger sample in order to obtain a ‘theoretical saturation’ that validates the drivers and filters identified in this research. Besides, the exploration of comfort and daily practices was limited to residential buildings. The interaction between users and buildings could be further investigated by looking at the relationship between the practices of comfort and the internal climate in buildings with different uses.

For a more detailed hygrothermal assessment several aspects of building performance need to be addressed: (i) a campaign of air pressure tests should be carried out to measure the effect of permeability on the internal climate, (ii) the physical properties of traditional materials should be fully characterised by means of laboratory testing and (iii) the air flow in the cavity between the masonry and the lath and plaster should be monitored and modelled. The numerical simulations carried out in this research omitted the effect of the external climate and therefore the coupled effect of both boundaries needs to be investigated. Different scenarios of WDR, initial moisture content or rising damp must be considered. Finally, a detailed study of numerical simulation should be performed to identify the highest acceptable indoor moisture loads that are compatible with acceptable wall performance levels after a retrofit.

The results of this research also opened new paths to investigate the relationship between user behaviour, material properties and building performance. Thermal mass and moisture buffering potential of certain materials offers the possibility of altering the response of buildings to users' behaviour without intervening in their daily practices directly. The feasibility of highly hygroscopic insulating materials (like calcium-silicate, wood or hemp-lime) in traditional buildings retrofit could be investigated. Lastly, there may also be the potential to explore the impact of information campaigns or feedback from different monitoring systems to promote suitable energy practices that are compatible with highly insulated and draught-proofed buildings.

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10 APPENDICES

APPENDIX 1 – INVITATION & REMINDER LETTERS

ROBERT GORDON
UNIVERSITY ABERDEEN

The Scott Sutherland School of Architecture & Built Environment
Robert Gordon University
Garthdee Road
Aberdeen
AB10 7QB
United Kingdom

Dear Sir/Madam,

My name is Daniel Herrera and I am a PhD researcher at Robert Gordon University where I am undertaking a research focused on the energy efficiency improvements in traditional buildings.

I am looking into the decision making process and the criteria adopted by stakeholders when refurbishing a traditional property. As part of my research I am undertaking interviews with private owners, housing associations or property developers who did or are planning to do some retrofitting or conversion for such type of buildings.

I am writing you in the hope that you, or any other member of your organisation, will be able to spare about 45-60 minutes of your time, at a time that suits you, in order to include your particular experience. Any information of your personal approach and decision making process would be really useful for my research.

Your help is very much appreciated and if you could participate the results of the research will of course be made available to you if you wish.

Please don't hesitate to contact me if you wish to discuss any aspect of the interview or the research.

Thanks in advance for your cooperation.

Kind regards,
Daniel Herrera

Daniel Herrera | DipArch, MSc
PhD Researcher
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Web: http://www.rgu.ac.uk/dmstaff/herrera-gutierrez-avellanosa-daniel

Appendix 1

ROBERT GORDON
UNIVERSITY ABERDEEN

The Scott Sutherland School of Architecture & Built Environment

Robert Gordon University
Garthdee Road
Aberdeen
AB10 7QB
United Kingdom

Dear Sir/Madam,

This is a polite reminder to participate in a PhD research project.

As explained in previous e-mail, I am undertaking a research focused on the energy efficiency improvements in traditional buildings. As part of my research I am undertaking interviews with private owners, housing associations or property developers who did or are planning to do some retrofitting or conversion for such type of buildings.

Please let me ask you again to take part in an interview, at a time that suits you, in order to include your particular experience. Your participation is essential to further research in this PhD project.

Please don't hesitate to contact me if you wish to discuss any aspect of the interview or the research.

Thank you very much for your time and cooperation.

Kind regards,
Daniel Herrera

Daniel Herrera | DipArch, MSc
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APPENDIX 2 – DECISION MAKING STUDY: BRIEFING & SCRIPT (OWNER-OCCUPIERS & NON-OCCUPIERS)

ENERGY EFFICIENCY IMPROVEMENTS IN TRADITIONAL BUILDINGS
Robert Gordon University
Aberdeen, UK
The Scott Sutherland School of
Architecture & Built Environment

1 of 4

Briefing

Thank you for taking part in this study.

I am investigating the decision making process of home owners and/or stakeholders when it is time to refurbish a traditional building. The main goal of this interview is to acquire some understanding regarding your opinions and preferences in relation to this particular field. Of course, there are no right or wrong answers, as I am only interested in gather you personal perspective and experiences.

I would like you to answer the questions only if you feel comfortable and in as much deep as you decide. With your consent, I would like to audio-record the interview for a later transcription and inclusion in my thesis. I would also like to take some pictures of the most relevant features of the house in order to illustrate the main topics addressed in this interview.

Unless you give permission to use your name, title, and/or quote in any publications that may result from this research, the information you tell me will be confidential.

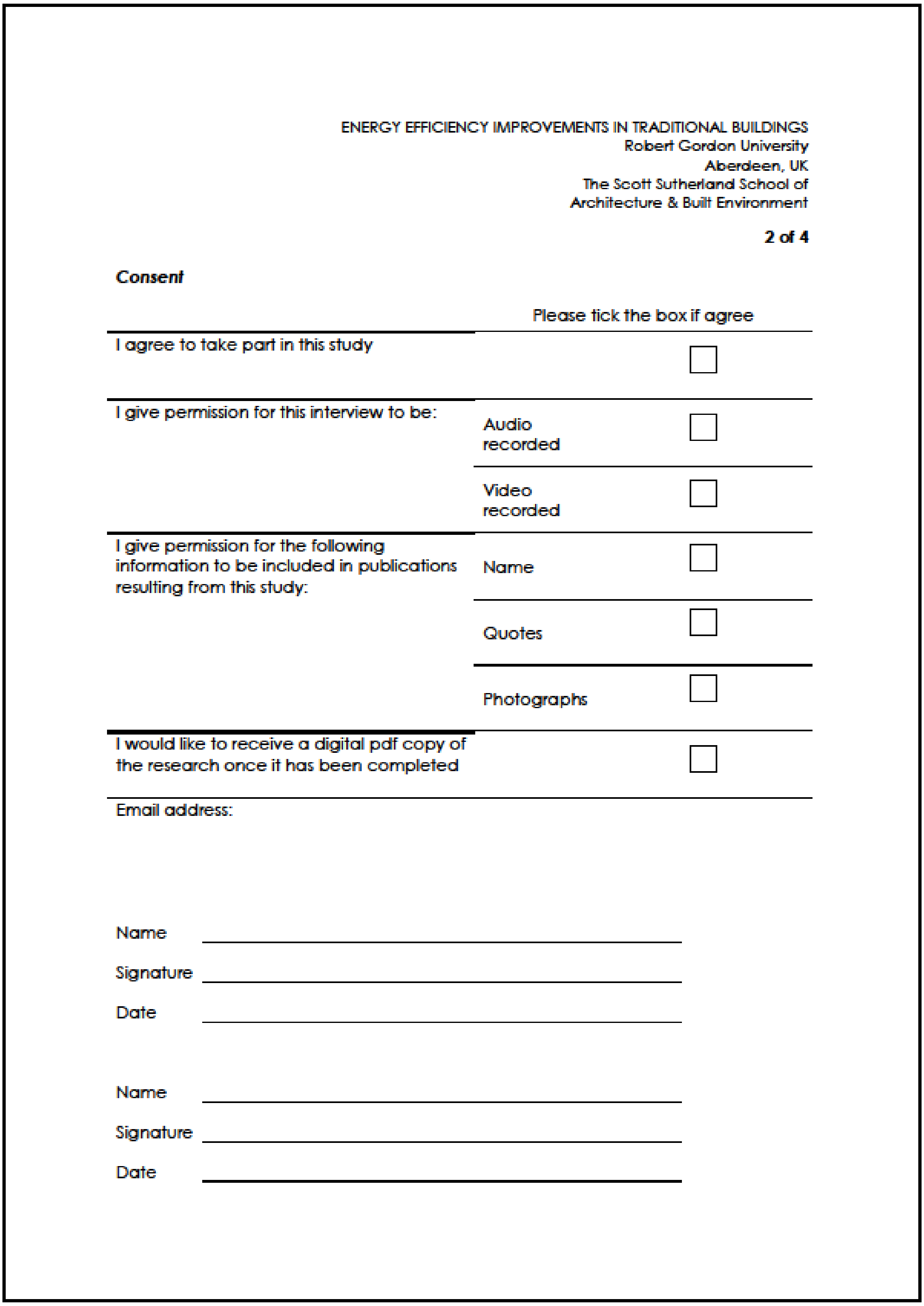
Please be aware that you have the right to withdraw from this interview at any time without giving any further reason. As well, you have the right to withdraw from this study at a later date.

If you have any doubt, please do not hesitate to ask.

Daniel Herrera Gutiérrez-Avellanosa
d.herrera-gutierrez-avellanosa@rgu.ac.uk

PhD research student

Appendix 2



ENERGY EFFICIENCY IMPROVEMENTS IN TRADITIONAL BUILDINGS
Robert Gordon University
Aberdeen, UK
The Scott Sutherland School of
Architecture & Built Environment

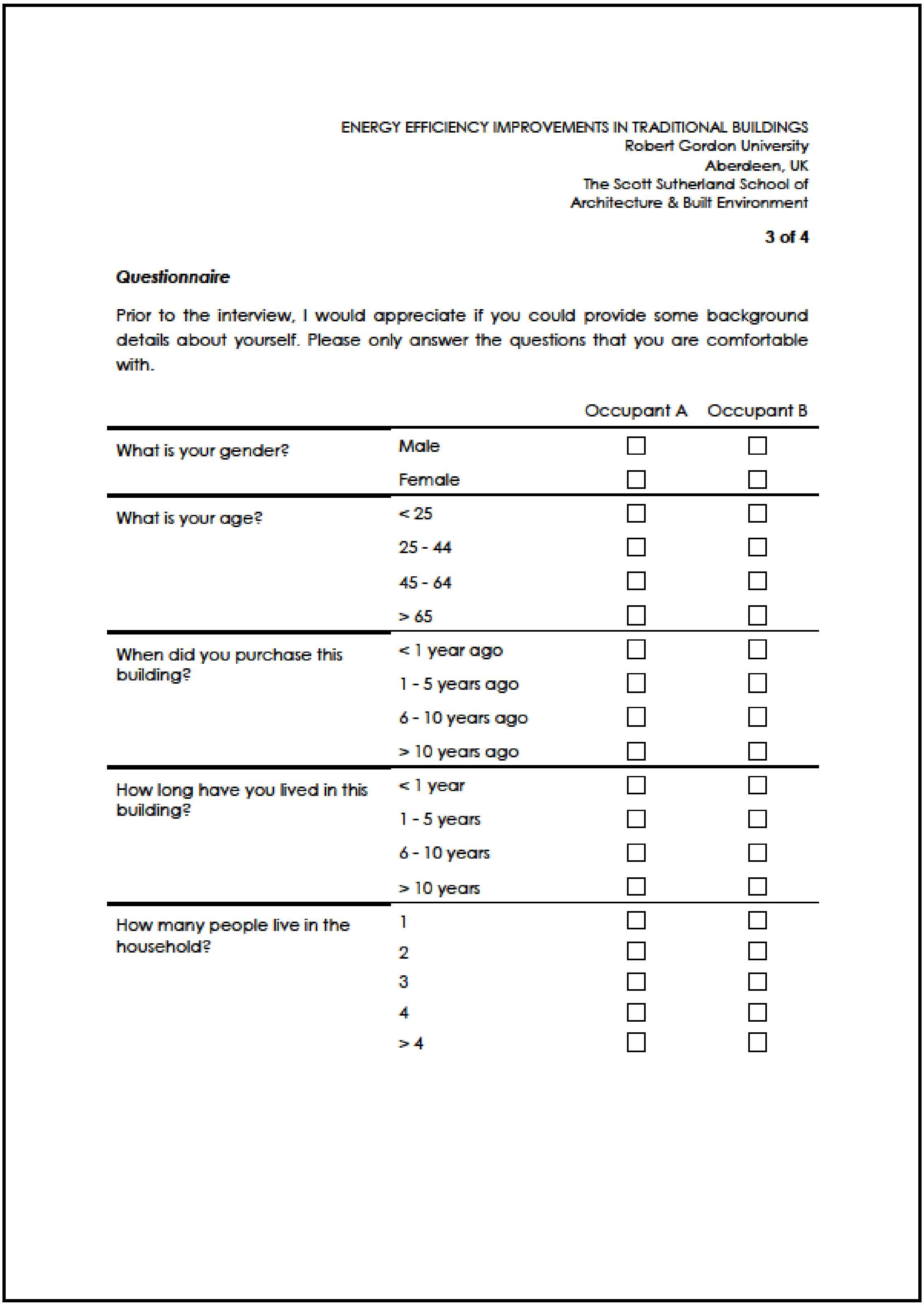
2 of 4

Consent

		Please tick the box if agree
I agree to take part in this study		☐
I give permission for this interview to be:	Audio recorded	☐
	Video recorded	☐
I give permission for the following information to be included in publications resulting from this study:	Name	☐
	Quotes	☐
	Photographs	☐
I would like to receive a digital pdf copy of the research once it has been completed		☐
Email address:		

Name ________________________________
Signature ________________________________
Date ________________________________

Name ________________________________
Signature ________________________________
Date ________________________________



ENERGY EFFICIENCY IMPROVEMENTS IN TRADITIONAL BUILDINGS
Robert Gordon University
Aberdeen, UK
The Scott Sutherland School of
Architecture & Built Environment

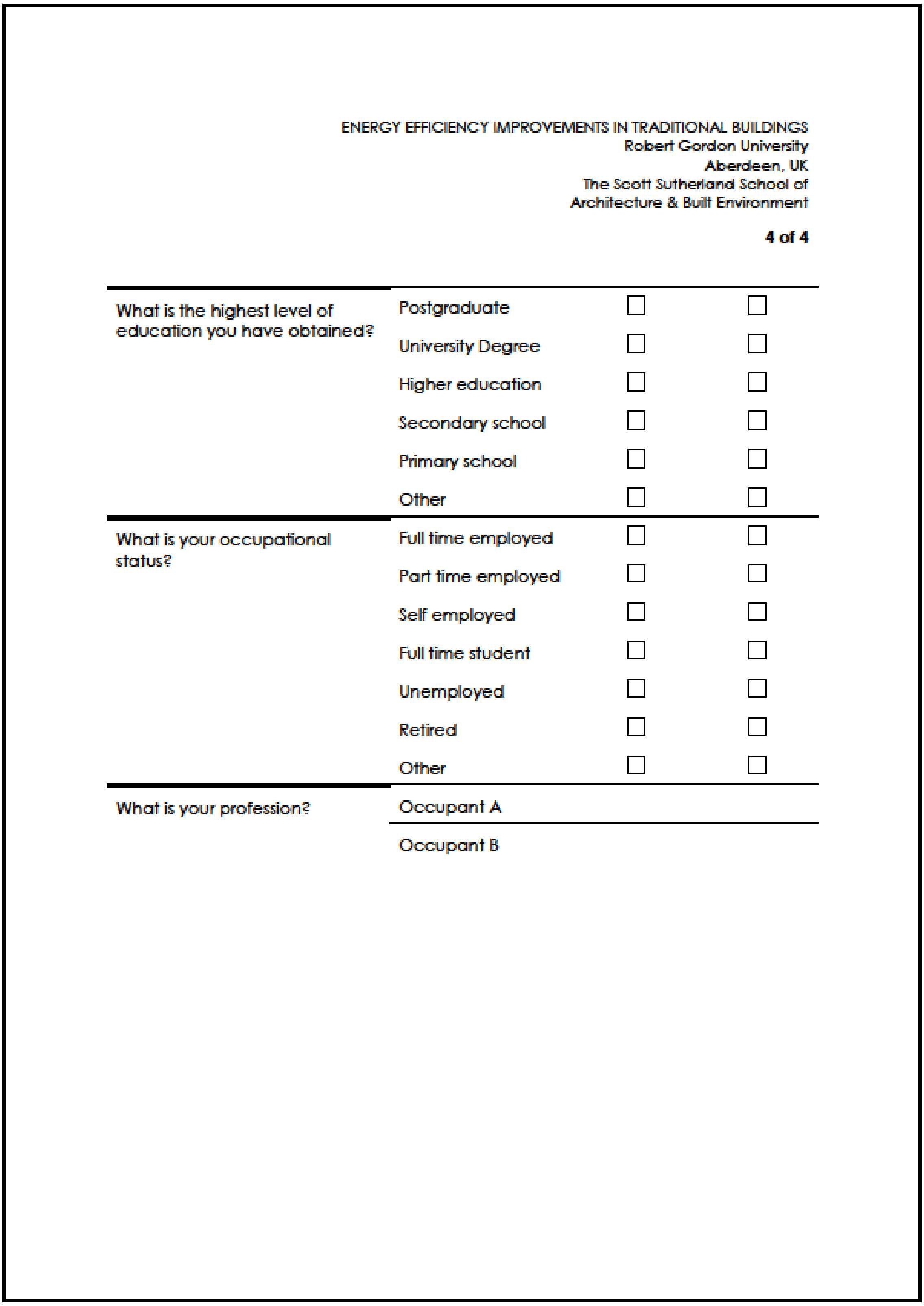
3 of 4

Questionnaire

Prior to the interview, I would appreciate if you could provide some background details about yourself. Please only answer the questions that you are comfortable with.

		Occupant A	Occupant B
What is your gender?	Male	☐	☐
	Female	☐	☐
What is your age?	< 25	☐	☐
	25 - 44	☐	☐
	45 - 64	☐	☐
	> 65	☐	☐
When did you purchase this building?	< 1 year ago	☐	☐
	1 - 5 years ago	☐	☐
	6 - 10 years ago	☐	☐
	> 10 years ago	☐	☐
How long have you lived in this building?	< 1 year	☐	☐
	1 - 5 years	☐	☐
	6 - 10 years	☐	☐
	> 10 years	☐	☐
How many people live in the household?	1	☐	☐
	2	☐	☐
	3	☐	☐
	4	☐	☐
	> 4	☐	☐

Appendix 2



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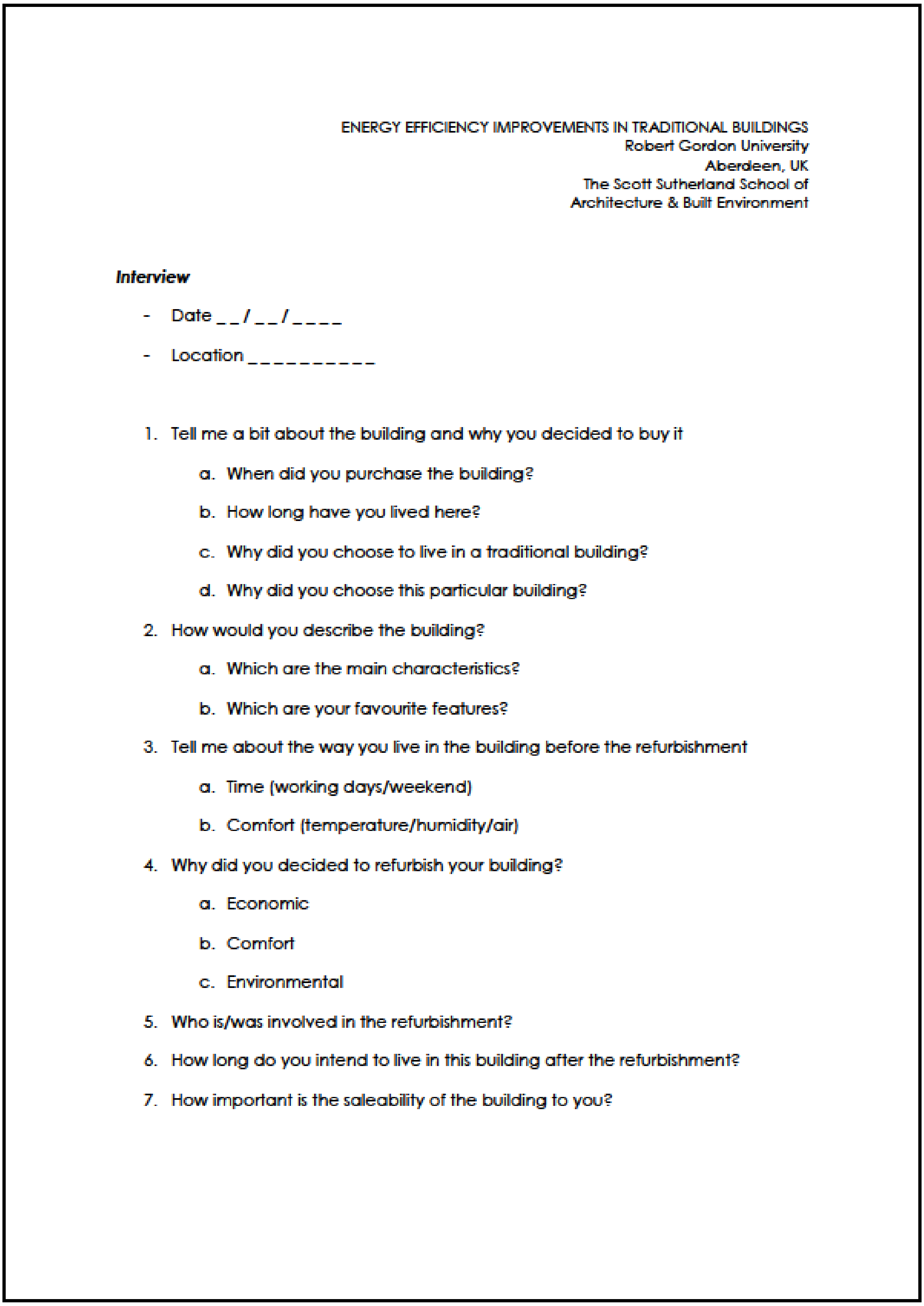
What is the highest level of education you have obtained?	Postgraduate	☐	☐
	University Degree	☐	☐
	Higher education	☐	☐
	Secondary school	☐	☐
	Primary school	☐	☐
	Other	☐	☐
What is your occupational status?	Full time employed	☐	☐
	Part time employed	☐	☐
	Self employed	☐	☐
	Full time student	☐	☐
	Unemployed	☐	☐
	Retired	☐	☐
	Other	☐	☐
What is your profession?	Occupant A		
	Occupant B		



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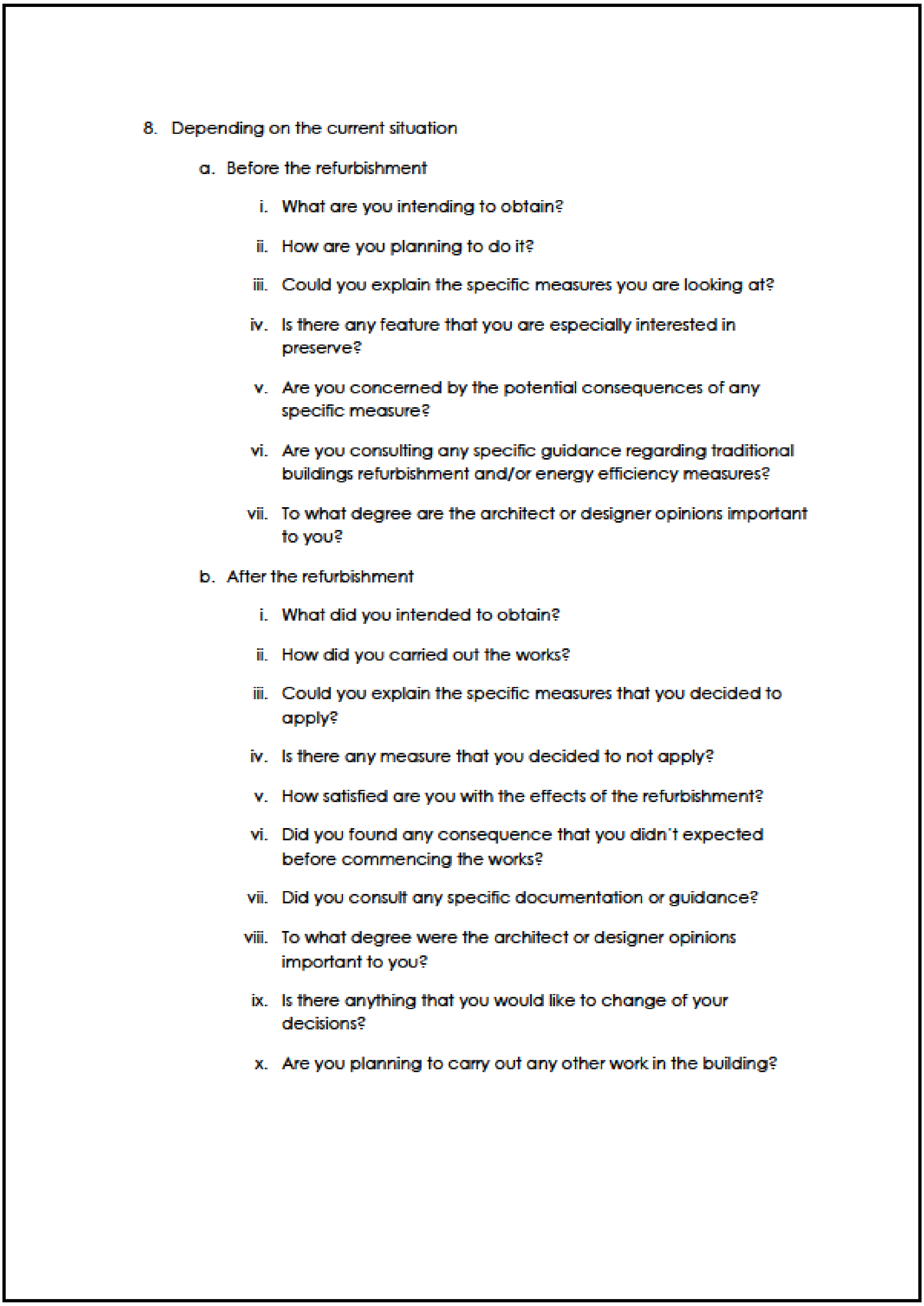
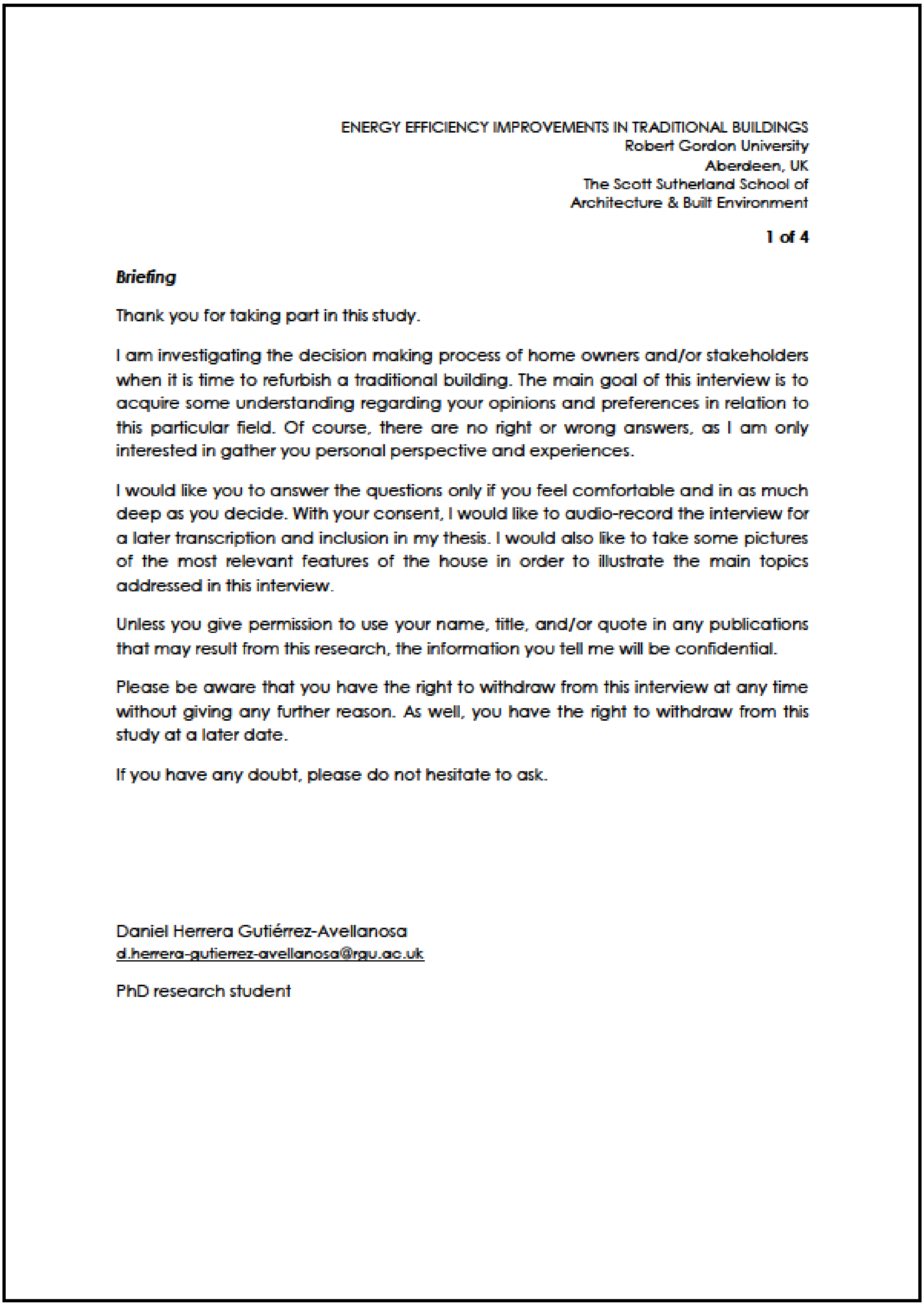
Interview

- Date _ _ / _ _ / _ _ _ _
- Location _ _ _ _ _ _ _ _ _ _

1. Tell me a bit about the building and why you decided to buy it
    a. When did you purchase the building?
    b. How long have you lived here?
    c. Why did you choose to live in a traditional building?
    d. Why did you choose this particular building?
2. How would you describe the building?
    a. Which are the main characteristics?
    b. Which are your favourite features?
3. Tell me about the way you live in the building before the refurbishment
    a. Time (working days/weekend)
    b. Comfort (temperature/humidity/air)
4. Why did you decided to refurbish your building?
    a. Economic
    b. Comfort
    c. Environmental
5. Who is/was involved in the refurbishment?
6. How long do you intend to live in this building after the refurbishment?
7. How important is the saleability of the building to you?



8. Depending on the current situation
    a. Before the refurbishment
        i. What are you intending to obtain?
        ii. How are you planning to do it?
        iii. Could you explain the specific measures you are looking at?
        iv. Is there any feature that you are especially interested in preserve?
        v. Are you concerned by the potential consequences of any specific measure?
        vi. Are you consulting any specific guidance regarding traditional buildings refurbishment and/or energy efficiency measures?
        vii. To what degree are the architect or designer opinions important to you?
    b. After the refurbishment
        i. What did you intended to obtain?
        ii. How did you carried out the works?
        iii. Could you explain the specific measures that you decided to apply?
        iv. Is there any measure that you decided to not apply?
        v. How satisfied are you with the effects of the refurbishment?
        vi. Did you found any consequence that you didn´t expected before commencing the works?
        vii. Did you consult any specific documentation or guidance?
        viii. To what degree were the architect or designer opinions important to you?
        ix. Is there anything that you would like to change of your decisions?
        x. Are you planning to carry out any other work in the building?



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Briefing

Thank you for taking part in this study.

I am investigating the decision making process of home owners and/or stakeholders when it is time to refurbish a traditional building. The main goal of this interview is to acquire some understanding regarding your opinions and preferences in relation to this particular field. Of course, there are no right or wrong answers, as I am only interested in gather you personal perspective and experiences.

I would like you to answer the questions only if you feel comfortable and in as much deep as you decide. With your consent, I would like to audio-record the interview for a later transcription and inclusion in my thesis. I would also like to take some pictures of the most relevant features of the house in order to illustrate the main topics addressed in this interview.

Unless you give permission to use your name, title, and/or quote in any publications that may result from this research, the information you tell me will be confidential.

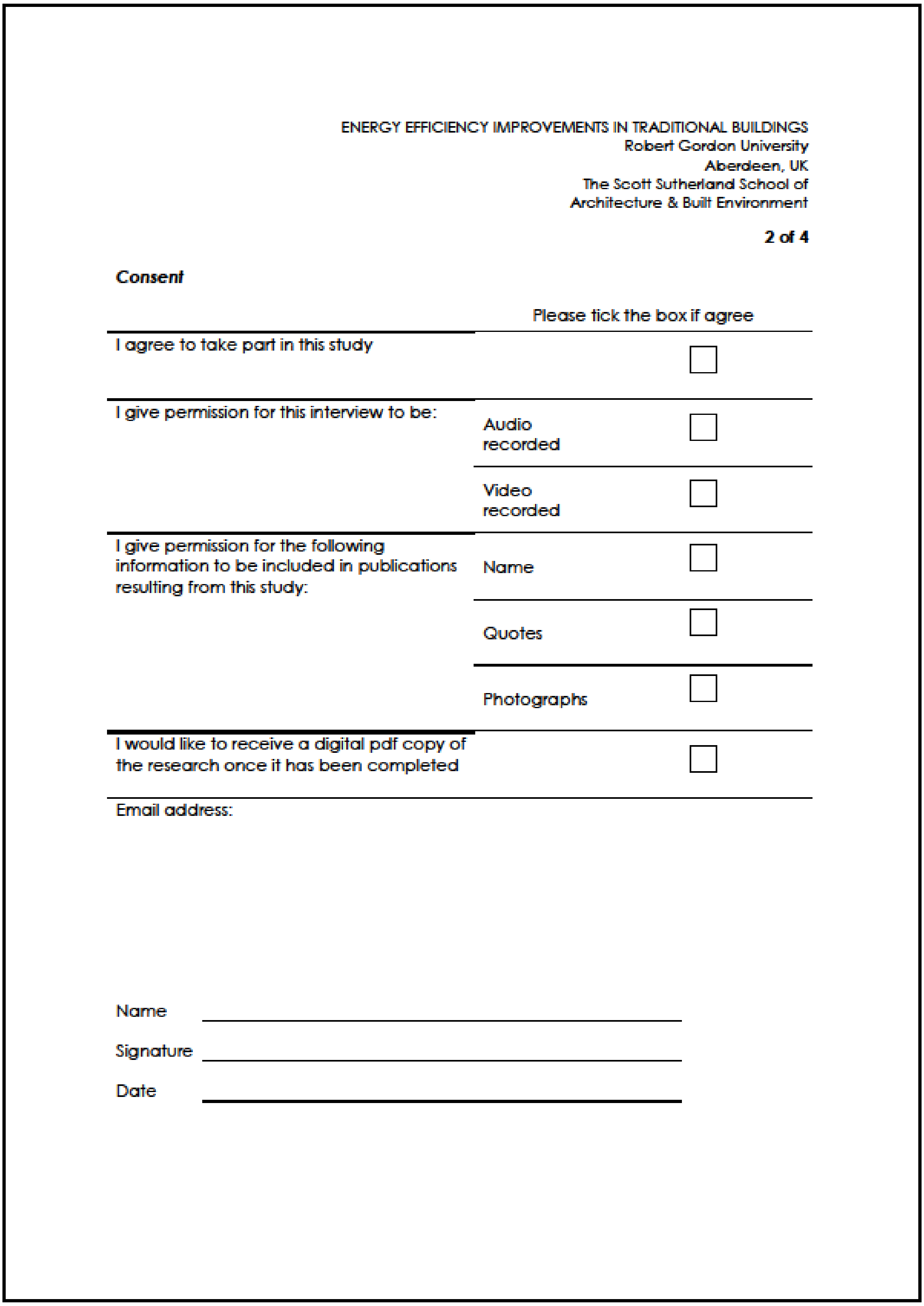
Please be aware that you have the right to withdraw from this interview at any time without giving any further reason. As well, you have the right to withdraw from this study at a later date.

If you have any doubt, please do not hesitate to ask.

Daniel Herrera Gutiérrez-Avellanosa
d.herrera-gutierrez-avellanosa@rgu.ac.uk

PhD research student

Appendix 2



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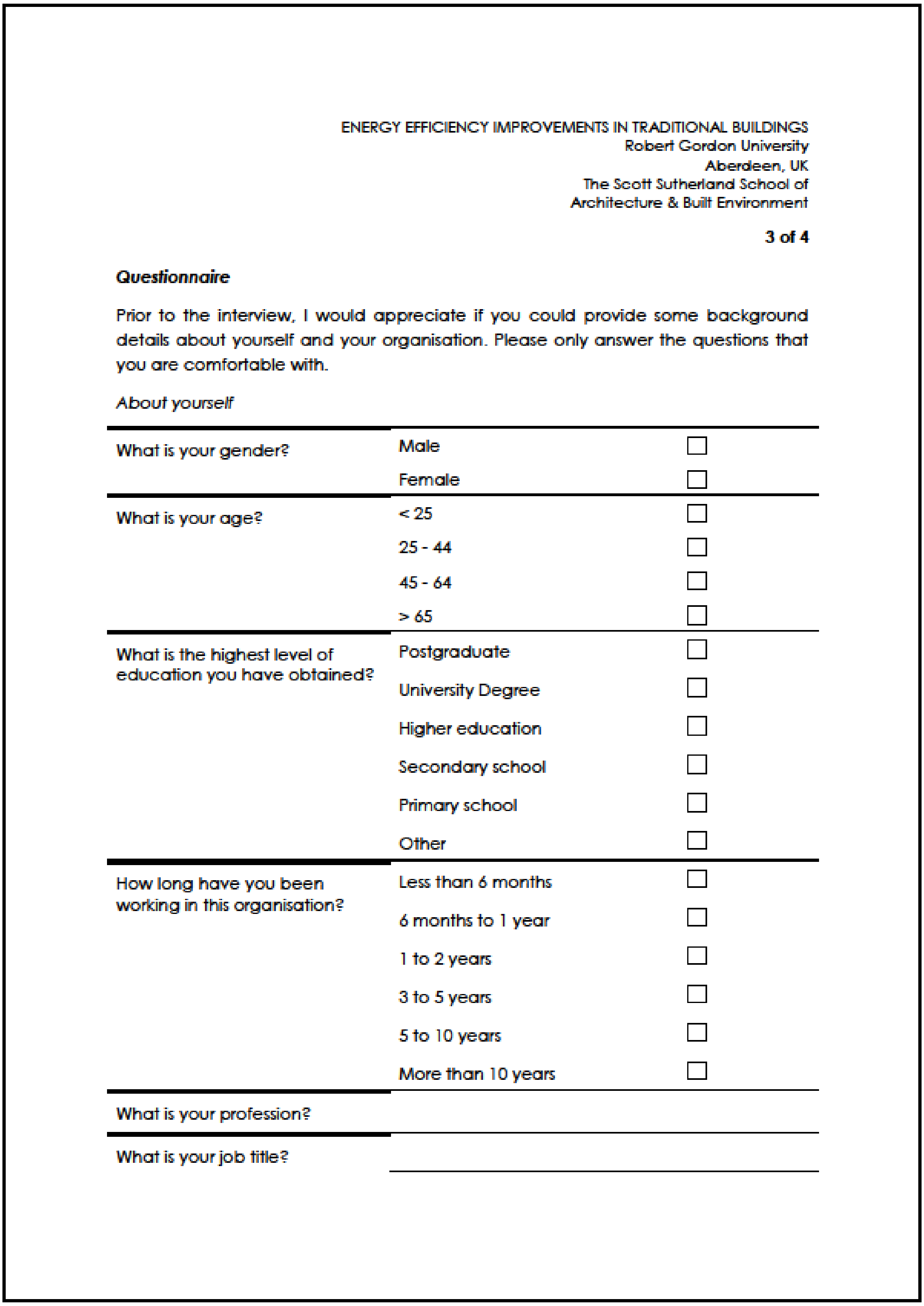
Consent

		Please tick the box if agree
I agree to take part in this study		☐
I give permission for this interview to be:	Audio recorded	☐
	Video recorded	☐
I give permission for the following information to be included in publications resulting from this study:	Name	☐
	Quotes	☐
	Photographs	☐
I would like to receive a digital pdf copy of the research once it has been completed		☐
Email address:		

Name ____________________

Signature ____________________

Date ____________________



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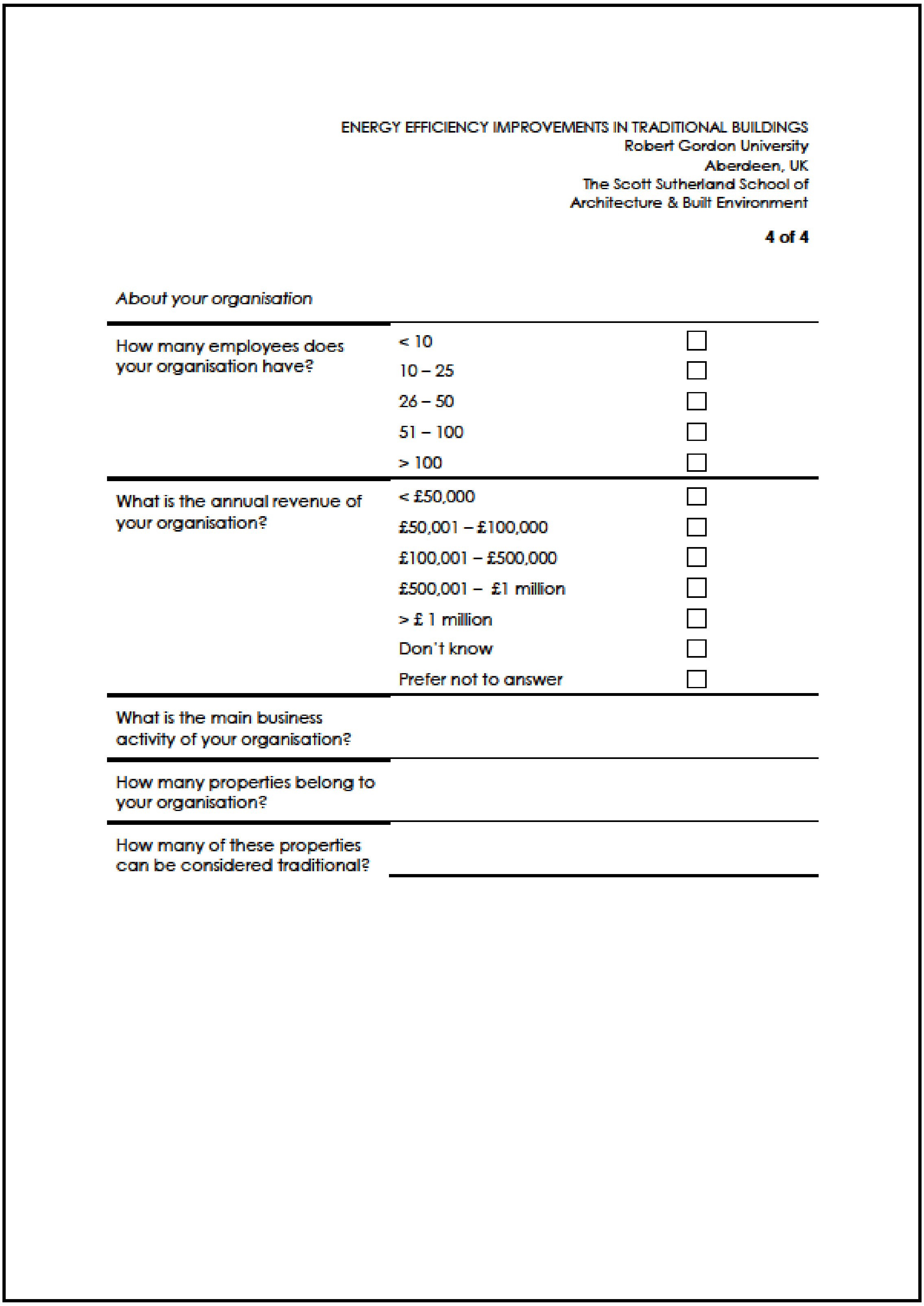
Questionnaire

Prior to the interview, I would appreciate if you could provide some background details about yourself and your organisation. Please only answer the questions that you are comfortable with.

About yourself

What is your gender?	Male	☐
	Female	☐
What is your age?	< 25	☐
	25 - 44	☐
	45 - 64	☐
	> 65	☐
What is the highest level of education you have obtained?	Postgraduate	☐
	University Degree	☐
	Higher education	☐
	Secondary school	☐
	Primary school	☐
	Other	☐
How long have you been working in this organisation?	Less than 6 months	☐
	6 months to 1 year	☐
	1 to 2 years	☐
	3 to 5 years	☐
	5 to 10 years	☐
	More than 10 years	☐
What is your profession?		
What is your job title?		



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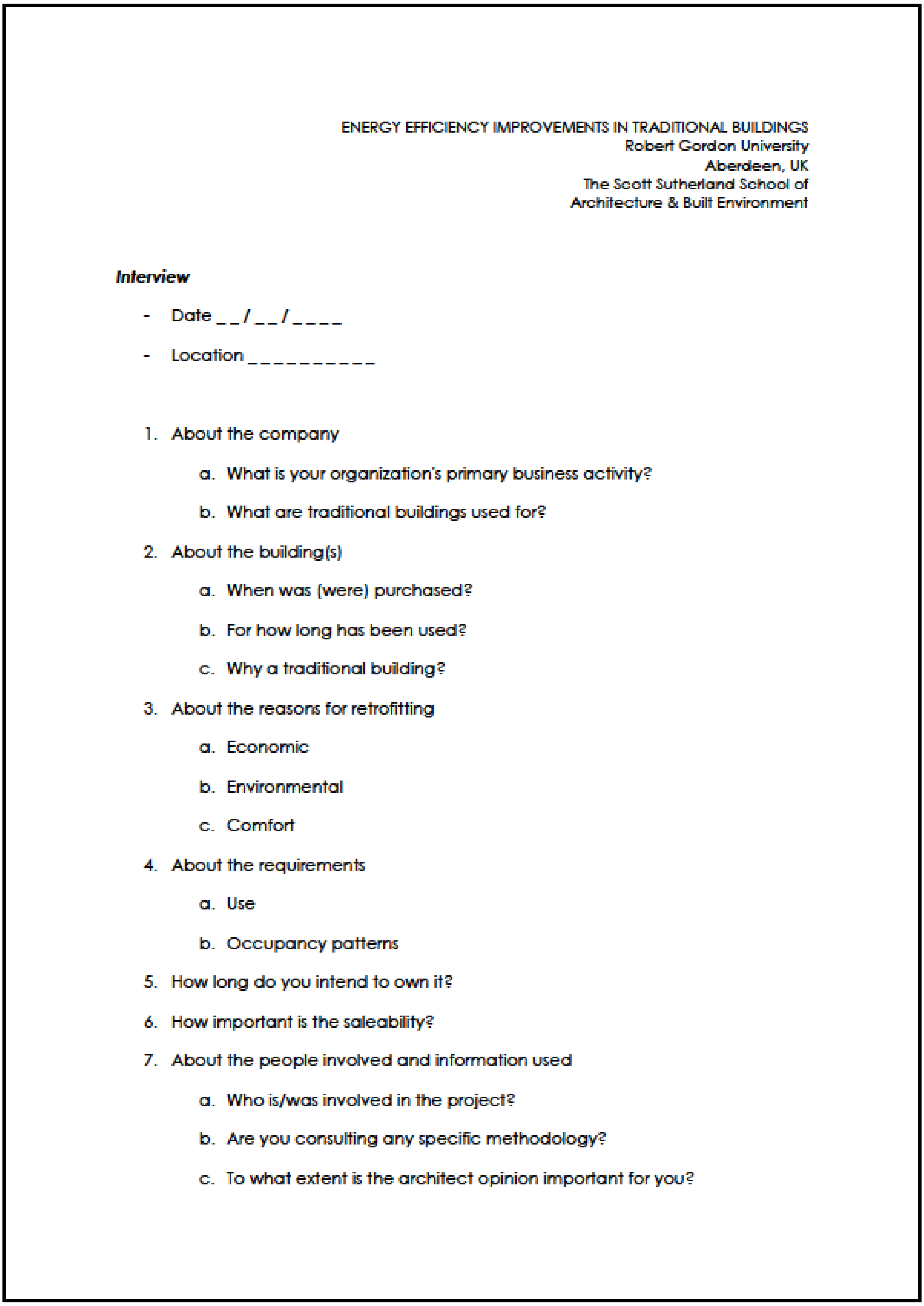
About your organisation

How many employees does your organisation have?	< 10	☐
	10 – 25	☐
	26 – 50	☐
	51 – 100	☐
	> 100	☐
What is the annual revenue of your organisation?	< £50,000	☐
	£50,001 – £100,000	☐
	£100,001 – £500,000	☐
	£500,001 – £1 million	☐
	> £ 1 million	☐
	Don't know	☐
	Prefer not to answer	☐
What is the main business activity of your organisation?		
How many properties belong to your organisation?		
How many of these properties can be considered traditional?		



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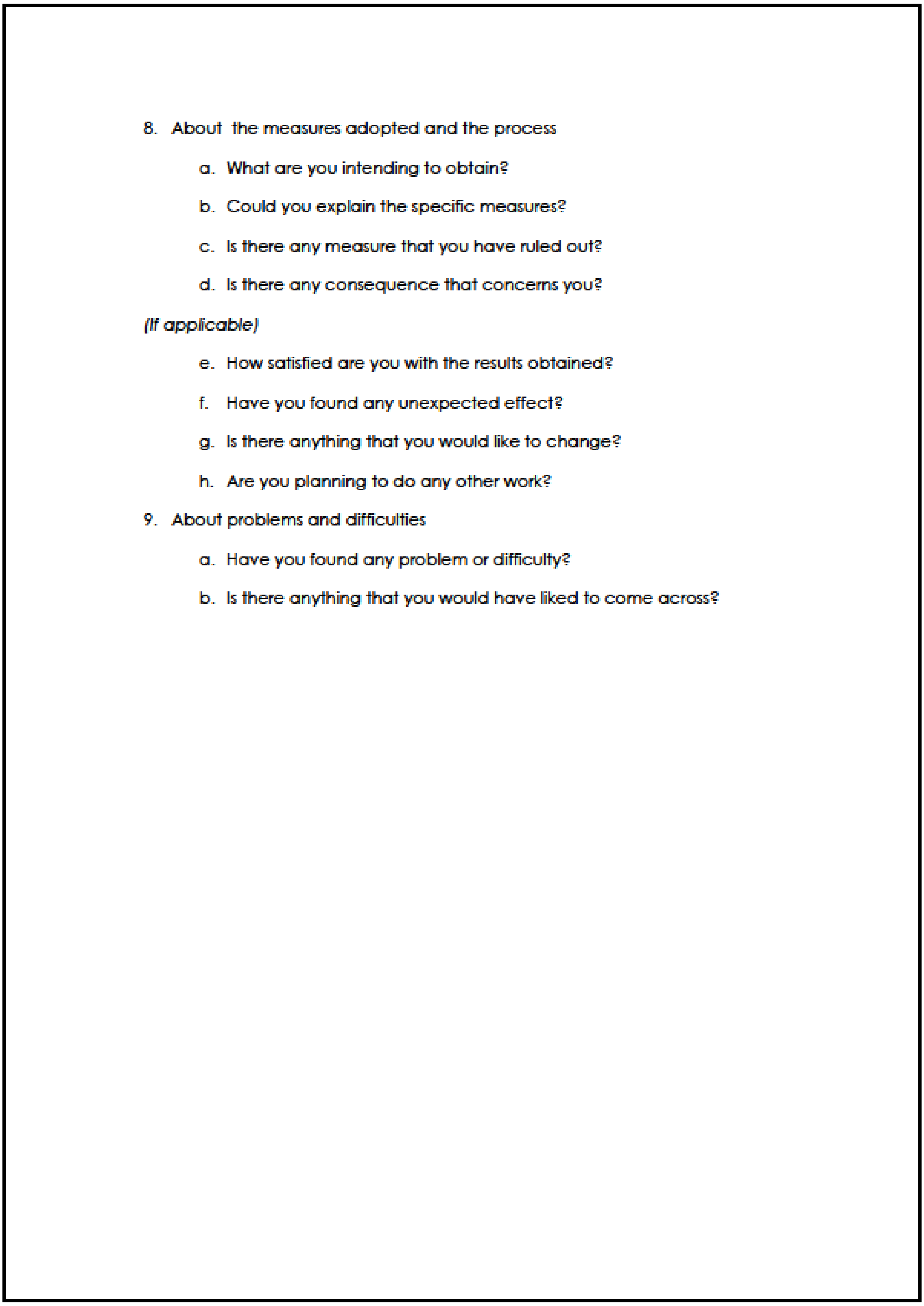
Interview

- Date __/__/____
- Location __________

1. About the company
    a. What is your organization's primary business activity?
    b. What are traditional buildings used for?
2. About the building(s)
    a. When was (were) purchased?
    b. For how long has been used?
    c. Why a traditional building?
3. About the reasons for retrofitting
    a. Economic
    b. Environmental
    c. Comfort
4. About the requirements
    a. Use
    b. Occupancy patterns
5. How long do you intend to own it?
6. How important is the saleability?
7. About the people involved and information used
    a. Who is/was involved in the project?
    b. Are you consulting any specific methodology?
    c. To what extent is the architect opinion important for you?



8. About the measures adopted and the process
    a. What are you intending to obtain?
    b. Could you explain the specific measures?
    c. Is there any measure that you have ruled out?
    d. Is there any consequence that concerns you?

(If applicable)

    e. How satisfied are you with the results obtained?
    f. Have you found any unexpected effect?
    g. Is there anything that you would like to change?
    h. Are you planning to do any other work?

9. About problems and difficulties
    a. Have you found any problem or difficulty?
    b. Is there anything that you would have liked to come across?

APPENDIX 3 – DECISION MAKING STUDY: EXAMPLE INTERVIEW TRANSCRIPT

17^Th^ September 2013

RESEARCHER: So, first I would like to know a bit about the house, when did you buy it? How long have you been living here...?

OWNER 1: Ok. So, we bought the house in April thousand and... seven, yeah. So, we have got the house for six years, towards six years. Hmm... we have lived in it for four years and then we went overseas for three years. And eh... it’s seven years we had the house... no, that’s right. And we stripped it off two years ago.

RESEARCHER: Ok

OWNER 1: Yeah, two years ago we stripped it off. No, tell you what. We didn’t lived here four years, we lived here three years to start, then we went overseas for two years and then we went back for a year. Yes, that’s better.

RESEARCHER: Ok

OWNER 1: So, we stripped it off two years ago. Before we went on our second overseas assignment and it was perfectly liveable before. We, at that time, in our first three years we rewired it and added central heating which didn’t have when we moved in. (It) didn’t have central heating.

RESEARCHER: So, how did it work? Just with an open fire?

OWNER 1: With a few electric heaters, storage heaters, and it didn’t work. So we lived the first two years with... one wooden burning stove... and that was it.

RESEARCHER: Where you able to heat the whole house with this?

OWNER 1: No. No, no, no, no...

OWNER 1: We just wore jumpers. We didn’t have any... we had no heat upstairs, did we? The storage heaters never worked from day one. They were so old, they never worked. So that kept the kitchen warm and the main double living room there was a wood burning stove and that’s all we had for the first two years.

RESEARCHER: OK. I guess the bedrooms were a bit cold.

OWNER 1: Yep

RESEARCHER: But you were living well. You were quite happy with the house.

OWNER 1: Cold, it was cold. And even when we installed the central heating our oil bill was huge. We were £5000...

OWNER 2: And even then, it wasn’t that warm.

OWNER 1: It wasn't that warm. So, when we had central heating, because the insulation is so poor, even with the radiators on it wasn't that... It wasn't comfortable. You still sat on a jumper. It wasn't warm as this is (referring the new shed). Not even close.

RESEARCHER: So, the only big difference was the bills.

OWNER 1: Yes. Our oil bill was £5,000 a year for heating the house. The last year we lived here was £5,000 a year, and it was still cold.

RESEARCHER: Ok, that's a good reason

OWNER 1: Which is quite normal for most people, to say that.

RESEARCHER: But they can live with that and they decide to don't do anything. I guess...

OWNER 1: Yeah, I guess they don't. What we decided is quite a lot of money each year.

RESEARCHER: Ok. But, why did you choose to live in this type of traditional buildings?

OWNER 1: Because we always liked traditional buildings. Our last two properties we had have been a hundred years old buildings.

RESEARCHER: Rented or...

OWNER 1: Owned. This is the third property we own.

RESEARCHER: Also here in Aberdeenshire?

OWNER 1: No, the other two... We had one... Two flats in the west end of Aberdeen. So, there was a two bedroom flat, which we kept, we bought and we kept for about two years and sold it and we had a five bedrooms flat that we bought, restored and then sold. And then we moved here.

It's quite normal for people up here to buy their houses. People don't tend to rent for ages. A lot of people came out university and buy... Quite soon.

RESEARCHER: And then if they want to move the sell it and...

OWNER 1: They sell it, yeah. In Aberdeen, it's been always...

RESEARCHER: How was the house searching? Why did you decided by this specific house? Did you know the area?

OWNER 1: Yeah, we are both from around this area. So, I brought up in that village, eight miles that way and Maria brought up in that village six miles... Is that six miles that way?

OWNER 2: Yeah

OWNER 1: So, when we lived in Aberdeen we had Beth, she was two, and we decided we wanted to move back to the country. Because we had been in Aberdeen since University.

OWNER 2: We wanted to raise the children in the countryside.

OWNER 1: We wanted to raise the children in the countryside so we moved back to countryside.

OWNER 1: And then... We didn't look at many houses when we came to buy our main house.

OWNER 2: No, I look to one and I said we are buying this house.

OWNER 1: That was kind how it went. We tried to look at another one but it was so old, the day we phoned up to go to have a look at it... So, we didn't go to see it. We went to look at one farm cottage which it was really round on. But it was too small and when I was away, Maria came to look at this and we bought it.

RESEARCHER: So, you never thought about buying a piece of land and the build your own house.

OWNER 1: Yeah, we did actually. No, that was kind of our plan. Wasn't it?

OWNER 2: We considered buying a piece of land and trying to build and old looking house.

OWNER 1: But it would be a traditional looking house.

RESEARCHER: Ok

OWNER 1: So, yeah... we did. We kind of were looking for a plot of land or a big old house like this in this surrounding area which is so commutable to Aberdeen. And we always wanted the south of Aberdeen. Because we are from South of Aberdeen. So, yeah... but we did... There was one plot of land but we were never very sure... but there are not a lot of plots of land around here.

RESEARCHER: But, in any case, you were always interested in having a house with the appearance or looking like an old house.

OWNER 1: Yes! Correct.

RESEARCHER: So, You are not interested in modern architecture.

OWNER 1: No. We stayed in Norway in a brand new modern white box. But we didn't... It was very good for renting but we wouldn’t want to live in one forever.

OWNER 2: It was quite boring and bland... It was the same as everything in the street.

OWNER 1: No, we have to say we like the character of our house.

RESEARCHER: So, how would you describe the building? This building?

OWNER 1: This is a cross between a Georgian and a Victorian house built in 1843.

OWNER 1: A very old house period for the area. A lot of houses around here or Aberdeen are in general a hundred years old; the majority of the houses are 110 120 years old. This is 168 years old I think.

OWNER 1: So, It's old. It's an old manse. It was originally the manse which could belong to the minister with the three churches of Scotland. So that's why the features on the gates have got the churches features on them. The church was up there but it is now knock down.

RESEARCHER: So, I guess that this kind of historical features is something that you like.

OWNER 1: Yeah, usually when you buy an old house it's been a manse or a vicarage. It's usually quite a substantial house and it's usually been built quite well because it was for the vicar or the minister at the time and that person at that time was very, very important, sort of thing. Not important now, but in that time they were a very, very important person in the village. So the quality of the house was usually quite good. Which I guess it tells why the roof is leaking for the first time in 170 years, so... That's a...

I guess the other thing that attracted us was the large garden. So we almost got an acre of garden and there are nice-- interesting with bits here and bits there and it's flat. So, it's a good, it's a good sized garden compared with what you get when you but a new house. So, for us was quite important, to have a big garden. And the other thing that would be important for us, which we have always done, we always wanted a sunny garden. So we struggled to buy a house that was here, because the sun comes around that way so we get the sun in our garden from 10 in the morning till it sets. Whereas if we were in the other side of the road we wouldn't get that in our garden so we would probably only buy a house which we have done with our last two flats. But in this direction we get the sun in our garden all the time. And this house has...

RESEARCHER: Especially when you were living here, what were your favourite features or what were your favourite places to be in the house?

OWNER 1: What was our favourite place to be in the house? The conservatory before it was knocked down.

OWNER 2: Yeah... Living room!

OWNER 1: The living room. The kitchen was quite nice.

RESEARCHER: Any specific reason? Because of the atmosphere..?

OWNER 1: Warmth!

RESEARCHER: That's a good reason!

OWNER 2: I think the living room it's sunny and you can see the garden and we had a burning stove that was on all time.

RESEARCHER: Ok. So, I would like to know a bit about your way of live. How many days of work a week? What times? How much time do you spend in the house... if you are going out during weekends...

OWNER 1: I work five days a week. Maria doesn't work at the moment

OWNER 2: Yeah, I just stay at the house most of the time.

OWNER 1: You are at the house most of the day, basically whereas I am away for at least ten hours a day if not longer. And... Weekends we spend... probably a lot of time at the house. We do go away for the weekend away let's say Edinburgh, Glasgow that kind of things we do or hiring a log cab wherever or hiring a cottage somewhere... usually old! But we do spend a fair amount of time here. But we spend a lot of time in the garden as well as in the...

RESEARCHER: Even during winter?

OWNER 1: Yeah. We put around some stoves and get some pieces outside.

RESEARCHER: That's great. How do like to feel at home in terms of temperature? Are you OK living in a house where you need to wear a jumper?

OWNER 1: So, Maria doesn't mind wearing a jumper. She is quite happy doing that but she likes to be really warm. I like sitting around as you can see. In my T-shirt and I don't want to wear a jumper. When you leave I will put my pyjama bottoms on.. and not any socks. So, I like-- but not that I like a roasting house but I don’t want to have to wear a jumper

RESEARCHER: Ok. Do you need to wear a jumper with 18 degrees?

OWNER 2: Yes! I would need to wear my socks on

OWNER 1: Whereas I probably wouldn't. I don't know. We don't need the house to be roasting and certainly our bedrooms are never hot.

OWNER 2: I would prefer to have-- In the wintertime I always have my socks on and big jumper

OWNER 1: But if it is cold, we light the fire over putting the central heating on. So, I'd rather spend five minutes lighting the wood burning stove that I would switch the central heating on kind of thing... And I like wearing a T-shirts but it doesn't need to be roasting home for to do that.

RESEARCHER: I guess your case is a bit different in terms of why you decided to refurbish your house, because... mainly because of the...

OWNER 1: Mainly because of the woodworm.

OWNER 2: But that was something that we always discussed. It was something we had in the back of our mind thinking of maybe... because we used to hear rumblings at the back behind the plasterboard. Something was happening with the walls. But...

OWNER 1: Yeah, going away overseas gave us the option of to strip everything off and finding the woodworm and it was quite extensive woodworm that it was like that is going to be everywhere. So... let's just-- while we have the opportunity, let's just strip all back. If that hadn't be for that, the house would be still as it was. We would still put a new roof because we always knew that we needed a new roof. But-- and we would be still restoring the windows, but we would had never take the lath and plaster off. We would have just lived with trying to insulate under the floors and in the attic. Yeah, we would have done the minimal insulation, which we already have done the attic. But we would probably redone that when redoing the roof. But we would just tried to make it as warm as possible that way and we wouldn't have done all this extra insulation we are going to put into the wall

RESEARCHER: I understand that the main reason for refurbishing the house even when you install the central heating is to be more comfortable in the house , warmer...

OWNER 1: Yeah, yes. Convenience.

RESEARCHER: It is not form economic reasons, it is not for saving CO_2, it is mainly for being comfortable at home, right?

OWNER 1: Yeah. It wouldn't be for being environmentally friendly. We are doing it for be-- save money and be comfortable. And save money because this is our— hopefully, our forever home. So we spend a lot of money just now, that £5000 oil bill will hopefully be a £1000 per year bill of some other sort and the money we spent out we cut over the next…

RESEARCHER: You are not trying to make a profit but you don't mind to invest money in a place...

OWNER 1: Don't mind to invest money to make it warm and comfortable and in the long run it should save us money.

RESEARCHER: So you are definitely not worried about the saleability of the house or the profit you can make with the house?

OWNER 2: No, no.

OWNER 1: No, but it's nice to think that we are increasing the value by doing what we are doing in case we ever need to sale it. So, I guess we keep a check on that but not with the notion of selling it, at all. We wouldn't have our main sight-- Our last property we had in the main sight of we were doing this that we will eventually move from it. Because we finished it in Christmas time and we moved the following April. So, that was done with the view that we don't want to stay here forever whereas this is done with the view that we will stay here forever.

RESEARCHER: Is there any difference in the way you are doing the refurbishment between these two properties? When you know or you want to sell the house afterwards and when you are trying to build your own house forever?

OWNER 1: We did quite high quality job in our last place because this is just the kind of thing I do. I don't really do cheap... I don't do corner cutting. I'd rather take a week longer doing this right than-- because then-- I look at the way we are going to live with it for the next 20 years, so-- if I scrimp on a material and put in 75 mm insulation instead of 100 mm maybe-- well I might save a little bit of money just now but for the long term is probably better to put on 100 mm and.... We will spend time getting it right so it makes our lives easier going forward in the future. For example, we put that shelves after the weekend and you could lie on those shelves. But I don't want the hassle of shelves coming of the wall in the next two years while we are doing the rest of the house and we have to redo the shelves on the wall. So, we spent a bit of time doing…

RESEARCHER: Doing it properly

OWNER 1: Yes, we probably spend more effort getting this right. We need to replace skirting boards and that will be done in hardwood, nothing is going to be done in MDF, for example.

RESEARCHER: That's a good example.

OWNER 1: Yes, that is a good example. Nothing will be MDF, at all. It will be proper wood.

RESEARCHER: So far, who has been involved in the project of the house? For the planning permission, for the stripping...

OWNER 1: We have got our proper architect and we had-- we had Maria's uncle and a couple of guys stripped most of the house and then I have stripped a lot of the house since we came back as well. So, we are probably 50/50 between hired labour and me. And then we have also a full time architect involved...

RESEARCHER: Since when is he involved?

OWNER 1: The architect has been involved with the last-- just for the planning permission bit. So the last three months with the architect something like that? Just to get the planning permission, because gaining planning permission in Stonehaven is notoriously bad. Very, very, very difficult. So... that's why we took an architect on board rather than trying to do ourselves.

RESEARCHER: Ok. So, are you saying that you are mainly hiring an architect because you need their expertise to go through the planning application?

OWNER 1: Well, we hired an architect to make sure thing were-- well, we have someone hired that we could make sure we could get through all the loopholes and everything like that. So, we have the expertise I guess. No, not loopholes, that is not the world I'm looking for... because this is a listed building, which makes things very hard... and to make any changes to a listed building, we are making quite a few changes in reality. Moving a kitchen from side of the house to other side of the house, you need planning permission for doing it in a listed building.

RESEARCHER: Did you know beforehand that you want to move the kitchen from side to the other?

OWNER 1: Yes.

RESEARCHER: She is just helping with administrative and technical--

OWNER 1: Yeah. Well, no, no. They are also doing a full set of plans and they are doing all the plans for the insulation, they are doing all the plans for the framing, the wiring, the plumbing... So, all of that-- So at the end of the day we are not only just getting plan permission. We are going to get planning permission, we get listed building consent, and we get full plans to give out to a-- if we want it to give out to someone, to a team of joiners or builders, to say here it is a set of plans give us a quote for. To get a quote against the plans set and we also get a building warrant as well. So, she is doing all the paperwork and a lot of drawings for us. We haven't discussed yet in terms of how much insulation we will put in. In theory that is included in all the stuff we are getting back

RESEARCHER: I guess you told the architect all the-- what you are planning to do with the house, the idea of conservation and the...

OWNER 1: Yes, yes. She knows that we want every previous feature to go back and we have to take that into account and she knows that we want to move rooms and change things about and what types of slates we want to try to use.

RESEARCHER: Did you change any previous idea since she is involved in the--

OWNER 1: We did... Originally, when we contacted her we were going to try to change the attic into a third floor

OWNER 2: Oh yes. She persuaded us to...

OWNER 1: Yeah. She kind of persuade us to not to on-- We don't really have enough height in the roof to do it and if we want to do it we'll be trying to change the roof pitch and take the whole roof off and new timbers and everything and it would be very unlikely that planning people will give us permission for that because you are changing the outside structure. You are not adding a little extension you are completely changing the roof and she said it would be expensive and to get a staircase to match your lower staircase would be very difficult in terms of the high and the distribution and might look a bit odd.

OWNER 2: And fire regulations as well.

OWNER 1: And fire regulations. We worked around the fire regulation and that wasn't too bad but... So, when we went originally we were trying to put two rooms or three rooms at the top, but we decided not to. So, her telling us how hard it would be and the cost that we would have to add to the build would be extra-- a lot, so..

RESEARCHER: Even if you pass the approval from the planning office, it could be a massive work.

OWNER 1: Yeah. I mean it would have added a lot of cost already in an expensive build so... I can't remember if she gave us any numbers... We had some quotes before... I can't remember what the numbers were... but something like an extra 40 or 50 thousand pounds to the attic. So, when we are looking at spend maybe... somewhere between a 120 and a 150 thousand just to do the house, adding another 50 was a fair…

RESEARCHER: Another 30%

OWNER 1: Yeah, another 30% on top of what we are already doing and... We tough we would just leave it.

RESEARCHER: How did you choose the architect? Or how do you find her?

OWNER 1: We actually, about 5 ago, got plans up for a new conservatory and everything like that and we used to have her when she was a new business- when she was very cheap, but she was very good and we never submitted those plans to get planning permission. But she was good, easy to work with. So, when we decided to do this time we just phone her and said, “Can you do this again” and then she said, “Do you know that my fees have going up exceptionally?” But she has got us the planning permission so at the end of the day she is doing a good job. That-- you don't really know any architect I guess as one thing; because this is an oil industry area, there is not a lot of architects. She is always quite professional and stuff and-- compared to-- our friends at Laurencekirk they are now doing an extension at their side. Their architect is being a disaster, he has got all the drawings wrong, the widths of the walls were wrong, the door widths were wrong, the builders had to knock down the wall and build up new walls. And I sent the stuff to our friends that our architect has given to us, we are doing this, this and this and our friends just sitting in going we never got anything like this, we just got a quote. While we just got all the stuff with the architectural foundation in Scotland whatever, contracts, and this and that will be done and this is the individual cost of each stage. She is very professional. So we just talk with her, so-- and she is close, she is in Stonehaven and she is used to deal with Stonehaven planning permission. So, we probably could get an architect who was in Brechin or Forfar but they wouldn't be-- because is a different-- Angus they are used to deal with-- they are not used to deal with Stonehaven. We also wanted someone that was used to deal with Stonehaven planning department and her office-- she is based in Stonehaven and the planning is in Stonehaven, so..

RESEARCHER: How did you explain to her what you were trying to achieve with this refurbishment?

OWNER 1: Basically we said we want a lot warmer house but we want to keep all the original features. We have stripped the whole inside of the house already to which she said you might get find you shouldn't done that but what you've done what you've done and basically we said we want to Kingspan insulate all the outside walls, insulate between the inside walls, and we want to put back all the period features and we want you to take care of all the planning permission issues

RESEARCHER: Does she say-- Does she give you any other advice in terms of energy efficiency of the house?

OWNER 1: Yeah, she said she would stay away from any new technology. So, that stuff that our friends are using, she said she would not touch it until it is not tested for rot for long enough and she said Kingspan is the best way to go, or Kingspan equivalent. It is basic to go for these types of houses for what we are trying to achieve and she advise us to get structural surveyor around to structure the whole place so we did that and get timber specialist which we did that. We already had the house all sprayed for wood worm and stuff like that and we are going to do it again now that we can get a better access to make sure we can put the-- preserve the timber in the old house. Because...

RESEARCHER: This is not going to happen anymore.

OWNER 1: Yes, before when we did it, all the lath was still on. The plaster was off but the lath was on, so the access was good but not brilliant so now that all the lath is off we are going to paint on all the stuff again and do it again. Because the bits that we found-- I found they haven't managed to spray around so-- or unlikely to spray. Our main concern at that time was we have done so much work already that is going to cause us a problem to getting planning permission to do what we want to do. So... I guess because we look into her before she-- she is kind of just taking care of the process in reality I guess.

OWNER 2: Yes.

OWNER 1: And making sure that we have all the right pieces of paper so we don't get in a trouble. But I think, for how thick the insulation-- that goes in with the building warrant plans once you go for the building warrant. So for getting the planning permission thickness of insulation or anything doesn't matter but the building warrant we will have to have the detail plans. I think we maybe said we want as warm as a modern house standards if not better if we can. But more likely to come down to how much room space you want to lose, I think that could be the reality. But I think is going to be better that what we had.

RESEARCHER: Maybe, if you don't mind we could have a walk around the house so you can explain to me the specific measures that you'll be applying. Are you concerned about any potential consequences of applying-- well you said about this modern technique of filling the cavity...

OWNER 1: Yeah, no. One of the things that I wanted to do is going with rigid insulation like Kingspan. It is a fact that we can still leave that traditional 25-300 mm air gap between the brick and the insulation, and that-- I want to leave that because that means that I am not in a different position with my house than we were before we did any work, so we shouldn't get any damage to the brick work. Because I don't want to-- I don't want the lime start deteriorating or anything like that and...

RESEARCHER: So, I guess you are happy reading about this type of houses and how to refurbish...

OWNER 1: I've got a lovely book, I found it the other day (...) House insulation manual and it's got a whole section on old houses as well I've also got books-- I have been reading and scan over the last couple of years which are all about insulating old houses, how to restore old houses, what not to do. And we get all the period living and period homes and home building renovation self-built... So I get about four magazines, five magazines per month, all on houses

RESEARCHER: Even before deciding--

OWNER 1: Oh, I have been buying them for-- Ten years?

OWNER 2: We have a little bit odd compulsive disorder with magazines.

OWNER 1: But generally I buy the house magazines and read all the stuff in them. And look at what people eventually did and stuff like that, see where we agree-- but it is not too difficult, when you are an engineer as a trade and your degree is engineering and you are used to deal with kind- a building stuff it's pretty straight forward, so...

RESEARCHER: You told me that because it is a listed building class C you need to keep all the external and internal appearance of the building.

OWNER 1: That is right, yes. That's what they would like and that's what we want to do.

RESEARCHER: Exactly, even before you knew that you had to preserve all the internal appearance of the house you were--

OWNER 1: We were always going to reinstate all the cornicing, original wooden doors, original skirting and surrounds. The house came with no-- it came with one or two fire surrounds that maybe original but the rest not, they are reproductions. 10 years old horrible things so we will go sourcing, reproducing—well, we'll go sourcing all products from all the salvage yards in probably Glasgow, Edinburgh and Aberdeen the main ones and go pick fire places to super keeping with the house. So we've got a lot of extent to make sure the period features are back in and suitable period features. We won't put any period features in from a 1930 or something like that, it all will be older to suit with the house that we've got.

RESEARCHER: I guess, I was just wondering, why do you like so much these traditional houses and all these traditional--

OWNER 1: Just because of the charm and the warmth that gives you when you finally have all finished. so, we have done our last flat-- It had period features and I think that are quite nice to look at and I think...

RESEARCHER: It's like you said, the house you were living in Norway it was really comfortable but it is not the place that you want to live.

OWNER 1: No, no, no. And-- I like-- I didn't mind my house before we stripped it, the fact is it was kind of falling down it's a bit rustic and rough and ready and... But even when you look at-- You might know the company, When I look at doing new build, a house, my idea-- one of the builds I quite like to do is company Hebridean Homes which I don't know if you have seen them or not but they are based on the Isle of Skye but they do replica of old fisherman cottages, these white cottages? Well, from the front they look like an old cottage in inside you can have either look old or modern, but generally the back of them they make great big sliding patio doors which I quite like it as well but you have got the old feature in old shapes and it's old proportions are done to the same as all the fisherman cottages that would have been in the past and they are quite nice and desirable. I guess as well to some people. No, we just always liked the period features houses, aren't we?

OWNER 2: Yeah.

OWNER 1: We used to go wondering around in the streets when we stayed in Aberdeen, because we stayed in the posh part of Aberdeen-- we used to wonder around Christmas time when everybody is with the curtains open, with all that heat lost, and the lights on, and we went looking... Whoa, it's really fancy cornicing, or that's quite a really nice interior, didn't we? So, I guess we just like old period.

RESEARCHER: Ok. Because this is kind of a different case, can you tell me a bit about how was the process when you discover all these woodworm in the timber and how you moved here and how you build this extension...

OWNER 1: Ok

RESEARCHER: And how you are planning the works over the next years. Because I think you told me that you are not hiring a full team.

OWNER 1: So, we were moving overseas again, so we thought we were actually moving all the furniture out of the house and storage it or in a container to go overseas. As we were taking the grand piano through the ground floor, the whole floor collapsed so we then cut the floorboards and we realised there was a big pile of sawdust. I can give you a fantastic photo of this. And at that point we decided we are going to strip the house so we decided then-- so we were going away the following week to go overseas, so at that point we said, right, we will take all the plaster off, leave the lath on, leave the cornicing on. At that point and time and then we are going to get it sprayed and the we will just put insulated plasterboard on top of the lath and the frame and all be there and everything like that be nice and easy, but.. So we had all the plaster stripped and while we were stripping all the plaster most of the cornicing felt off, so... we just decided to take all the cornicing off because at the end of the day it was quite loose. So, that left us with all the lath on and no floor because the whole was taken out. So, we then had a team to woodworm spray and fix a few joist for wet rot, the whole house sprayed for the woodworm.

OWNER 2: We got a damp course.

OWNER 1: We got damp course put around the utility room, but it doesn't look that it has worked, and then-- we went away for a year and then we decided to come back. Came back to the house, the house had been sprayed for the woodworm, house is empty and I just started looking at all the lath and it was crumbling in my hands so about a good 50-60% of it was completely rotten. So, we then decided that there is no point in keeping all this lath on and we take all the lath off as well. So we stripped the whole house off, all the lath and basically what we found is all the main timber didn't have that much woodworm, very, very, very little. The lath is taken because is a softer wood, it's taken all the woodworm damage. So, at that point we then rebuilt the whole floor because it was a bit awkward to have down the whole floor. And because we came home and we wanted-- expected to come home for three or four years we decided that we needed somewhere to live, so we could rent somewhere which it was quiet expensive and we wanted to be on site because we've got a nice garden and its quite nice being here and we can work in the house while the kids are here so it's quite convenient. So, we-- in a twelve week period we turn the garage into a two bedroom cottage with a living room-kitchen-dining room at the front, bedroom in the middle, shower and toilet, and a bedroom in the back, which we have lived in for about... 8 months and then we decided that it wasn't enough room for two children. We again looked to rent in somewhere but we keep thinking that this is too expensive and it is going to be too much hassle and double bills for everything so I decided to be a good idea to buy a big shed and basically we bought this big shed, 26 foot by 12 foot, to put the living room and the kitchen in. And now we have almost-- but we are not quite finished working here but we have almost three bedrooms in the garage and we got a living room and a kitchen. And one of the other reasons for doing this shed is well, it is an experiment with the Kingspan, to see how warm and cosy would be. So, this shed is a Kingspan box with 50 mil Kingspan- a lot of money doing this- 50 mil Kingspan in the floor, 50 mil Kingspan in the roof 25 mil Kingspan in the walls, just all well fitted, and then normal plasterboard on top and the seal up all the gaps as well. Around the edges, and-- just making sure there is no draughts. And painting and put the kitchen and stuff like that as you can see it today.

OWNER 2: It's incredibly warm

OWNER 1: It's incredibly warm even with… we haven't really needed the heater recently, until the last week or so, but with the heater, little tiny heater here at the moment this place is like a sauna.

RESEARCHER: And this is somehow what you would like to have in the big house.

OWNER 1: Yes. We ended having this big heater off. But we actually have, coming Thursday or Friday, whatever day it is, a wood burning stove for in here, which is going in that wall over there. So, because actually this, the electricity bills are large with this oil heaters, so I will get a big pile of wood. So we are going to have a wood burning stove coming in for here, because we've got a wood burning stove through there as well. But, in the garage is freezing, because in the garage-- we framed the whole thing in the garage and I only used cheaper polystyrene insulation 25 mil thick and we didn't seal all the draughts properly and...

OWNER 2: It's uncomfortable

OWNER 1: It's cold. Uncomfortable cold unless the burning stove is on, which only really heats the old living room, which now will be our bedroom. And it doesn't heat all the way through because the draughts take away the heat. So we'll probably spend a bit of extra time trying to seal up all the holes in that before the winter comes.

RESEARCHER: So, I guess you've experienced in your own lives the difference between--

OWNER 1: So we got-- The difference between how good Kingspan is compared to how good 25 mil polystyrene is, which is not fitted very well either. So, this is substantially better.

RESEARCHER: And what are you planning to do with the shed?

OWNER 1: Well, that is the other advantage of having a shed is-- the shed is basically-- once we are back in the house we'll strip all the plasterboard off and we'll move the shed in to the other corner of the garden, because we've got a big garden and this will be used as a normal garden shed. I wouldn't mind to reuse the Kingspan, or maybe use it in the house. Depending how swap overtime is gone. So, the thought was, because we spent £10,000 building the shed, for doing everything, all the electrics, all the plumbing, cooker guys come on Thursday morning to fit the cooker, all the plasterboard, all the Kingspan... and at least we spent £10,000, but £3,000 of that was the shed. The chances are we would have bought another shed, a big shed for the garden in the future, so it is not a waste of money. We have gain two rooms for the next couple of years for a fraction-- because the price renting around here for the size of house we need is £36,000 for 3 years, so in reality we have spent 10 which 3 of it we still get to use as a garden shed in the future. And the fact that-- the main reason-- other push for doing this is because we still always on site and we have always the use of the garden and the kids can walk to school, and we have our house and doing all the work as we go forward. So, it's been a good success doing a shed. I wish I'd have done the garage with Kingspan and high quality as we did this and make sure all the gaps are done up and everything like that.

RESEARCHER: So, when you say that you are planning works in the big house for the next two years, how are you planning to do that? Are you hiring people for specific work?

OWNER 1: For specific work, yes. So, if we go with the plan and we start everything next April, so... just getting the planning permission just now. We are planning to do stuff that doesn't get damaged-- between now and April we are planning to do things that don't get damaged when the roof is off. So, at the moment between now and April we are looking at repointing the whole inside of the house we are looking at stripping the 5% of the house that still needs strip and some plaster take off, the utility room walls, there is a tiny bit of lath-- we have got a lot of tidy at the moment, you´ll see. So, that's the jobs that don't cost too much money that basically me and another guy we'll do at some point between now and April next year and trying to get all stone inside the house... in a period as well we might start restoring the sash and case windows because it doesn't cost too much money at the moment and...

OWNER 2: Although we are considering taking them out. That is what the planning permission lady told us.

OWNER 1: Oh yes, there is an option we take the windows out and get replicas made which is cheaper rather than restoring which we thought is quite odd.. I don't know, our windows are in good condition, I'd be a shame that...

OWNER 2: Yes, but just looking at the finish that might be better.

OWNER 1: Yeah, that's in discussion-- but that is one of things we will be doing between now and April. The reason we have to wait until April is we don't really want to do our roof coming winter. So, hence it's...

So, that take as through till next April .

(Owner 1 receives a phone call)

OWNER 1: Sorry about that

RESEARCHER: No problem. I think we are actually done here, so if you don't mind we could have a walk around the house and you can explain in more detail.

OWNER 1: Yes, so the building works. So we will be trying to do some stuff inside between now and April. April next year take the roof off, do the roof and then after that we start framing up and... Basically the roof... the roof and the chimneys and harl it´s getting done by someone else and then the windows and the interior will be done by me and Maria's uncle and people like that coming to work.

RESEARCHER: Is it something that you are not trying to finish fast, that you are almost enjoying?

OWNER 1: Nooo, well it would be nice to finish it fast.

OWNER 2: I don't know if we are enjoying it

OWNER 1: I´m not enjoying it anymore but... It would be nice to get a team and do the whole lot but then we would spend an absolutely amount...

So, shall we go to have a look around?

RESEARCHER: Yes.

OWNER 1: So, what would you like to know?

RESEARCHER: Are you planning to apply insulation in all the external walls?

OWNER 1: Yes, so all these external walls. So for example here, here, here behind here that external wall same for the back... more than likely Kingspan, I think it's meant to be the best so... But basically the same width, so very sturdy frame and leave an air gap put the Kingspan in whatever depth we decide on and then put the normal plasterboard on top and we might... we might actually put a skin over the top of the plasterboard to be honest rather than taping it.. I´m not too sure. In the roof up here we will fill this with insulation as well

RESEARCHER: Even in the intermediate floor?

OWNER 1: Yes. Because originally they had insulation in it because they had-- which is like ground powder stuff-- which can I said is like a semi concrete type of thing, and that was in there. So we will put that between-- Probably just use normal glass wall insulation between each of them and don't think we will go to the extent of Kingspan. Under the floors I'm planning to go to the extent of Kingspan and put that between the beams to stop the draught which is coming up.

RESEARCHER: Any membrane or damp course?

OWNER 1: We might put down a damp course on the floor and cover the sand but it will be very difficult to do. It is only that much... So it is quite hard because the cold air comes in the front of the house and it comes up. I think that's where we lose a lot of heat in this house before. So I think insulation under the floor is going to make quite a big difference .

RESEARCHER: Are those the modern windows you told me about?

OWNER 1: No, that's the modern one. These are an add-on in 1929. So these are going to-- All these windows are going to have conservation double glazing. Every window, that one, that one

RESEARCHER: Really? in these big window, you can put the double glazing

OWNER 1: Yes, that's what they have just done up in-- I think it's been done in Edinburgh. They have a big window in Edinburgh.

RESEARCHER: I think I've only seen small six pane windows

OWNER 1: Well, in Fasque they have done that, because this is what the planning lady told us. Their windows are bigger than that. Yeah, because it is a bigger house. So, their roof should be like 15-20 feet ceilings high, and-- The one in Edinburg I thought it was like that as well. Because they did big window in Edinburgh in the Historic Scotland building. A temporary thing to try and then they changed back to the original glass. There is picture of it.

RESEARCHER: I don't know why I always thought about this six pane windows

OWNER 1: Even between these we are planning to put some form of insulation. Maybe like ah-- What's called? Rockwool type thing in between there. Again we are going to insulate all these floors.

RESEARCHER: So, you are insulating almost each room as an individual space in order to only need to heat the room that you are actually using

OWNER 1: Yeah. That's the plan. Since there is no air coming up here at all because this is straight until the floor boards, you don't have to worry about any damp. Yeah, and the same thing will happen in here and the same thing with the double glazing in the windows and I don't know what we are going to do through there but we´ll probably frame all that up through there and insulate it well.

RESEARCHER: We have been talking about this cavity thing as a measure that you will not apply because you are not confident. Is there any other measure that you have read about and you--

OWNER 1: Well, the cavity stuff. I would consider trying the cavity stuff on an area that doesn't need to breathe. I have thought about that like for example under the floor. Because then it still the wood to breath. Because if you install that cavity stuff in between the beams of the floor, or for example in there (internal walls) it wouldn't matter because it doesn´t need to breath. If you install it in here it wouldn't matter either. And, for example if you install it under the floor and you only put it in the depth of the beams the air still comes underneath so... I would be tempted to try, I don't know. My architect, she wasn't keen on, needs to be tried and tested, you don't want to mess this up. So, but definitely I won't put this against the brick wall.

RESEARCHER: I just remembered, about the windows. You are not sure yet, you haven't decided yet if restore it or replace it.

OWNER 1: Maria thinks that might be better. The planning officer says you could look at replacing it with replicas and then-- we hadn't thought that. Maria is quite keen on that, but I would rather restore them because you always get better original detail with restored ones and our windows are not in bad condition so we will be restoring them. I can guarantee you.

The only thing that would put us restoring them is if we don't have enough thickness on the wood to get the insulated double glazed but-- conservation double glazing in, then if the planning department let us have the architect-- I'm not sure how they call them. If they say that it would be slightly thicker, then I would consider doing new windows but I probably only get new windows and the frames I would just leave the frames where they are and reuse the frames. Because the majority of them it's only—it's very little—It's so much paint on it over the years, they stay in so good condition. We can only open one or two windows in this house.

RESEARCHER: We were talking about your skirting, you conserve all the--

OWNER 1: Yes. Better show you upstairs. Stairs, we are going to have the stairs staying, is the only thing is not rotten

RESEARCHER: So you have been quite lucky.

OWNER 1: Yes, yes. Because if you have a look here, most of these are good. But, yeah, here it was all the woodworm. The woodworm is in all the lath so we removed this, got rid of that and eh—that's the complicated bit because you are taking the walls outside slightly, so for example for us doing this outside wall it's quite easy to put 50, 100, 75 mm insulation. That's quite easy, that wall. This is a lot more difficult because of the window. So, there is not enough-- That is basically our air gap that you want-- So, there is not a lot of room. Is not that easy trying to put 50 or 75 or 100 mm in here, we might have, on these walls here, we might have to leave with less thickness. But if could get 50 mm on these walls, here with the windows I'd be quite happy, to be honest. It's a thing that is going to be a struggle to get, to get the thickness of insulation.

RESEARCHER: Otherwise you would have to rebuilt this framing.

OWNER 1: Yeah. Which is not the end of the world to be honest. I'd probably end doing that.

RESEARCHER: Are you keeping the shutters?

OWNER 1: Yes. We'll keep the shutters because is a great source for heat loss. They all need refurbish but we'll keep them at the end of the day.

RESEARCHER: You have really nice windows with all these timber features around.

OWNER 1: The only thing is they are a very, very thin to get insulated double glazing in it.

RESEARCHER: That might be a really hard wood to be so thin.

OWNER 1: It's hard wood. That's a good advantage that we have small panels' hard wood and-- But you need something like 11 mm which I think we are on the border. We are very much on the borderline. I mean these windows are 170 years old or 60 years old, so they have done...

RESEARCHER: Are those the original doors?

OWNER 1: All the original doors, all the original pieces.

RESEARCHER: Mouldings from the doors?

OWNER 1: Mouldings from the doors. Window frames.

RESEARCHER: So, the only thing you couldn't get was the cornicing. You have some samples.

OWNER 1: I have made 12 samples of that wall. Because downstairs cornicing is slightly different from upstairs

RESEARCHER: And you told me that you didn't know that the listed building required to preserve the interior, so you kept the cornicing because you already wanted to.

OWNER 1: That's correct, yes. Yes, yes, yes. Definitely we-- you can actually-- Nowadays there is a couple of places down in Edinburgh, the chances are they got them all or they got some very, very similar which we'll probably do. As long as is very similar that could be enough, but with the amount we are doing in here it makes sense to get our own mould and then copy. What we want with this house-- but the other thing, we've got the structural stuff on here, bits and pieces to put everything in place and because-- the worry is, these nails are holding it at the moment in all these joists but they are very old so what we are going to add those metal things like up there to hold all these connections to make sure it´s good. Give us that extra strength we've got to add the-- they call them which are a bit of wood-- Because you can see this wood is something very flimsy so we'd got to add above it like three inch by three inch block of wood to strength enough across. So, a lot of time consuming jobs like that. And the we are just going to insulate the floor and the loft and then leave the upper part of the loft that just be cold.

RESEARCHER: Just, one more question. Regarding these materials, do you have any preference for eco-friendly material or you just get some good materials that you can trust?

OWNER 1: In terms of normal insulation stuff, I'd quite like to use sheep wool but it is very, very expensive. And... in terms of 'econess', no particularly. More, I'd like to use sheep wool because it is easy to install and you don't have all these horrible fibre going out there and Maria is allergic to it, so she wouldn't help with installing it while sheep wool is quite friendly and it is easy to do. Kingspan is friendly and easy to do. No, I think we are-- environmental we'll be more making it air tight. Making it not lose-- CO_2 emissions making it minimum-- minimum fuel we have to use will give us the environmental bit and the money in our pocket I guess. But-- we are not going to reinstall an oil tank, we'll have no oil here, we are going to go with the wood pellets and burn the wood pellets and you can now get a wood pellet boiler attached to a log boiler that will burn the logs preferentially over the pellets but if the logs run out, it automatically starts with the pellets from a hopper in my garage. So, where my double bed is in my garage it's going to be a big five tons hopper and I'm going to feed the pellets underground into that utility room at the back and put the pellet burner in there with the log burner beside of it. I'm also going to link my mean wood burning stove downstairs into the boiler so all the time we would have the wood burning stove on, so we will be burning logs which are a lot cheaper than pellets and we will-- so when we are in the house we will always have the wood burning on and even through the summer we will probably put it on but then you also got the convenience of the pellet system that automatically kick in to keep open-- unlike a friend, who they have to feed everything manually. A lot, a lot of hard work. We-- pellets is just like ordering oil to me so-- we can see my wood supply down there.

RESEARCHER: That would be a really big heating system, it will cost quite a--

OWNER 1: Around £20,000.

RESEARCHER: But you are quite convinced about this system.

OWNER 1: We are going to be spending £5000 pounds a year in oil. So, whereas that amount of wood down there…

RESEARCHER: You are here off the gas network

OWNER 1: Yes, we don't have direct gas. We have to get a gas tank although the main gas line is about 200 metres that way, that connects the whole country, we don't have gas in the village, so we don't have an option for gas, you don't have to buy gas-- oil and gas is going to get more expensive going forward-- so as pellets but logs so far I have always saw it quite constant for years and years and years. Log prices are—they've gone up slightly recently but you can always get wood for a reasonable price. So, you buy 10 tons of wood for £220 and going pick up yourself and that's a lot of wood.

RESEARCHER: Have you thought of any other renewable system?

OWNER 1: I'd like to do the electric solar panels.

RESEARCHER: Photovoltaic?

OWNER 1: Yes. They wouldn't go on this roof because it wouldn't look right in the house but since we have no one behind us and we plan to put a big green house at the back of there eventually. So, where that big tree is, we are going to have a decent size greenhouse there and I'd like to either put the electric panels on the roof of the greenhouse or we have also another space in that field which is about two metres, put them on the ground in the field so basically they get the sun from about 11 o'clock in the morning all the way around until just now.

RESEARCHER: And you cannot almost see them.

OWNER 1: And we don't see them and is not as the heating hot water so you get heating loss coming back in the house it's just doing electricity so I would really-- It's one of the future projects that I'd quite like to do because you use-- I'd love to do. I'd love to do heating the water by digging my front garden and putting a heating coil in but it never generates what they say as this doesn't generate enough-- it's great for under floor heating but it's not strong enough to run even modern radiators and you need a lot of electricity pumped in to run the whole system so-- if we could can-- the cost of buying pellets and logs by having electric panels and having a very low electricity bill or anything at all that might be quite nice. That people, said us the day they put an electric solar panel in the roof of their shed and on their house but you don't see them from the front of the house so it's quite nice and my uncle in Edinburgh he has done it as well, he just sits and watches his metre. He did it when it was the 45 pens tariff and they did it when it was 25, 21 whatever it was, but now I think is down to 15 or something. So whether is worth nowadays I don't know but then we happen-- but with pellets system you get the grant, the fuel grant as well so that's quite-- You kind of offset the cost of installing it or almost. But—I'm really keen-- I really would like to be putting on the electric solar panels that would be a quite nice thing to do but yeah.. That's kind of a rough plan.

RESEARCHER: For the next--

OWNER 1: Yes, when we move back in here, what we will be going to do is getting back here as quicker is put an immersion boiler in, have all the radiators in place, all the plumbing in place-- but that stage we would be so desperate to get back in here we won't want to spend a lots of money putting pellets central heating system in a straight away so what we would do is well actually-- because we'll have wood burning stove everywhere. We won't be putting anything to heat the radiators we'll just put an immersion boiler that could run a shower and hot water for the sink and live with that for a few years because we will probably go back overseas. This is the other thing we have at the back of our minds, we will go back overseas so I don't want to spend money on technology like solar panels or wood pellets heating systems when if we go back overseas for 5, 6, 7, 8 years, 10 years the technology would move on greatly. So my thoughts-- our thoughts are come back in here, have everything in place but we'll just put in a big immersion boiler live with the extra expenses-- probably by the time we finish this place we will be overseas again. We might be overseas by august next year and do this remotely so that's our—that's why I don't buy a new car because we might go back overseas. I hate my old car, I normally have a brand new wagon or year old nice car and I have that and I'm car man so—It's because in the back of our minds is we could be away next august. So, that is sort of ours-- when we are looking at things to put in, we are looking at putting all the pipe work and all the electrics... actually the immersion boiler as much as the cost of the money to run is fantastic.

RESEARCHER: So I guess, at the end of the day the only thing that is attaching Maria and you to Aberdeen is this house.

OWNER 1: Yes. It's quite a call in why we-- because Norway wasn't working out for us, so that was in the back of my mind I have got a house to do when we go home so it's quite a nice thing come home a do and get done and everything like that so. That's one of the things we do, if we have to go away again next year, next august, we want have the roof done, we want have the repointing inside and out done, we want have the windows done and want to have the harl done and the chimneys done. So we have a structurally completely sound building and then we can pay people to come in and reframe it and put the insulation and stuff like that so that kind of our way-- we might not be here a while. It’s always possible and now that we have somewhere to live in outside we can still come back in holidays quite easy because we have somewhere to stay. There is a big-- six leaks on this roof when starts to rain so…

RESEARCHER: And you know that is going to be worst with time and you want to fix it so--

OWNER 1: There are more leaks every year and stuff like that so it’s only getting worst. If we are getting it solid in all ways and then-- to be honest the inside is quite easy, it’s not a lot of work. That is probably our rough plan of how we will insulate the house and trying to get back all the period features.

RESEARCHER: Great, I think we’ve finished actually. I’m going to stop recording.

OWNER 1: That’s all right.

APPENDIX 4 – MULTI-CASE STUDY: BRIEFING, INSTALLATION TEMPLATE & INTERVIEW SCRIPT.

PAGE 1 of 4

ROBERT GORDON
UNIVERSITY ABERDEEN
The Scott Sutherland School of Architecture & Built Environment
Robert Gordon University. Garthdee Rd
Aberdeen. AB10 7QB. United Kingdom

Briefing

Thank you for taking part in this study.

I am investigating the improvement of the energy efficiency in traditional buildings. As part of my research I am exploring the influence of users' behaviour in the energy demand for space heating. The project involves the installation of two data loggers in your home and a short interview. The loggers are used to measure the temperature and humidity inside your home. These devices are very small, are battery powered, produce no noise and they won't cause any damage to your property.

The main goal of the interview is to acquire some understanding of the heating and ventilation patterns in order to obtain a more robust analysis of the recorded data. I would like you to answer the questions you feel comfortable with and in as much depth as you decide. Of course, there are no right or wrong answers, as I am only interested in gather you personal perspective and experiences. With your consent, I would like to audio-record the interview for a later transcription and inclusion in my thesis. I would also like to take some pictures of the most relevant features of the house in order to illustrate the main topics addressed in this interview.

Unless you give permission to use your name, title, and/or quote in any publications that may result from this research, the information you tell me will be confidential.

Please be aware that you have the right to withdraw from this interview at any time without giving any further reason. As well, you have the right to withdraw from this study at a later date.

If you have any doubt, please do not hesitate to ask.

Daniel Herrera | DipArch, MSc
PhD Researcher
The Scott Sutherland School of Architecture and Built Environment
Robert Gordon University
Garthdee Road
ABERDEEN AB10 7QB
UK

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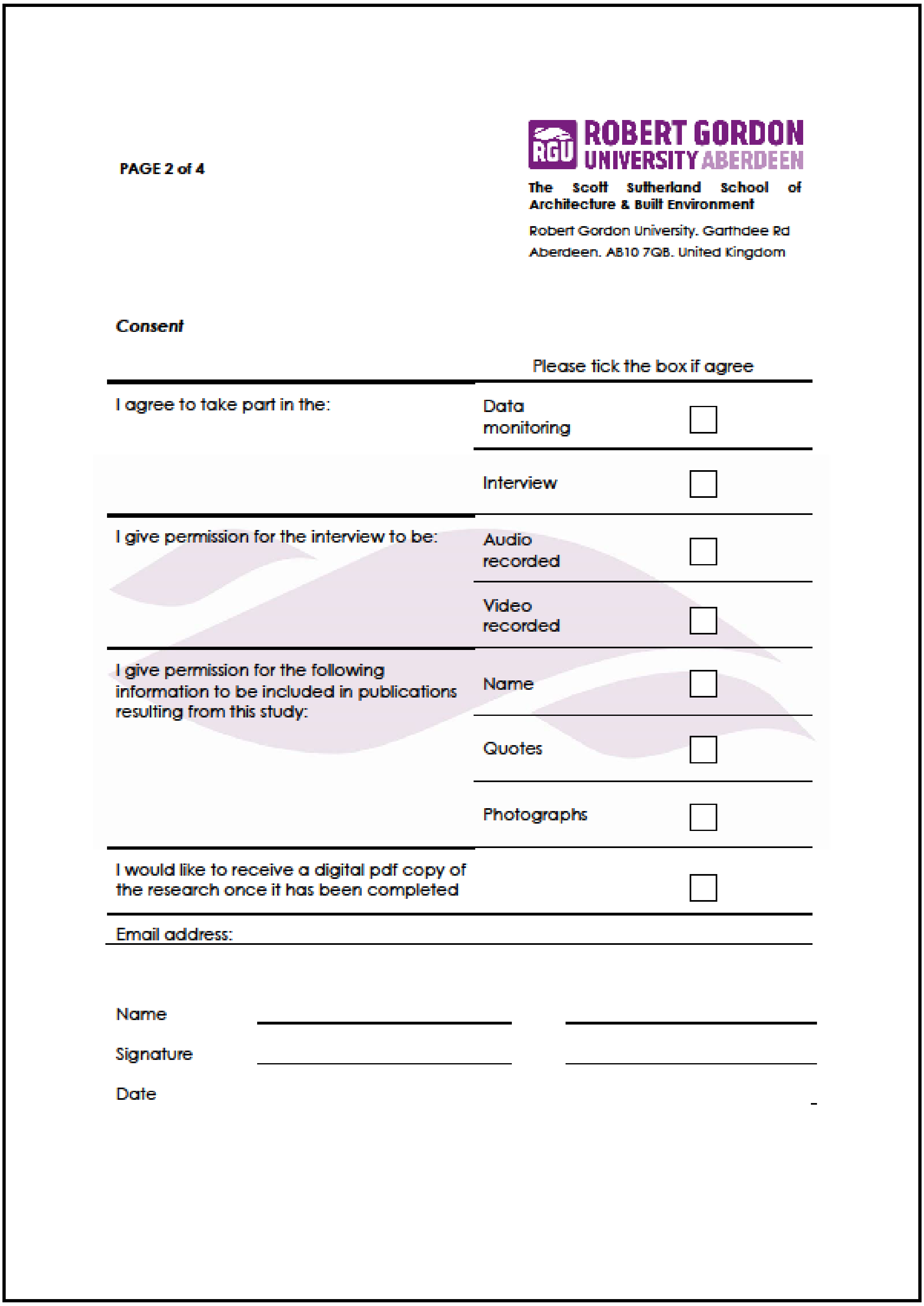
Email: d.herrera-gutierrez-avellanosa@rgu.ac.uk
Web: http://www.rgu.ac.uk/sss

Appendix 4



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ROBERT GORDON UNIVERSITY ABERDEEN
The Scott Sutherland School of Architecture & Built Environment
Robert Gordon University. Garthdee Rd
Aberdeen. AB10 7QB. United Kingdom

Consent

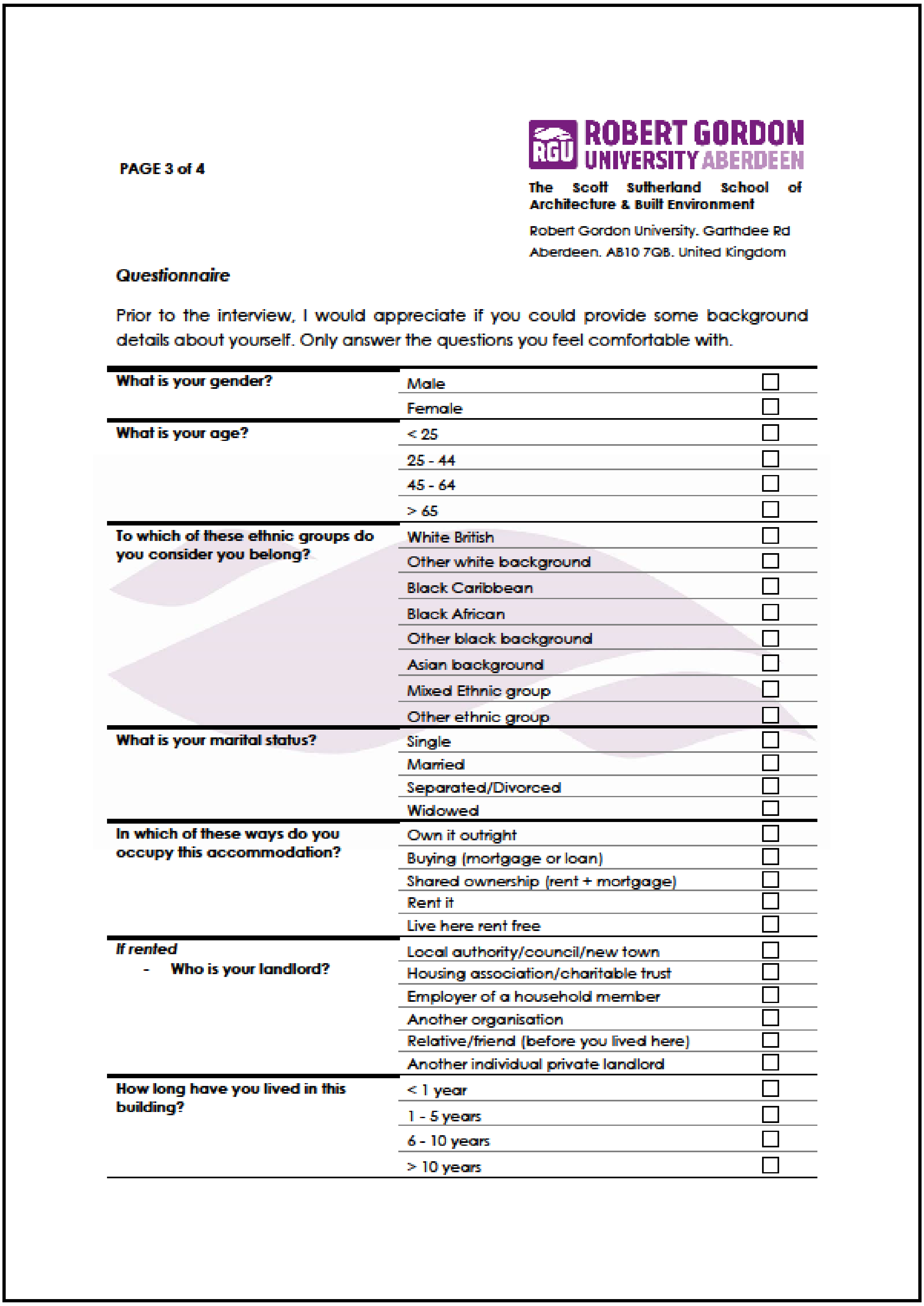
	Please tick the box if agree	
I agree to take part in the:	Data monitoring	☐
	Interview	☐
I give permission for the interview to be:	Audio recorded	☐
	Video recorded	☐
I give permission for the following information to be included in publications resulting from this study:	Name	☐
	Quotes	☐
	Photographs	☐
I would like to receive a digital pdf copy of the research once it has been completed		☐

Email address:

Name ________________ ________________

Signature ________________ ________________

Date



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ROBERT GORDON UNIVERSITY ABERDEEN

The Scott Sutherland School of Architecture & Built Environment

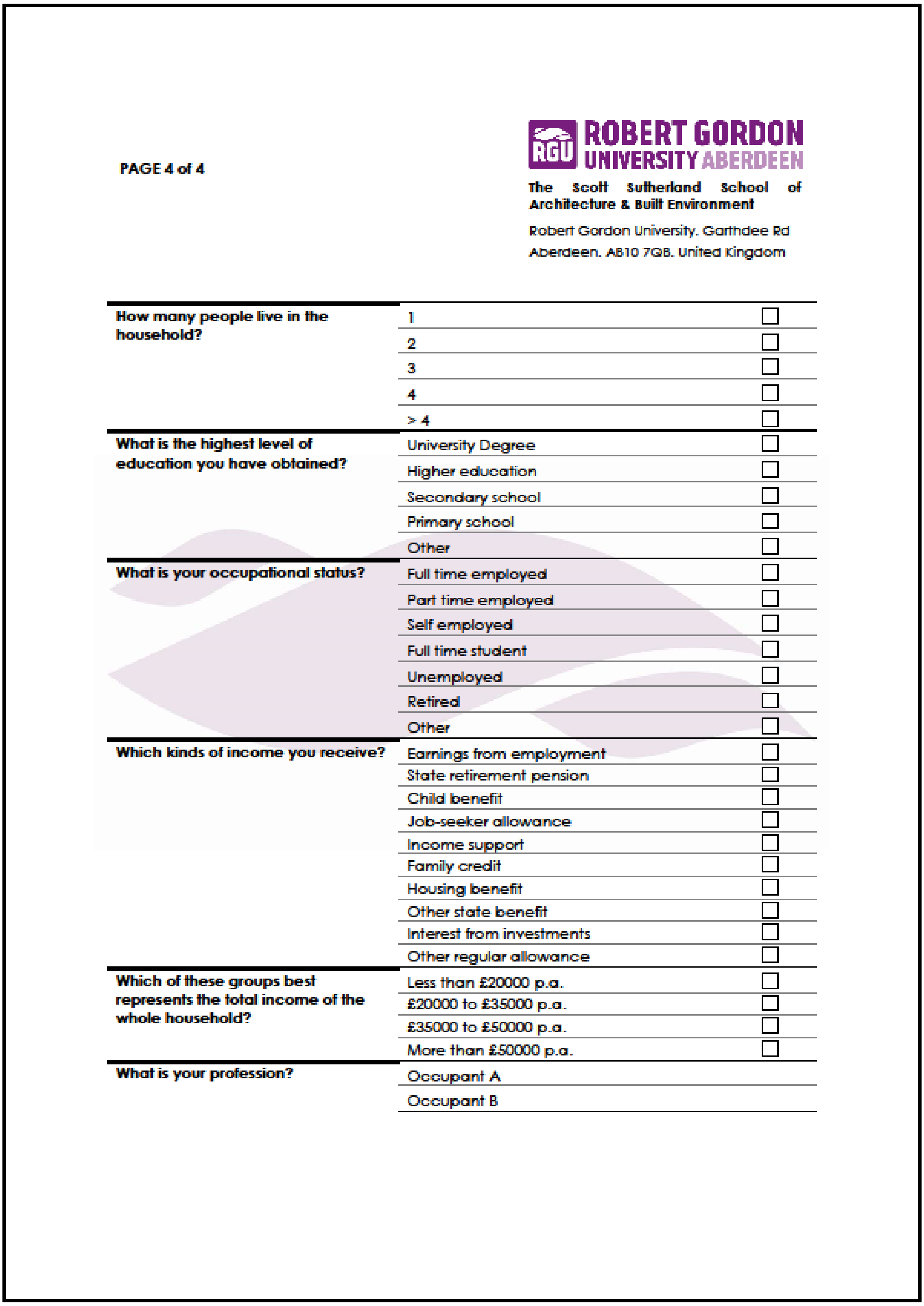
Robert Gordon University. Garthdee Rd
Aberdeen. AB10 7QB. United Kingdom

Questionnaire

Prior to the interview, I would appreciate if you could provide some background details about yourself. Only answer the questions you feel comfortable with.

What is your gender?	Male	☐
	Female	☐
What is your age?	< 25	☐
	25 - 44	☐
	45 - 64	☐
	> 65	☐
To which of these ethnic groups do you consider you belong?	White British	☐
	Other white background	☐
	Black Caribbean	☐
	Black African	☐
	Other black background	☐
	Asian background	☐
	Mixed Ethnic group	☐
	Other ethnic group	☐
What is your marital status?	Single	☐
	Married	☐
	Separated/Divorced	☐
	Widowed	☐
In which of these ways do you occupy this accommodation?	Own it outright	☐
	Buying (mortgage or loan)	☐
	Shared ownership (rent + mortgage)	☐
	Rent it	☐
	Live here rent free	☐
If rented - **Who is your landlord?**	Local authority/council/new town	☐
	Housing association/charitable trust	☐
	Employer of a household member	☐
	Another organisation	☐
	Relative/friend (before you lived here)	☐
	Another individual private landlord	☐
How long have you lived in this building?	< 1 year	☐
	1 - 5 years	☐
	6 - 10 years	☐
	> 10 years	☐

Appendix 4



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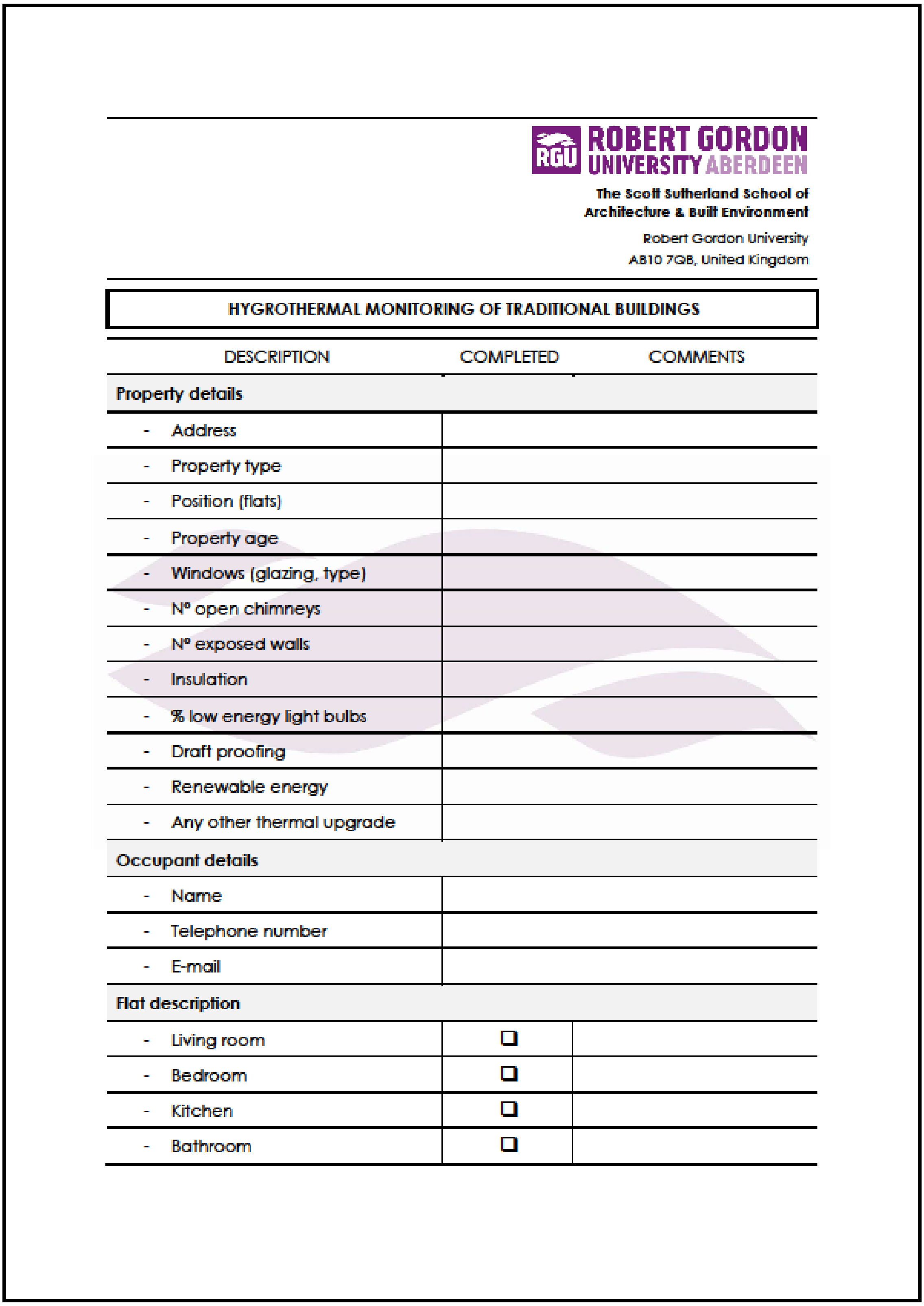
How many people live in the household?	1	☐
	2	☐
	3	☐
	4	☐
	> 4	☐
What is the highest level of education you have obtained?	University Degree	☐
	Higher education	☐
	Secondary school	☐
	Primary school	☐
	Other	☐
What is your occupational status?	Full time employed	☐
	Part time employed	☐
	Self employed	☐
	Full time student	☐
	Unemployed	☐
	Retired	☐
	Other	☐
Which kinds of income you receive?	Earnings from employment	☐
	State retirement pension	☐
	Child benefit	☐
	Job-seeker allowance	☐
	Income support	☐
	Family credit	☐
	Housing benefit	☐
	Other state benefit	☐
	Interest from investments	☐
	Other regular allowance	☐
Which of these groups best represents the total income of the whole household?	Less than £20000 p.a.	☐
	£20000 to £35000 p.a.	☐
	£35000 to £50000 p.a.	☐
	More than £50000 p.a.	☐
What is your profession?	Occupant A	
	Occupant B	



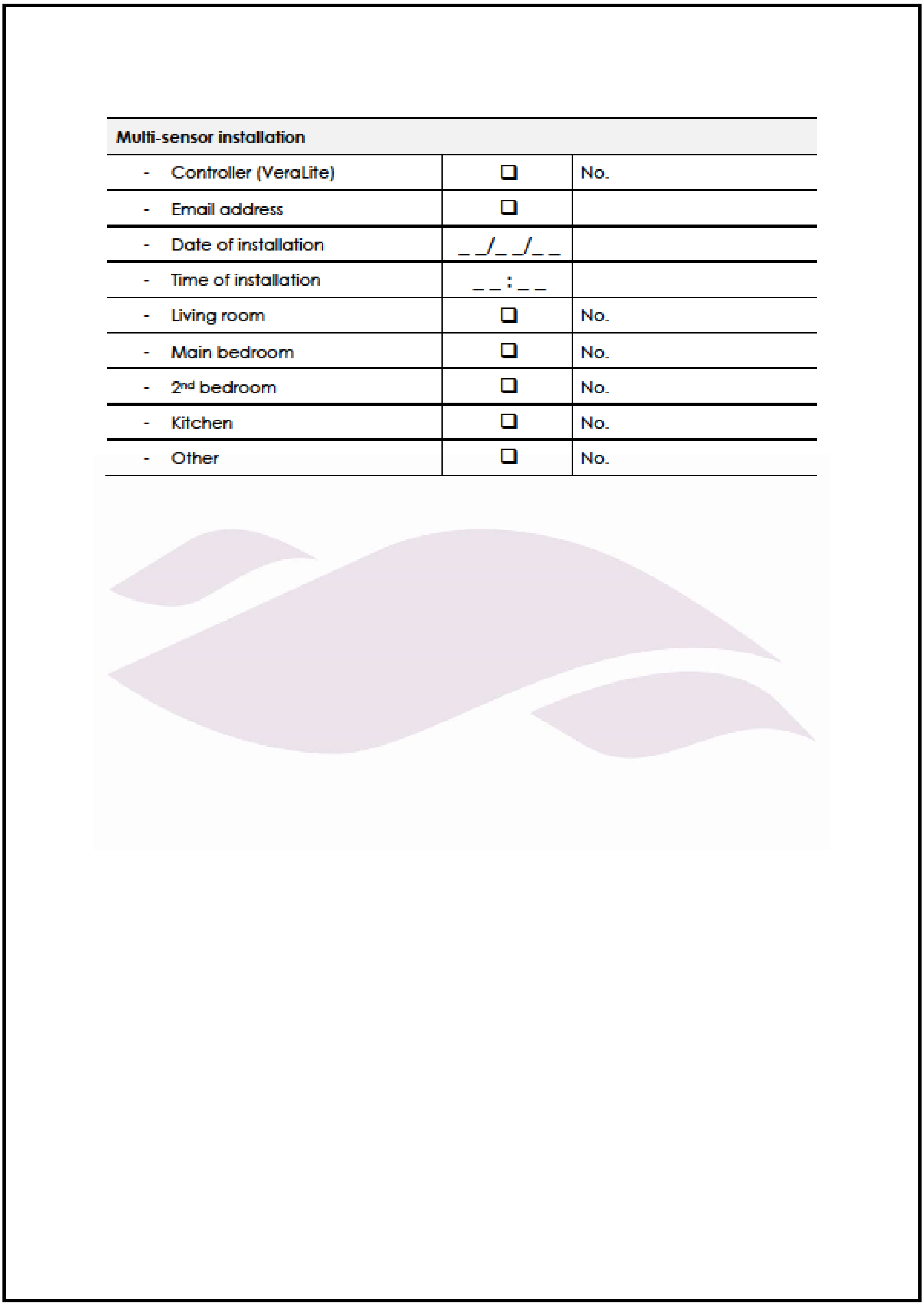
ROBERT GORDON UNIVERSITY ABERDEEN

The Scott Sutherland School of
Architecture & Built Environment

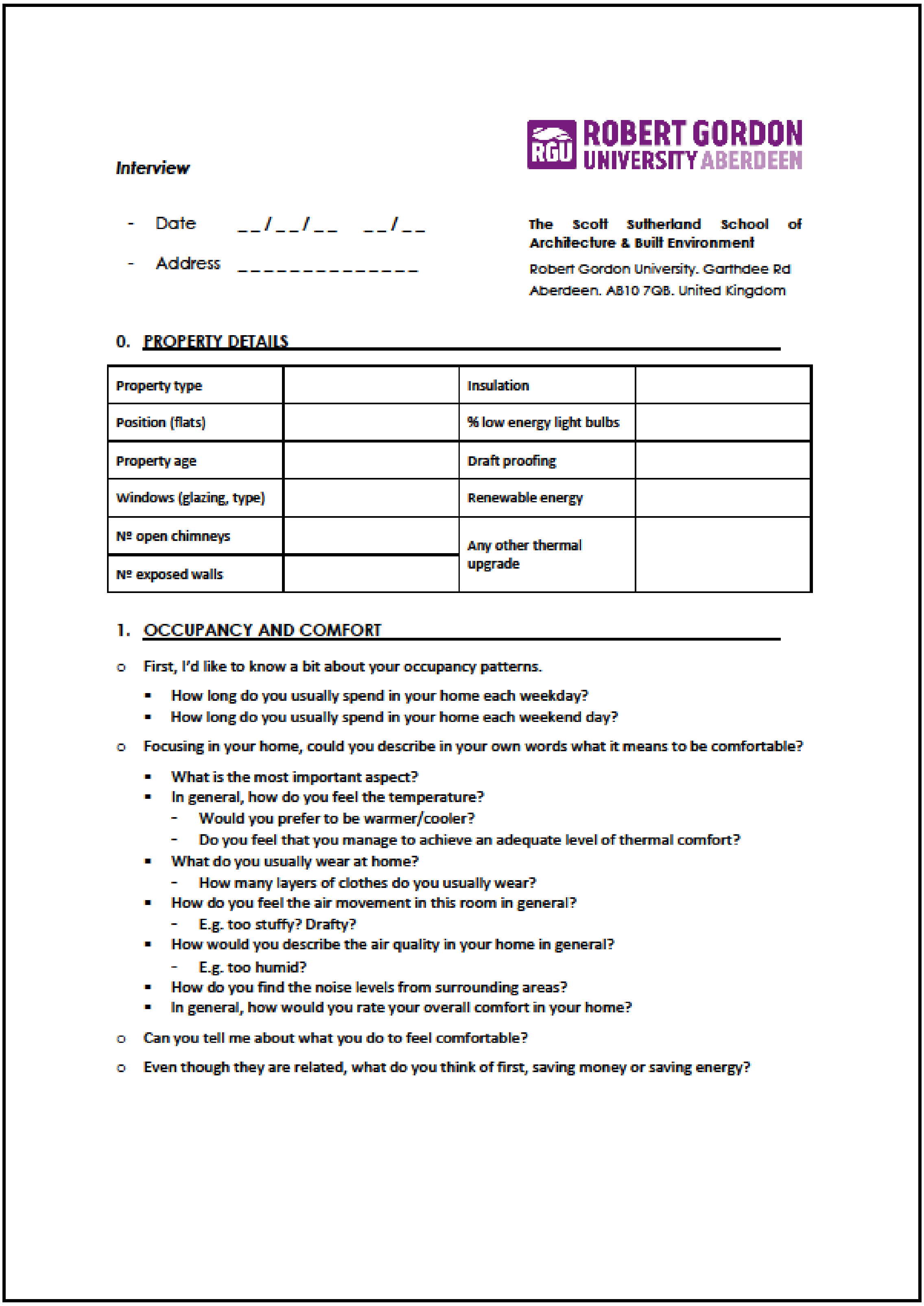
Robert Gordon University
AB10 7QB, United Kingdom

HYGROTHERMAL MONITORING OF TRADITIONAL BUILDINGS

DESCRIPTION	COMPLETED	COMMENTS
Property details		
- Address		
- Property type		
- Position (flats)		
- Property age		
- Windows (glazing, type)		
- Nº open chimneys		
- Nº exposed walls		
- Insulation		
- % low energy light bulbs		
- Draft proofing		
- Renewable energy		
- Any other thermal upgrade		
Occupant details		
- Name		
- Telephone number		
- E-mail		
Flat description		
- Living room	☐	
- Bedroom	☐	
- Kitchen	☐	
- Bathroom	☐	



Multi-sensor installation		
- Controller (VeraLite)	☐	No.
- Email address	☐	
- Date of installation	_ _/_ _/_ _	
- Time of installation	_ _ : _ _	
- Living room	☐	No.
- Main bedroom	☐	No.
- 2nd bedroom	☐	No.
- Kitchen	☐	No.
- Other	☐	No.



ROBERT GORDON UNIVERSITY ABERDEEN

Interview

- Date __/__/__ __/__
- Address ______________

The Scott Sutherland School of Architecture & Built Environment

Robert Gordon University. Garthdee Rd
Aberdeen. AB10 7QB. United Kingdom

0. PROPERTY DETAILS

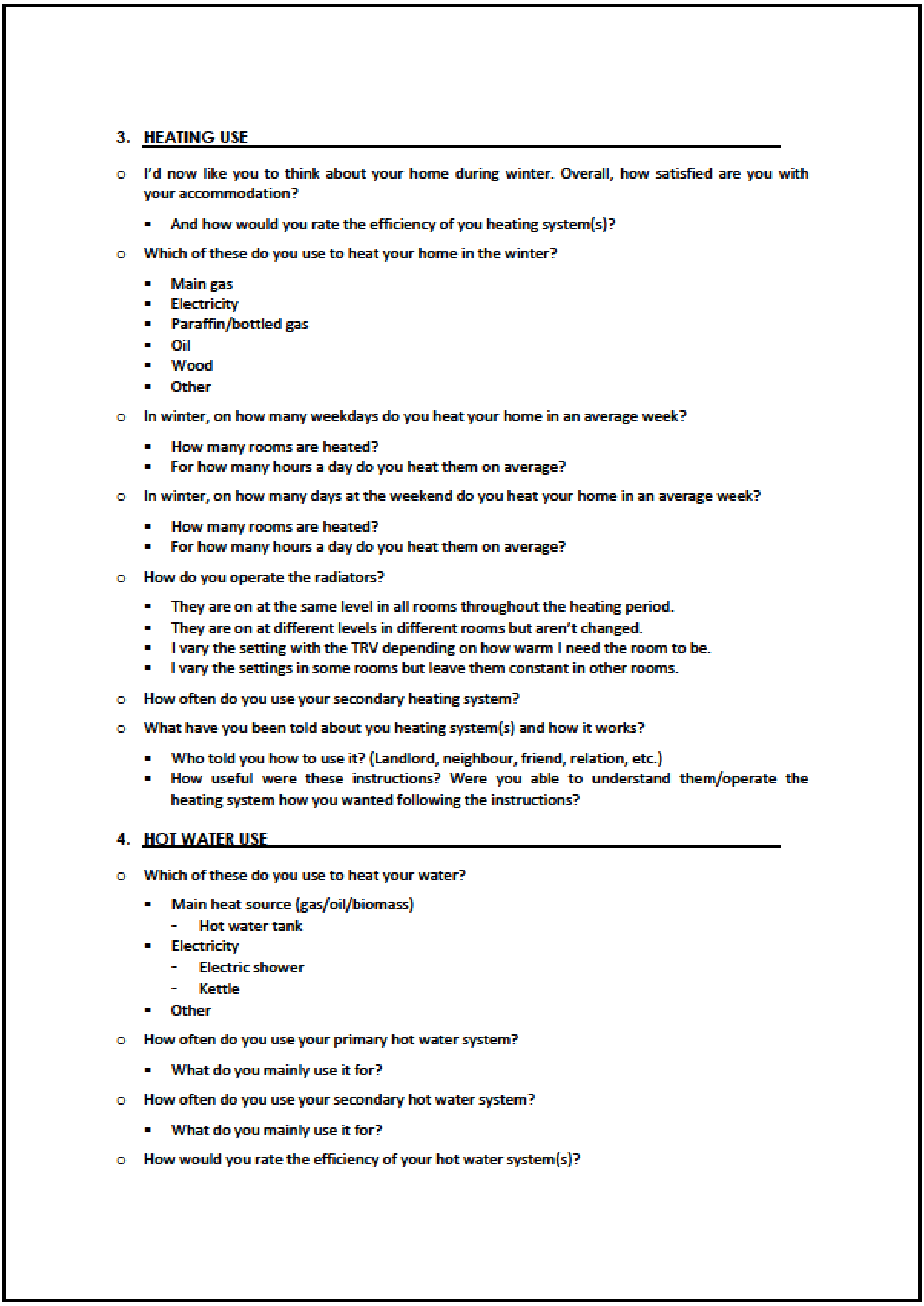
Property type		Insulation	
Position (flats)		% low energy light bulbs	
Property age		Draft proofing	
Windows (glazing, type)		Renewable energy	
Nº open chimneys		Any other thermal upgrade	
Nº exposed walls			

1. OCCUPANCY AND COMFORT

- First, I'd like to know a bit about your occupancy patterns.
    - How long do you usually spend in your home each weekday?
    - How long do you usually spend in your home each weekend day?
- Focusing in your home, could you describe in your own words what it means to be comfortable?
    - What is the most important aspect?
    - In general, how do you feel the temperature?
        - Would you prefer to be warmer/cooler?
        - Do you feel that you manage to achieve an adequate level of thermal comfort?
    - What do you usually wear at home?
        - How many layers of clothes do you usually wear?
    - How do you feel the air movement in this room in general?
        - E.g. too stuffy? Drafty?
    - How would you describe the air quality in your home in general?
        - E.g. too humid?
    - How do you find the noise levels from surrounding areas?
    - In general, how would you rate your overall comfort in your home?
- Can you tell me about what you do to feel comfortable?
- Even though they are related, what do you think of first, saving money or saving energy?

2. APPLIANCE USE

- Thinking about your home appliances. Can you tell me which of these appliances you will use in your home this winter?
  - Hob
  - Oven
  - Microwave
  - Kettle
  - Washing machine
  - Dishwasher
  - Tumble dryer
  - Steam iron
  - Other
- What is the main type of fuel you use for your oven?
  - How many days a week do you use your oven to cook?
  - And in winter, do you ever use your oven to heat the room?
  - On a day in winter when you use your oven to heat the room, for how many hours a day do you use it?
- What is the main type of fuel you use for your hob?
  - How many days a week do you use your hob to cook?
  - And in winter, do you ever use your hob to heat the room?
  - On a day in winter when you use your hob to heat the room, for how many hours a day do you use it?
- Now, thinking about your washing machine. How many loads would you put in your washing machine in an average week?
  - And of these loads, how many would you put in your tumble dryer?
  - And of the remaining loads, how many would you dry somewhere else in your home?
  - How is the moisture inside your tumble dryer usually vented?
    - A condensing dryer (nothing needed)
    - Permanently vented outside
    - Vented outside when used
    - Don't bother to vent outside
    - Other
- How many loads do you put in your dishwasher in an average week?
- Do you have a bath in your home?
  - In winter, how many baths do you and your family usually take each week?
- Do you have a shower in your home?
  - In winter, how many showers do you and your family usually take each week?
- Do you have any electric extractor fan?
  - In winter, on how many days do you use the extractor fan in your "ROOM"?

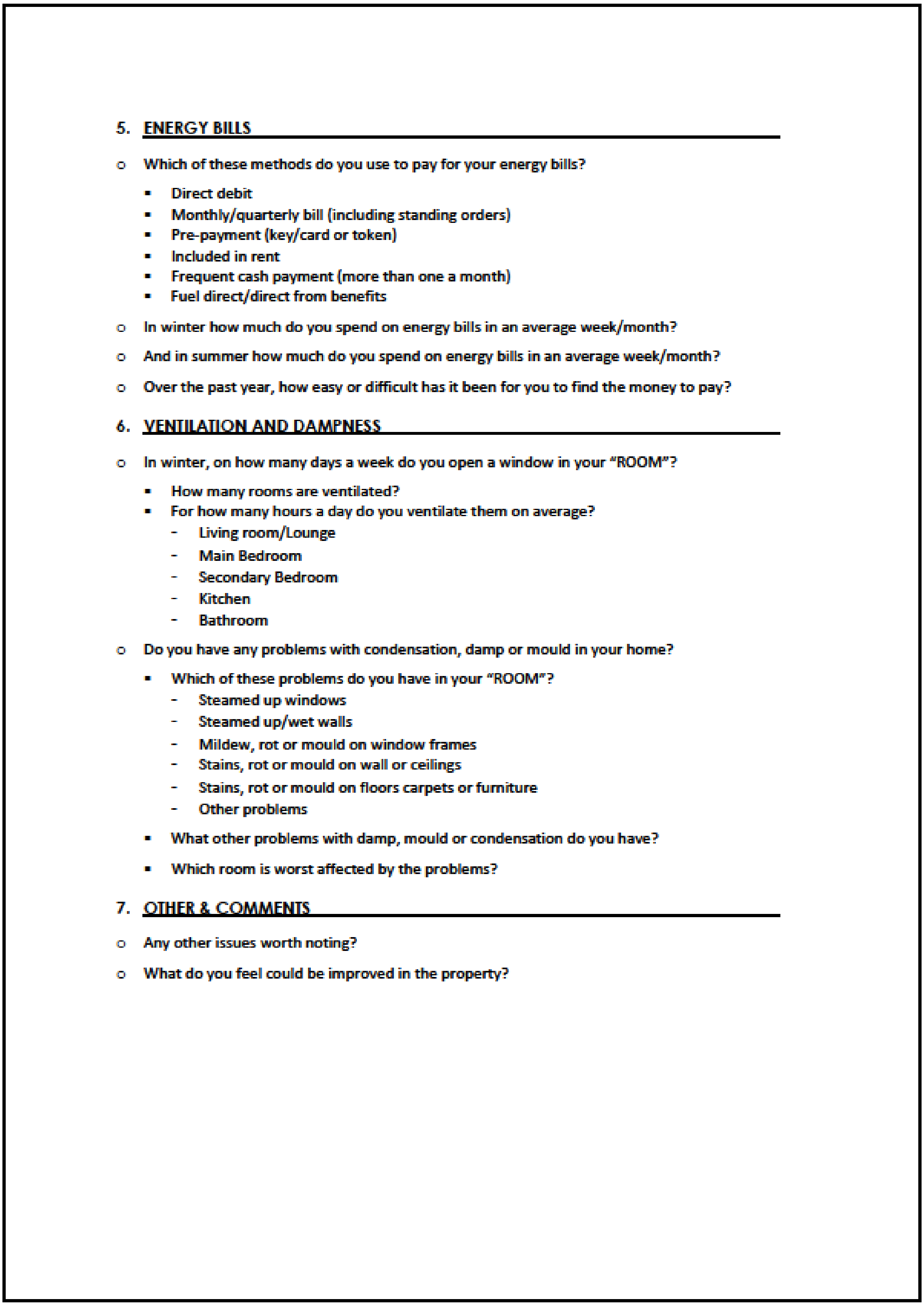


3. HEATING USE

- I'd now like you to think about your home during winter. Overall, how satisfied are you with your accommodation?
  - And how would you rate the efficiency of you heating system(s)?
- Which of these do you use to heat your home in the winter?
  - Main gas
  - Electricity
  - Paraffin/bottled gas
  - Oil
  - Wood
  - Other
- In winter, on how many weekdays do you heat your home in an average week?
  - How many rooms are heated?
  - For how many hours a day do you heat them on average?
- In winter, on how many days at the weekend do you heat your home in an average week?
  - How many rooms are heated?
  - For how many hours a day do you heat them on average?
- How do you operate the radiators?
  - They are on at the same level in all rooms throughout the heating period.
  - They are on at different levels in different rooms but aren't changed.
  - I vary the setting with the TRV depending on how warm I need the room to be.
  - I vary the settings in some rooms but leave them constant in other rooms.
- How often do you use your secondary heating system?
- What have you been told about you heating system(s) and how it works?
  - Who told you how to use it? (Landlord, neighbour, friend, relation, etc.)
  - How useful were these instructions? Were you able to understand them/operate the heating system how you wanted following the instructions?

4. HOT WATER USE

- Which of these do you use to heat your water?
  - Main heat source (gas/oil/biomass)
    - Hot water tank
  - Electricity
    - Electric shower
    - Kettle
  - Other
- How often do you use your primary hot water system?
  - What do you mainly use it for?
- How often do you use your secondary hot water system?
  - What do you mainly use it for?
- How would you rate the efficiency of your hot water system(s)?



5. ENERGY BILLS

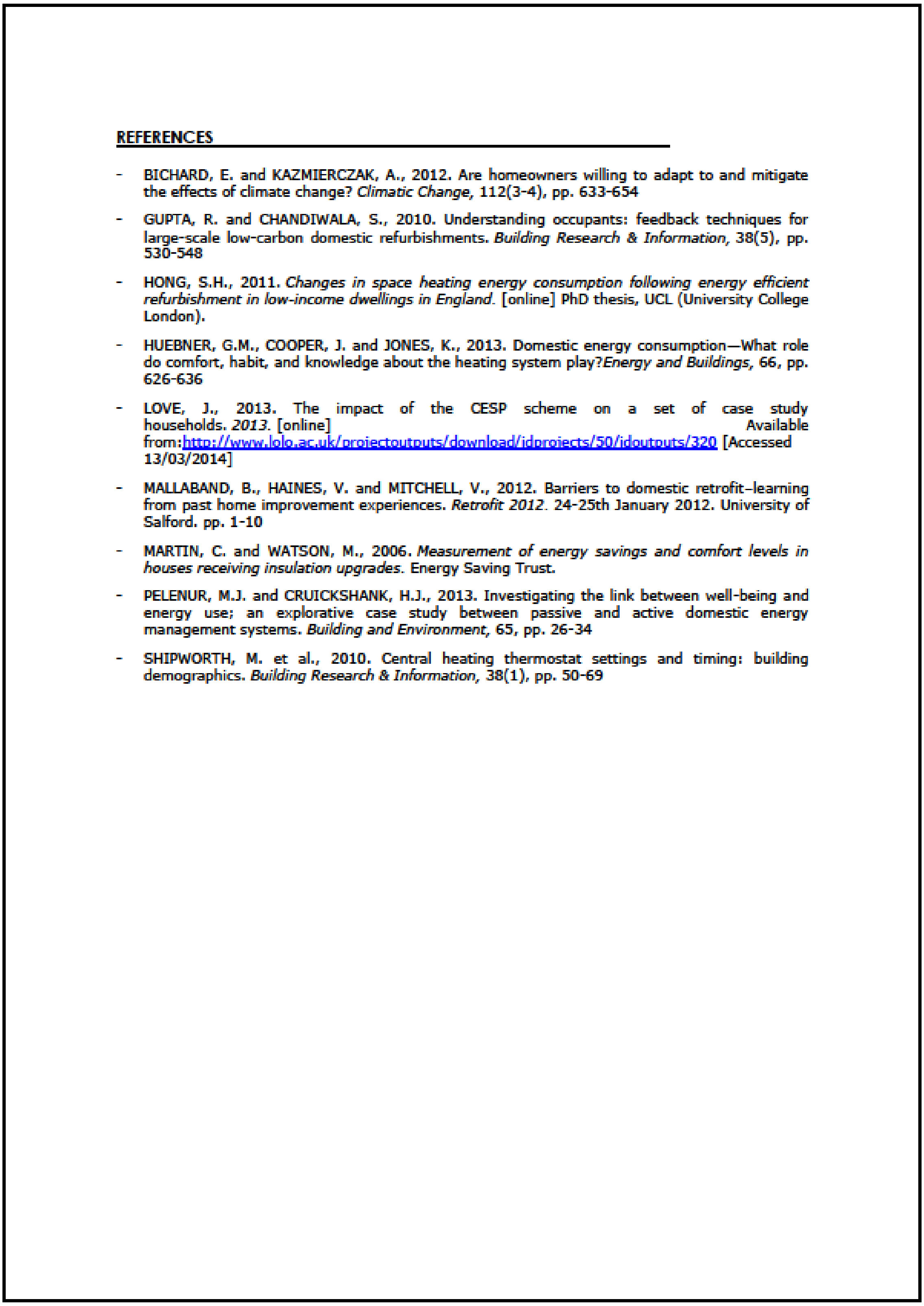
- Which of these methods do you use to pay for your energy bills?
  - Direct debit
  - Monthly/quarterly bill (including standing orders)
  - Pre-payment (key/card or token)
  - Included in rent
  - Frequent cash payment (more than one a month)
  - Fuel direct/direct from benefits
- In winter how much do you spend on energy bills in an average week/month?
- And in summer how much do you spend on energy bills in an average week/month?
- Over the past year, how easy or difficult has it been for you to find the money to pay?

6. VENTILATION AND DAMPNESS

- In winter, on how many days a week do you open a window in your "ROOM"?
  - How many rooms are ventilated?
  - For how many hours a day do you ventilate them on average?
    - Living room/Lounge
    - Main Bedroom
    - Secondary Bedroom
    - Kitchen
    - Bathroom
- Do you have any problems with condensation, damp or mould in your home?
  - Which of these problems do you have in your "ROOM"?
    - Steamed up windows
    - Steamed up/wet walls
    - Mildew, rot or mould on window frames
    - Stains, rot or mould on wall or ceilings
    - Stains, rot or mould on floors carpets or furniture
    - Other problems
  - What other problems with damp, mould or condensation do you have?
  - Which room is worst affected by the problems?

7. OTHER & COMMENTS

- Any other issues worth noting?
- What do you feel could be improved in the property?



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APPENDIX 5 – MULTI-CASE STUDY: EXAMPLE INTERVIEW NOTES

27Th October 2014

0. PROPERTY DETAILS

Property type	Detached	**Insulation**	Wall + Ceiling + Roof + Floor
Position (flats)	---	**% low energy light bulbs**	LED
Property age	?	**Draught proofing**	YES
Windows (glazing, type)	Double glazing Original timber frame	**Renewable energy**	NO
Nº open chimneys	2 (1 stove & 1 sealed)	**Any other thermal upgrade**	New doors
Nº exposed walls	4		

1. OCCUPANCY AND COMFORT

We moved in 2012, July. So, two and a half years. They just finished the works a couple of months before we moved in.

We had seen a couple of houses-- we wanted to live closer to Aberdeen but we realised that in our price range we couldn't find anything nice in Aberdeen so started looking further and further away and just by chance we saw this one and just fell in love. We saw the view and we didn't need to see the house inside. We went inside and we saw that it was completely renovated as well.

- **First, I'd like to know a bit about your occupancy patterns.**

Basically, I work usually about five months a year being away from home. So I'm not at home maybe five months. I don't know if you can see it in your graphs. There is usually more washing going on when I'm here as well. More cooking as well, I guess. This year as, a rough idea, I was away whole of April, whole of June, a bit of July, a bit of August and whole September. I don't work at all when I'm home.

So, when I'm away, Monika is here basically all the time, most of the day. My son is at school between 8 and 5 o'clock every day. The youngest one, up until today was at home all the time as well. Maybe apart from few hours here and there. During the day the just come and go, do shopping sometimes.

- **How long do you usually spend in your home each weekday?**
- **How long do you usually spend in your home each weekend day?**

Weekends are pretty much the same; it's just that my son is here all the time.

- **Focusing in your home, could you describe in your own words what it means to be comfortable?**

Never thought about it. I guess it is like a mixture of all. I guess... yes, noise. If it's quiet, I feel comfortable. I don't like it too hot, so the temperature is secondary for me. But for Monika for example, she likes definitely warmer. For her would be temperature, very important. I'm never cold.

- **What is the most important aspect?**

Noise/Temperature

- **In general, how do you feel the temperature?**

For me it's OK. We installed the thermometer, and then we have one that you carry around some times to see how the temperature changes. The fluctuations are, if you have 20 degrees here, it is usually about 18 in the bedroom and upstairs it is pretty much as down here, maybe slightly hotter even, maybe 21. Because all the warm air goes up obviously. The porch, that used to be Monika's office when she writes her thesis, it is not possible to do it during the cold months because the temperature goes down to 14. Usually are 16, so you have 2 degrees between.

For me the most comfortable would be the bedroom, 18, and for Monika would 20, 21.

- **Would you prefer to be warmer/cooler?**
- **Do you feel that you manage to achieve an adequate level of thermal comfort?**

This bloody system doesn't work as it should

- **What do you usually wear at home?**

It depends… I'm pretty much like this, T-shirt and maybe shorts even. But my wife on the same day would wear a jumper or a fleece or something like this. We are probably two extremes, something in the middle, maybe for an average person would be just like a light jumper maybe…

- **How many layers of clothes do you usually wear?**
- **How do you feel the air movement in this room in general?**
- **E.g. too stuffy? Draughty?**

No, it is not draughty but it is quite fresh. For example if you leave the ventilation in the windows (trickle vents) open, sometimes you can feel the air moving coming through. So we usually just leave them open on one side of the house for example. Or in the winter, if it gets really cold we just close them all. Although these help the condensation to gather on the windows.

- **How would you describe the air quality in your home in general?**
- **E.g. too humid?**

You can see the condensation on the windows, usually in the bedroom and upstairs bedrooms as well even the one that we don't really use which is an office right now. You can see the condensation all along the edges of the glass in the windows and with time, it will produce some mould or something like this, that was quite annoying. So we had to, every week, we had to clean to bleach or something just to remove it. And remove the condensation itself every day, if you don't remove it every morning when you wake up, and you don't always have time, then after a couple of days, because it is very warm inside, you are getting there slightly mouldy thing, dark, green-brown… something growing on. Even if you leave the vent on it will just dry out the immediate neighbourhood of the vent or the area next to it and then the rest would still be condensate. Since we installed this dehumidifier, it is much better.

- **How do you find the noise levels from surrounding areas?**

Apart from the wind howling and occasional cows, there is no noise at all. If all the windows are closed, you can't even hear the wind usually. But if you go outside you can hear the cars passing through A98. But it is not a problem to open the windows. We usually open the windows in the morning to fresh the house.

- **In general, how would you rate your overall comfort in your home?**

It is quite a comfortable home apart from the heating system. If you have an oil heating system… perfect. It is just a lot of work involved, but otherwise it is quite comfortable.

- **Can you tell me about what you do to feel comfortable?**
- **Even though they are related, what do you think of first, saving money or saving energy?**

Hard to say really, because we don't really pay much for electricity. It is OK because we don't really use much, it is just the appliances. Lighting is energy efficient and we only have the lights on whenever we are in the room so we are energy aware at this level. But to heat the house you need to buy wood, so there is no choice. And because it is also hot water then you basically need to do it all the time so you don't really have a choice. We look for cheaper suppliers, so the economy is very important as well but there is only so much we can do in this.

The amount of work is the main downside of living in this house. I think money wise, if we have an oil fired central heating it would be pretty much the same cost as wood. Because I don't know how much it is oil heating but I think is around a grand a year, something like this. £1000 is probably the cost of a full tank and I'm not sure how much we would use in this house.

It is difficult to say, we would like to save more but we can't because we have to run it all the time.

- **For what reasons would you be willing to reduce your energy consumption?**
    - **I would be willing to reduce my energy consumption in order to save money.**
    - **I would be willing to reduce my energy consumption in order to protect the environment.**

2. APPLIANCE USE

- **Thinking about your home appliances. Can you tell me which of these appliances you will use in your home this winter?**

- ✓ Hob
- ✓ Oven
- ○ Microwave
- ✓ Kettle
- ✓ Washing machine
- ✓ Dishwasher
- ✓ Tumble dryer
- ✓ Steam iron (very rarely, just for the school clothes every other day for half an hour in the morning)
- ✓ Other – Coffee machine (Almost on all the time)

- **What is the main type of fuel you use for your oven?**

Electric

- **How many days a week do you use your oven to cook?**

Not very often, maybe twice a week. Probably more in the winter because you need all sort of comfort foods like cookies and cakes.

- **And in winter, do you ever use your oven to heat the room?**

No, no point really. If you bake something just leave the door open, just let the heat outside.

- **On a day in winter when you use your oven to heat the room, for how many hours a day do you use it?**
- **What is the main type of fuel you use for your hob?**

Electric

- **How many days a week do you use your hob to cook?**

Twice or three times a day. It is more used when I am at home because we cook a bit more.

- **And in winter, do you ever use your hob to heat the room?**

- **On a day in winter when you use your hob to heat the room, for how many hours a day do you use it?**
- **Now, thinking about your washing machine. How many loads would you put in your washing machine in an average week?**

At least once a day.

- **And of these loads, how many would you put in your tumble dryer?**

We barely use it. Every now and then but only if it is really wet outside, because we usually try to-- with wind like this two hours and our clothes are dry. In the winter when it is wet all the time, inside the house even with the dehumidifier takes a couple of days to dry. So we sometimes use it but not very often.

- **And of the remaining loads, how many would you dry somewhere else in your home?**

If inside, we dry them in our bedroom. Usually we keep them in the bedroom for the day and for the night we move it here. Or sometimes in the bathroom if it is something that it is not used very often like towels and it just stays there for a few days.

- **How is the moisture inside your tumble dryer usually vented?**

✓ A condensing dryer (nothing needed)
○ Permanently vented outside
○ Vented outside when used
○ Don’t bother to vent outside
○ Other

- **How many loads do you put in your dishwasher in an average week?**

Once a day (7 a week)

- **How would you describe your use of lighting in the home?**
    - ○ **Very economical**
    - ○ **Average**
    - ○ **Very uneconomical**

- **Do you have a bath in your home?**

Yes

- **In winter, how many baths do you and your family usually take each week?**

Maybe 1 or 2 a week. The kids want to play in the water. That is the problem, because if you want to take a proper bath then you use up more than half of the tank, so you really need to work towards your bath.

- **Do you have a shower in your home?**

Yes

- **In winter, how many showers do you and your family usually take each week?**

I usually take showers with the kids, so it is one long shower for us and then Marta showers separately. So it would be three showers a day (21 a week)

- **Do you have any electric extractor fan?**

Yes. The one upstairs is very weak, but the one downstairs is very powerful. If you have it on maximum and you take a shower, usually the mirror doesn't steam up.

- **In winter, on how many days do you use the extractor fan in your "ROOM"?**

Always when showering (independent switch)

3. HEATING USE

- **I'd now like you to think about your home during winter. Overall, how satisfied are you with your accommodation?**

The way the system works you fire up the boiler (stove), it pumps the water to the back of the boiler, heats up the hot water tank and then this is our hot water for the taps and it also supplies hot water for the central heating system. So if you fire up the boiler here, this room becomes hot. It goes from 26, 28 degrees in this side of the room to 22 in this side. And the bedroom is still maybe going up to 19. If you turn on the central heating—it has thermostats but not inside the house, but outside the house for some reason. You can set it up, if it is getting colder outside you can have it colder in the house if you go away for example so it is more stabilised. Or you can set it up that if it is getting colder outside it is getting hotter inside. I never fully worked out how it works because it doesn't have a very user-friendly interface. It is just two knobs that you need to adjust, and there is-- these knobs adjust the difference between the temperature outside and inside, like a curve-- you can have a curve more steep or more flat, and then you can move the curve around the X-axis, which is the outside temperature.

- **And how would you rate the efficiency of you heating system(s)?**

Just move the wood twice a day it is a lot of work. And then, you need to clean it up as well. If you burn four tubes like this a day you need to clean it up every day as well. So it is a lot of work. When we moved, they told us it's a good system so you just fire it up once a day, it heats up the water in 20 minutes, which sometimes it does but just for the taps it takes much longer to heat up the whole system.

In theory, you could set up the temperature of the radiators to be to your liking depending on what temperature is outside but it's not very straightforward. For the system to work on its best, you need to have the maximum capacity of the temperature in the tank which is about 75 degrees and to reach that you need to burn a lot of wood and keep it burning every 12 hours just to keep the temperature stable and that is what we are doing in the winter. What we have found is that it is actually better to fire it up later in the morning and then just keep it lit up throughout the day, just through one or two logs every now and then. Just to keep it warm and then in the evening, fill it up. Because most of the family life is around this area, the warmth that goes out of the stove itself goes to this room and then we just keep the radiators...

- **Which of these do you use to heat your home in the winter?**

You need to buy it (wood) basically. Usually twice during summer time, a load is around 4-5 m^3. And then in the winter we buy nearly every month a load. So, it is a lot of wood. They just bring it on and there is another thing because you have to store everything. They just dump it in front of your gate. And it takes about three or four hours to stack all the wood for maybe 1.5 loads. So it is quite time consuming and work consuming. And if you don't have time, you need to remember to cover it with something otherwise it gets wet and you can't use it anymore.

- ○ Main gas
- ✓ Electricity
- ○ Paraffin/bottled gas
- ○ Oil
- ✓ Wood
- ○ Other

- **In winter, on how many weekdays do you heat your home in an average week?**

In the winter if we have the heating on maybe three times a day for two hours, two hours in the morning just before we wake up, then two hours around lunch time and two hours before we go to bed maybe. That would require for us to fire up the boiler twice a day. So in the morning and in the evening as well. It takes two plastic tubes to bring it up to a proper level of temperature in the hot water tank.

- **How many rooms are heated?**

We usually do (heat all the rooms), this one (radiator close to the kitchen) is on because it gets cold from the windows, this one is of (the other radiator in the living room) we don't use it at all, and then the one in the utility room is off as well. So, there are two radiators that are off and the rest is pretty much on.

- **For how many hours a day do you heat them on average?**

(In summer) If it's a nice warm day we only fire it up every 36 hours and we just try to run down the hot water tank until it is nearly empty and then we work it up again, and we try to look for better ways of using this wood, to see if it's better to fire it up in mornings in the evenings or to keep it on. In the summer it doesn't really matter, you can fire it up every 36 hours, but in the winter it is better to keep it on most of the time.

- **In winter, on how many days at the weekend do you heat your home in an average week?**

Idem

- **How many rooms are heated?**
- **For how many hours a day do you heat them on average?**
- **How do you operate the radiators?**

This doesn't control anything. As long as it is turned on between two and four... The temperature of the radiator is controlled by the box… so as long as it is on you will get the same temperature that it is set up from the control box. The control box controls the temperature-- the mixing of the water, the hot and cold water, that goes to the radiators and this, will then depend on the temperature of the water in the tank.

○ They are on at the same level in all rooms throughout the heating period.
✓ They are on at different levels in different rooms but aren't changed.
○ I vary the setting with the TRV depending on how warm I need the room to be.
○ I vary the settings in some rooms but leave them constant in other rooms.

- **How often do you use your secondary heating system?**

We have electric back up but we never use it because it is quite expensive. In the winter if we go for a holiday, for a weekend somewhere away we turn on the electric one so it heats up a little bit just to keep the pipes from freezing.

We have a small electric heater. We basically use it sometimes to heat up the bathroom, because the bathroom is one of the coldest places in the house, before the kids take a shower. Once a day pretty much for maybe 25 or 15 minutes. And not every day either it is just occasional.

- **What have you been told about you heating system(s) and how it works?**

They told us how to use it; the thing is when-- it is the only one they have in the estate. They never used it before, they only used it a couple of times to see how it works and then they asked us to test it. We told them, it would be a perfect system if you have a backup, they said we have electric backup. Yes right, but it is quite expensive.

- **Who told you how to use it? (Landlord, neighbour, friend, relation, etc.)**

- **How useful were these instructions? Were you able to understand them/operate the heating system how you wanted following the instructions?**

4. **HOT WATER USE**

- **Which of these do you use to heat your water?**
- **Main heat source (gas/oil/biomass)**

Hot water tank

- **Electricity**

Kettle (Three times a day but we never boil more than we need. Two full kettles all together. But the coffee machine is on most of the time. It's maybe four or five times a day)

- **Other**
- **How often do you use your primary hot water system?**
- **What do you mainly use it for?**
- **How often do you use your secondary hot water system?**
- **What do you mainly use it for?**
- **How would you rate the efficiency of your hot water system(s)?**

5. **ENERGY BILLS**

- **Which of these methods do you use to pay for your energy bills?**

o Direct debit
✓ Monthly/quarterly bill (including standing orders)
o Pre-payment (key/card or token)
o Included in rent
o Frequent cash payment (more than one a month)
o Fuel direct/direct from benefits

- **In winter how much do you spend on energy bills in an average week/month?**

For wood is around £100 per load, so I would say we see around seven or eight loads a year. So it is not that much. We are still looking for cheaper alternatives but basically we can't save on it, we need to have hot water so…

It can be double in the winter, something like £200 maybe. We are supposed to have this tariff where the electricity is cheaper between 11pm and 6am. So we usually turn the dishwasher and washing machine overnight.

- **And in summer how much do you spend on energy bills in an average week/month?**

For the electricity, it is around £120 for 3 months

- **Over the past year, how easy or difficult has it been for you to find the money to pay?**

No, usually it is not much of a problem.

6. VENTILATION AND DAMPNESS

- **In winter, on how many days a week do you open a window in your "ROOM"?**

We try to do it every day. But if it is really cold, if it is raining we don't do it. There is always wind and rain so it drives the rain so we can't open the window. If it is not raining we try to do it every day, both living room and bedroom. Well, this window in the kitchen is open most of the time. The bedrooms are open from morning until lunchtime, and usually a couple of hours in the evening as well, if the weather it is nice. It all depends on the weather. We barely open windows upstairs, apart from the Velux.

- ▪ How many rooms are ventilated?
- ▪ For how many hours a day do you ventilate them on average?

✓ Living room/Lounge
✓ Main Bedroom
○ Secondary Bedroom
✓ Kitchen
○ Bathroom

- **Is your home draughty?**
- **Is that throughout or in parts?**
- **Do you have any problems with condensation, damp or mould in your home?**
- **Which of these problems do you have in your "ROOM"?**

✓ Steamed up windows
○ Steamed up/wet walls
✓ Mildew, rot or mould on window frames.
✓ Stains, rot or mould on wall or ceilings
○ Stains, rot or mould on floors carpets or furniture
○ Other problems.

- **What other problems with damp, mould or condensation do you have?**

We noticed some dew in the stone wall inside the porch. Together with the bathroom is one of the coldest places in the house as well.

- **Which room is worst affected by the problems?**

7. OTHER & COMMENTS

- **Any other issues worth noting?**

If we have like a power cut, then there is no heating at all because we can't fir up the stove. Because when it reaches 40 degrees the water in the back, it automatically turns on the pump that pumps the water from the tank. And if it doesn't happen, the water starts to heat up too much in the pipes in the stove and starts pumping out from the system outside. And because the pump is not pumping the new water, the pipes are empty and maybe steaming up or something like this and it is not safe.

It happened last year twice. We had a power cut for more than 24 hours once.

- **What do you feel could be improved in the property?**

If we had like solar panels, it would keep the water at some sort of level of temperature in the hot water tank and then we would just fire it up in the evening, even in the winter probably it would be-- once would be enough. If it was our own house, yes I would probably go either for panels or for a turbine, depending on the costs.

APPENDIX 6 – NARRATIVES. CASE 16: PETER AND ANN

Peter and Ann are in their late 60's and they are both retired. She was a social worker and Peter, an agricultural engineer, still does some consultancy work. Peter and Ann bought their three bedroom semidetached house in 2006, after the children moved out and he retired. They were looking for a ground floor house. The garden, and having enough room for a wood workshop, was a key aspect in their choice, even more important than the style of the building.

Peter is a DIY enthusiastic and he always had in the 'back of his mind' trying to make an old house more energy efficient. Since they bought the house, they have renovated the living room, dining room, kitchen and the main bedroom with the en-suite included. The renovation included the insulation of the external walls, replacement of windows and full draught proofing. On top of that, they have replaced the boiler, after the previous one broke a couple of times. The main reason for them to insulate and improve the efficiency of the house was clearly environmental. Peter described it very graphically saying

> *"I can afford the energy bills. I could just turn up the radiator and say: that £1500, I don't care! The main driver (for the retrofit) is climate change and energy efficiency"*

Feeling *"warm enough"* is the most important aspect of comfort for them. They describe being warm as *"being able to move around or sit without feeling the need to put on more clothes or put up the heating"*. On the other hand, they do not like the house to be too hot and they think that it is usually around 16-18 degrees. Peter explains,

> *"I tend to put an extra jersey. I mean, (today) I have put the heating on for you".*

During the day, they enjoy being outdoors, working in the garden or the workshop. If the weather is too bad to be outside, they would mainly use the kitchen and the dining room. In the evening, they like sitting in the living room after dinner. They feel the temperature in their home comfortable and they are satisfied with the overall comfort in their home.

They have configured the heating system to follow their routines, trying to heat only the rooms they are occupying. The heating system is split in three circuits (kitchen and dining room, living room and bedroom) and each of the loops starts at different time (5:30, 18:00 and 21:00 respectively). Besides the central gas heating system, they have a wood burning stove in the living room that they like to light when they want to feel *"nice and cosy"*, and especially when they have guests.

When asked about ventilation and moisture Peter said,

> *"The humidity is never too high. Even though I have sealed everything, there is still plenty of fresh air to make the atmosphere feel all right".*

In order to reduce heat losses, they are trying to eliminate any draught and to minimise any unnecessary ventilation. The trickle vents are always kept closed and the window in the bedroom was sealed up because it was too leaky (now it has been replaced by a new one that it is very airtight). As a result of this, they are experiencing some important condensation on the bedroom windows, especially at night before going to sleep. Their solution to avoid the steamed up windows is to close the doors so the warm and moist air does not go up into that room.

Table 10-1 Environmental conditions of Case 16

		Mean	**StDev**	**Mean**	**StDev**	**Mean**	**StDev**
Winter	Living room	16.1	3.0	57.3	3.6	2.4	1.6
	Bedroom	12.6	2.3	71.9	5.2	2.5	1.2

Table 10-2 Air infiltration tests of Case 16

	[m^3/h@50Pa]	**[ach@50Pa]**	**[m^2]**	**[m^3]**	**[-]**
Case 16(1)	3696	9.02	400	410	Semidetached

(1) Blower door test results provided by the tenant

APPENDIX 7 – NUMERICAL SIMULATION: SETTINGS EXAMPLE

Below, the settings used for the configuration of a front wall insulated with blown-in-cellulose simulated with a humidity class III are presented.

```
1.4.3 2D1_CELLULOSE_Class3

[PROJECT_INFO]

  FILE_VERSION              = 5.8.1
  CREATED                   = Mon Jan 26 20:03:16 2015
  LAST_EDIT                 = Fri Jul 10 16:52:24 2015

COMMENTS:
This is the default project file template.

; *********************************************************************

[DIRECTORIES]

  MATERIALS                 = C:/Program Files (x86)/IBK/Delphin
5.8.1/DB_material_data
  USER_MATERIALS            =
C:/Users/1211912/AppData/Roaming/IBK/material_data
  CLIMATE                   = C:/Program Files (x86)/IBK/Delphin
5.8.1/DB_climate_data
  SALT                      = C:/Program Files (x86)/IBK/Delphin
5.8.1/DB_salt_data
  VOC                       = C:/Program Files (x86)/IBK/Delphin
5.8.1/DB_VOC_data
  USER_CLIMATE              =
C:/Users/1211912/AppData/Roaming/IBK/climate_data

; *********************************************************************

[INIT]

  [GENERAL]
    BALANCE_EQUATIONS         = ENERGY MOISTURE
    USE_KIRCHHOFF             = yes
    USE_GRAVITY               = no
    USE_BUOYANCY              = no
    USE_HYDROSTATIC           = no
    PRESSURE_UPDATE_INTERVAL = 0 s
    START_YEAR                = 2000
    START_TIME                = 10368000
    DURATION                  = 914 d
    ISOTHERMAL_T_REF          = 20 C

  [SALT_SETTINGS]
    USE_EXTRA_SALT_OUTPUT     = no
    USE_OVERSATURATION        = no
    USE_DENSITY               = yes
    FLOW_RESISTANCE_FACTOR    = 0
```

```
  [SOLVER_SETTINGS]

    [CVODE_SOLVER_SETTINGS]
      INITIAL_DT                = 0.01 s
      MAX_DT                    = 30 min
      MIN_DT                    = 1e-05 s
      REL_TOL                   = 0.0001
      ABS_TOL_ENERGY            = 1
      ABS_TOL_MOISTURE          = 1e-06
      ABS_TOL_AIR               = 1e-06
      ABS_TOL_SALT              = 1e-10
      ABS_TOL_POLLUTANT         = 1e-12
      USE_AUTO_RECOVER          = yes
      MAX_ORDER                 = 5
      MAX_STEPS                 = 10000000
      USE_MONITORS_FILE         = no
      USE_ONE_STEP_MONITORS     = no
      PREVENT_OVERFILLING       = yes
      USE_STRICT_RANGE_CHECKING = no

; ********************************************************************

 [MATERIALS]

  [MATERIAL]
    EXTERNAL                 = $(MATERIALS_DIR)/LimePlasterHist_148.m6

    [IDENTIFICATION]
      NAME                      = Lime Plaster (historical)
      COLOUR                    = #ff409020
      UNIQUE_ID                 = 148

  [MATERIAL]
    EXTERNAL                 =
$(MATERIALS_DIR)/FichtenholzSWFiLongitudinal_459.m6

    [IDENTIFICATION]
      NAME                      = Spruce SW Longitudinal
      COLOUR                    = #ffff8040
      UNIQUE_ID                 = 459


  [MATERIAL]
    EXTERNAL                 =
$(MATERIALS_DIR)/AirGapVertical50mm_18.m6

    [IDENTIFICATION]
      NAME                      = Air gap 50 mm (vertical)
      COLOUR                    = #ffd8e8e9
      UNIQUE_ID                 = 18

  [MATERIAL]
    EXTERNAL                 =
$(MATERIALS_DIR)/GranitFindlingeSockel_463.m6

    [IDENTIFICATION]
      NAME                      = Granite boulder
      COLOUR                    = #ff10f0f0
      UNIQUE_ID                 = 463

  [MATERIAL]
```

```
    EXTERNAL                  =
$(MATERIALS_DIR)/LimeCementMortar_143.m6

    [IDENTIFICATION]
      NAME                      = Lime Cement Mortar
      COLOUR                    = #ffc0c0c0
      UNIQUE_ID                 = 143

  [MATERIAL]
    EXTERNAL                  = $(MATERIALS_DIR)/LehmmoertelLMH_128.m6

    [IDENTIFICATION]
      NAME                      = Clay Mortar (historical)
      COLOUR                    = #ffb1b163
      UNIQUE_ID                 = 128

  [MATERIAL]
    EXTERNAL                  =
$(MATERIALS_DIR)/WeatheredGranite_263.m6

    [IDENTIFICATION]
      NAME                      = Granite (weathered)
      COLOUR                    = #ff808080
      UNIQUE_ID                 = 263

  [MATERIAL]
    EXTERNAL                  =
$(MATERIALS_DIR)/CWACelluloseEinblasprodukt_580.m6

    [IDENTIFICATION]
      NAME                      = Blown-in Cellulose
      COLOUR                    = #ffff80ff
      UNIQUE_ID                 = 580

  [MATERIAL]
    EXTERNAL                  =
$(MATERIALS_DIR)/PolyurethaneFoam_195.m6

    [IDENTIFICATION]
      NAME                      = Polyurethane-foam
      COLOUR                    = #ffffff80
      UNIQUE_ID                 = 195

  [MATERIAL]

  [IDENTIFICATION]
    NAME                      = Polyurethane-foam [Open]
    LABORATORY                = DE: Literatur |EN: Literature |IT:
Letteratura |RU: Литертура
    DATE                      = 08.04.14
    COLOUR                    = #ff80ff80
    FLAGS                     = AIR_TIGHT WATER_TIGHT
    USE_INSTEAD               = 0
    CATEGORY                  = INSULATION
    DBTYPE                    = 1,4,5,7,11
    HATCHING                  = 13

  [STORAGE_BASE_PARAMETERS]
    RHO                       = 7.5 kg/m3
    CE                        = 1470 J/kgK
    THETA_POR                 = 0.99 m3/m3
    THETA_EFF                 = 0.92 m3/m3
```

```
    THETA_80                     = 0.00021 m3/m3


  [TRANSPORT_BASE_PARAMETERS]
    LAMBDA                       = 0.037 W/mK
    AW                           = 0.0001 kg/m2s05
    MEW                          = 2.38 -
    KLEFF                        = 0 s

  [MOISTURE_STORAGE]
    FUNCTION                     = Theta_l(pC)_de
0                0.3              0.4              0.5
0.6              0.7              0.8              0.9              1
1.1              1.2              1.3              1.4
1.5              1.6              1.7              1.8
1.9              2                2.1              2.2
2.3              2.4              2.5              2.6
2.7              2.8              2.9              3
3.1              3.2              3.3              3.4
3.5              3.6              3.7              3.8
3.9              4                4.1              4.2
4.3              4.4              4.5              4.6
4.7              4.8              4.9              5
5.1              5.2              5.3              5.4
5.5              5.6              5.7              5.8
5.9              6                6.1              6.2
6.3              6.4              6.5              6.6
6.7              6.8              6.9              7
7.1              7.2              7.3              7.4
7.5              7.6              7.7              7.8
7.9              8                8.1              8.2
8.3              8.4              8.5              8.6
8.7              8.8              8.9              9
9.1              9.2              9.3              10
        0.92             0.9199687476     0.9199541012
0.9199313496     0.919907494      0.9198714668     0.9198338296
0.9197786296     0.919721194      0.9196393508     0.919554536
0.9194371256     0.9193159156     0.9191529468     0.918985332
0.9187664824     0.918542168      0.9182577868     0.9179673152
0.9176097848     0.917245796      0.9168108568     0.9163695052
0.9158575712     0.9153397124     0.9147566808     0.9141686996
0.9135262452     0.9128802396     0.9121952444     0.9115084368
0.9108017112     0.9100950408     0.9093890236     0.9086846624
0.9079985632     0.9073141108     0.906647902      0.9059767896
0.9052517652     0.904493032      0.9033635204     0.90211129
0.8995087204     0.8965706176     0.8899406008     0.8825862956
0.867262426      0.850704404      0.820566676      0.788810438
0.739245024      0.6881575436     0.6203220152     0.5517109912
0.47456682       0.3977793236     0.3249163264     0.2533624524
0.1962133312     0.1407240556     0.1034986108     0.0676960748
0.047550338      0.0283270944     0.0192545052     0.0106527536
0.007231798      0.0040035548     0.0028958656     0.001852006
0.0015105848     0.0011863768     0.0010515876     0.0009207176
0.0008329312     0.0007461844     0.0006707812     0.000596068
0.0005288988     0.0004625024     0.000404662      0.0003476772
0.00030015       0.0002534784     0.0002162828     0.0001798784
0.0001521588     0.00012512       0.0001054596     8.63328e-05
7.30572e-05      0
    FUNCTION                     = pC(Theta_l)_de
        0                7.30572e-05      8.63328e-05
0.0001054596     0.00012512       0.0001521588     0.0001798784
0.0002162828     0.0002534784     0.00030015       0.0003476772
```

```
0.000404662      0.0004625024     0.0005288988     0.000596068
0.0006707812     0.0007461844     0.0008329312     0.0009207176
0.0010515876     0.0011863768     0.0015105848     0.001852006
0.0028958656     0.0040035548     0.007231798      0.0106527536
0.0192545052     0.0283270944     0.047550338      0.0676960748
0.1034986108     0.1407240556     0.1962133312     0.2533624524
0.3249163264     0.3977793236     0.47456682       0.5517109912
0.6203220152     0.6881575436     0.739245024      0.788810438
0.820566676      0.850704404      0.867262426      0.8825862956
0.8899406008     0.8965706176     0.8995087204     0.90211129
0.9033635204     0.904493032      0.9052517652     0.9059767896
0.906647902      0.9073141108     0.9079985632     0.9086846624
0.9093890236     0.9100950408     0.9108017112     0.9115084368
0.9121952444     0.9128802396     0.9135262452     0.9141686996
0.9147566808     0.9153397124     0.9158575712     0.9163695052
0.9168108568     0.917245796      0.9176097848     0.9179673152
0.9182577868     0.918542168      0.9187664824     0.918985332
0.9191529468     0.9193159156     0.9194371256     0.919554536
0.9196393508     0.919721194      0.9197786296     0.9198338296
0.9198714668     0.919907494      0.9199313496     0.9199541012
0.9199687476     0.92
        10               9.3              9.2              9.1
9                8.9              8.8              8.7
8.6              8.5              8.4              8.3
8.2              8.1              8                7.9
7.8              7.7              7.6              7.5
7.4              7.3              7.2              7.1              7
6.9              6.8              6.7              6.6
6.5              6.4              6.3              6.2
6.1              6                5.9              5.8
5.7              5.6              5.5              5.4
5.3              5.2              5.1              5
4.9              4.8              4.7              4.6
4.5              4.4              4.3              4.2
4.1              4                3.9              3.8
3.7              3.6              3.5              3.4
3.3              3.2              3.1              3
2.9              2.8              2.7              2.6
2.5              2.4              2.3              2.2
2.1              2                1.9              1.8
1.7              1.6              1.5              1.4
1.3              1.2              1.1              1
0.9              0.8              0.7              0.6
0.5              0.4              0.3              0

; ********************************************************************

[CONDITIONS]

  [WALLS]

    [WALL_DATA]
      NAME                         = Wall North/Vertical/Aberdeen
      ORIENTATION                  = 0 Deg
      INCLINATION                  = 90 Deg
      LATITUDE                     = 57 Deg
      WALLAREA                     = 10 m2

  [CLIMATE_CONDITIONS]

    [CLIMATE_COND]
      TYPE                         = TEMPER
```

```
      NAME                     = Inside Temperature (constant)
      KIND                     = CONSTANT
      CONSTVALUE               = 20 C

    [CLIMATE_COND]
      TYPE                     = RELHUM
      NAME                     = Inside Relative Humidity (constan)
      KIND                     = CONSTANT
      CONSTVALUE               = 50 %

    [CLIMATE_COND]
      TYPE                     = TEMPER
      NAME                     = Outside Temperature (datapoints)
      KIND                     = DATLINEAR
      FILENAME                 = C:/_DANI/_Simulation WeatherStation
2.5 years/Boundaries WS 2.5years/External Temperature WS 25y.ccd
      USE_INTERPOLATION        = yes
      EXTEND_DATA              = yes
      CYCLIC_DATA              = no
      SHIFTVALUE               = 0 K

    [CLIMATE_COND]
      TYPE                     = RELHUM
      NAME                     = Outside Relative Humidity
(datapoints)
      KIND                     = DATLINEAR
      FILENAME                 = C:/_DANI/_Simulation WeatherStation
2.5 years/Boundaries WS 2.5years/External Humidity WS 25y.ccd
      USE_INTERPOLATION        = yes
      EXTEND_DATA              = yes
      CYCLIC_DATA              = no
      SHIFTVALUE               = 0 %

    [CLIMATE_COND]
      TYPE                     = DIRRAD
      NAME                     = Direct radiation
      KIND                     = DATLINEAR
      FILENAME                 = C:/_DANI/_Simulation WeatherStation
2.5 years/Boundaries WS 2.5years/External DirectRadiation TRY 25y.ccd
      USE_INTERPOLATION        = yes
      EXTEND_DATA              = yes
      CYCLIC_DATA              = no
      SHIFTVALUE               = 0 W/m2

    [CLIMATE_COND]
      TYPE                     = DIFRAD
      NAME                     = Diffuse radiation
      KIND                     = DATLINEAR
      FILENAME                 = C:/_DANI/_Simulation WeatherStation
2.5 years/Boundaries WS 2.5years/External DiffuseRadiation TRY 25y.ccd
      USE_INTERPOLATION        = yes
      EXTEND_DATA              = yes
      CYCLIC_DATA              = no
      SHIFTVALUE               = 0 W/m2

    [CLIMATE_COND]
      TYPE                     = TEMPER
      NAME                     = Inside Temperature (NoClassI)
      KIND                     = DATLINEAR
      FILENAME                 = C:/_DANI/_Simulation WeatherStation
2.5 years/Boundaries WS 2.5years/Internal Temperature NoClassI.ccd
      USE_INTERPOLATION        = yes
```

```
      EXTEND_DATA              = yes
      CYCLIC_DATA              = no
      SHIFTVALUE               = 0 K

    [CLIMATE_COND]
      TYPE                     = TEMPER
      NAME                     = Inside Temperature (NoClassII)
      KIND                     = DATLINEAR
      FILENAME                 = C:/_DANI/_Simulation WeatherStation
2.5 years/Boundaries WS 2.5years/Internal Temperature NoClassII.ccd
      USE_INTERPOLATION        = yes
      EXTEND_DATA              = yes
      CYCLIC_DATA              = no
      SHIFTVALUE               = 0 K

    [CLIMATE_COND]
      TYPE                     = TEMPER
      NAME                     = Inside Temperature (NoClassIII)
      KIND                     = DATLINEAR
      FILENAME                 = C:/_DANI/_Simulation WeatherStation
2.5 years/Boundaries WS 2.5years/Internal Temperature NoClassIII.ccd
      USE_INTERPOLATION        = yes
      EXTEND_DATA              = yes
      CYCLIC_DATA              = no
      SHIFTVALUE               = 0 K

    [CLIMATE_COND]
      TYPE                     = TEMPER
      NAME                     = Inside Temperature (YesClassI)
      KIND                     = DATLINEAR
      FILENAME                 = C:/_DANI/_Simulation WeatherStation
2.5 years/Boundaries WS 2.5years/Internal Temperature YesClassI.ccd
      USE_INTERPOLATION        = yes
      EXTEND_DATA              = yes
      CYCLIC_DATA              = no
      SHIFTVALUE               = 0 K

    [CLIMATE_COND]
      TYPE                     = TEMPER
      NAME                     = Inside Temperature (YesClassII)
      KIND                     = DATLINEAR
      FILENAME                 = C:/_DANI/_Simulation WeatherStation
2.5 years/Boundaries WS 2.5years/Internal Temperature YesClassII.ccd
      USE_INTERPOLATION        = yes
      EXTEND_DATA              = yes
      CYCLIC_DATA              = no
      SHIFTVALUE               = 0 K

    [CLIMATE_COND]
      TYPE                     = TEMPER
      NAME                     = Inside Temperature (YesClassIII)
      KIND                     = DATLINEAR
      FILENAME                 = C:/_DANI/_Simulation WeatherStation
2.5 years/Boundaries WS 2.5years/Internal Temperature YesClassIII.ccd
      USE_INTERPOLATION        = yes
      EXTEND_DATA              = yes
      CYCLIC_DATA              = no
      SHIFTVALUE               = 0 K

    [CLIMATE_COND]
      TYPE                     = RELHUM
      NAME                     = Inside Relative Humidity (NoClassI)
```

```
      KIND                         = DATLINEAR
      FILENAME                     = C:/_DANI/_Simulation WeatherStation
2.5 years/Boundaries WS 2.5years/Internal RelativeHumidity
NoClassI.ccd
      USE_INTERPOLATION            = yes
      EXTEND_DATA                  = yes
      CYCLIC_DATA                  = no
      SHIFTVALUE                   = 0 %

    [CLIMATE_COND]
      TYPE                         = RELHUM
      NAME                         = Inside Relative Humidity (NoClassII)
      KIND                         = DATLINEAR
      FILENAME                     = C:/_DANI/_Simulation WeatherStation
2.5 years/Boundaries WS 2.5years/Internal RelativeHumidity
NoClassII.ccd
      USE_INTERPOLATION            = yes
      EXTEND_DATA                  = yes
      CYCLIC_DATA                  = no
      SHIFTVALUE                   = 0 %

    [CLIMATE_COND]
      TYPE                         = RELHUM
      NAME                         = Inside Relative Humidity (NoClassIII)
      KIND                         = DATLINEAR
      FILENAME                     = C:/_DANI/_Simulation WeatherStation
2.5 years/Boundaries WS 2.5years/Internal RelativeHumidity
NoClassIII.ccd
      USE_INTERPOLATION            = yes
      EXTEND_DATA                  = yes
      CYCLIC_DATA                  = no
      SHIFTVALUE                   = 0 %

    [CLIMATE_COND]
      TYPE                         = RELHUM
      NAME                         = Inside Relative Humidity (YesClassI)
      KIND                         = DATLINEAR
      FILENAME                     = C:/_DANI/_Simulation WeatherStation
2.5 years/Boundaries WS 2.5years/Internal RelativeHumidity
YesClassI.ccd
      USE_INTERPOLATION            = yes
      EXTEND_DATA                  = yes
      CYCLIC_DATA                  = no
      SHIFTVALUE                   = 0 %

    [CLIMATE_COND]
      TYPE                         = RELHUM
      NAME                         = Inside Relative Humidity (YesClassII)
      KIND                         = DATLINEAR
      FILENAME                     = C:/_DANI/_Simulation WeatherStation
2.5 years/Boundaries WS 2.5years/Internal RelativeHumidity
YesClassII.ccd
      USE_INTERPOLATION            = yes
      EXTEND_DATA                  = yes
      CYCLIC_DATA                  = no
      SHIFTVALUE                   = 0 %

    [CLIMATE_COND]
      TYPE                         = RELHUM
      NAME                         = Inside Relative Humidity
(YesClassIII)
      KIND                         = DATLINEAR
```

```
      FILENAME                  = C:/_DANI/_Simulation WeatherStation 
2.5 years/Boundaries WS 2.5years/Internal RelativeHumidity 
YesClassIII.ccd
      USE_INTERPOLATION         = yes
      EXTEND_DATA               = yes
      CYCLIC_DATA               = no
      SHIFTVALUE                = 0 %

  [BOUNDARY_CONDITIONS]

    [BOUND_COND]
      TYPE                      = HEATCOND
      NAME                      = Inside Heat Conduction
      KIND                      = EXCHANGE
      EXCOEFF                   = 8 W/m2K
      TEMPER                    = Inside Temperature (YesClassIII)

    [BOUND_COND]
      TYPE                      = HEATCOND
      NAME                      = Outside Heat Conduction
      KIND                      = EXCHANGE
      EXCOEFF                   = 25 W/m2K
      TEMPER                    = Outside Temperature (datapoints)

    [BOUND_COND]
      TYPE                      = VAPDIFF
      NAME                      = Inside Vapor Diffusion
      KIND                      = EXCHANGE
      EXCOEFF                   = 3e-08 s/m
      SD_VALUE                  = 0 m
      TEMPER                    = Inside Temperature (YesClassIII)
      RELHUM                    = Inside Relative Humidity 
(YesClassIII)

    [BOUND_COND]
      TYPE                      = VAPDIFF
      NAME                      = Outside Vapor Diffusion
      KIND                      = EXCHANGE
      EXCOEFF                   = 2e-07 s/m
      SD_VALUE                  = 0 m
      TEMPER                    = Outside Temperature (datapoints)
      RELHUM                    = Outside Relative Humidity 
(datapoints)

    [BOUND_COND]
      TYPE                      = SHWRAD
      NAME                      = Sun radiation
      KIND                      = SUNRADM
      SURABSOR                  = 0.6 -
      GRDREFLE                  = 0.9 -
      WALLDATA                  = Wall North/Vertical/Aberdeen
      DIRRAD                    = Direct radiation
      DIFRAD                    = Diffuse radiation

  [INITIAL_CONDITIONS]

    [INIT_COND]
      NAME                      = 17C
      TYPE                      = TEMPER
      VALUE                     = 17 C

    [INIT_COND]
```

```
      NAME                     = 15C
      TYPE                     = TEMPER
      VALUE                    = 15 C

    [INIT_COND]
      NAME                     = 11C
      TYPE                     = TEMPER
      VALUE                    = 11 C

    [INIT_COND]
      NAME                     = 7C
      TYPE                     = TEMPER
      VALUE                    = 7 C

    [INIT_COND]
      NAME                     = 60%
      TYPE                     = RELHUM
      VALUE                    = 60 %

    [INIT_COND]
      NAME                     = 68%
      TYPE                     = RELHUM
      VALUE                    = 68 %

    [INIT_COND]
      NAME                     = 73%
      TYPE                     = RELHUM
      VALUE                    = 73 %

    [INIT_COND]
      NAME                     = 78%
      TYPE                     = RELHUM
      VALUE                    = 78 %

  [DEFAULT_CONDITIONS]

    DEFAULT_TEMPERATURE      = 20 C
    DEFAULT_RELHUM           = 80 %

; ********************************************************************

[DISCRETISATION]

  GEOMETRY                 = PLANE2D
  X_STEPS                  = 0.001 0.00129194 0.0016691 0.00169267
0.00169267 0.00169267 0.0016691 0.00129194 0.001 0.001 0.00129194
0.00185403 0.00185403 0.00185403 0.00185403 0.00129194 0.001 0.001
0.00129194 0.0016691 0.00215638 0.0027859 0.00359921 0.00464996
0.00523167 0.00523167 0.00523167 0.00464996 0.00359921 0.0027859
0.00215638 0.0016691 0.00129194 0.001 0.001 0.00129194 0.0016691
0.00215638 0.0027859 0.00359921 0.00464996 0.00600746 0.00776126
0.0100271 0.0129543 0.0180487 0.0180487 0.0180487 0.0180487 0.0129543
0.0100271 0.00776126 0.00600746 0.00464996 0.00359921 0.0027859
0.00215638 0.0016691 0.00129194 0.001 0.001 0.00129194 0.0016691
0.00215638 0.0027859 0.00359921 0.00464996 0.00523166 0.00523166
0.00523166 0.00464996 0.00359921 0.0027859 0.00215638 0.0016691
0.00129194 0.001 0.0025 0.004625 0.00855625 0.0171594 0.0171594
0.0171594 0.0171594 0.00855625 0.004625 0.0025 0.001 0.00129194
0.0016691 0.00215638 0.00319129 0.00319129 0.00319129 0.00319129
0.00215638 0.0016691 0.00129194 0.001 0.00425 0.0058225 0.00797683
0.0109283 0.0149717 0.0205254 0.0205254 0.0205254 0.0205254 0.0149717
0.0109283 0.00797683 0.0058225 0.00425 m
```

```
  Y_STEPS                  = 0.00385236 0.00385236 0.00351405
0.00189949 0.00102675 0.000555 0.0003 0.001 0.00129194 0.0016691
0.00215638 0.0027859 0.00359921 0.00464996 0.00600746 0.00776126
0.0100271 0.0145259 0.0145259 0.0145259 0.0145259 0.0100271 0.00776126
0.00600746 0.00464996 0.00359921 0.0027859 0.00215638 0.0016691
0.00129194 0.001 0.001 0.00129194 0.0016691 0.00215638 0.00258839
0.00258839 0.00258839 0.00215638 0.0016691 0.00129194 0.001 0.001
0.001 0.001 0.001 0.001 0.001 0.00129194 0.0016691 0.00215638
0.0027859 0.00359921 0.00464996 0.00600746 0.00776126 0.0100271
0.0129543 0.0130487 0.0130487 0.0130487 0.0130487 0.0129543 0.0100271
0.00776126 0.00600746 0.00464996 0.00359921 0.0027859 0.00215638
0.0016691 0.00129194 0.001 0.0003 0.0006 0.0012 0.0024 0.00525 0.00525
m
  Z_STEPS                  = 1 m
  THETA_Z                  = 0
  PIE_SLICE_ANGLE          = 360

; ********************************************************************

[OUTPUTS]

  [GENERAL]
    OUTPUT_FOLDER            = $(PROJECT_DIR)/1.4.3
2D1_CELLULOSE_Class3.results
    MAX_HYG_RELHUM           = 95 %
    EXP_REF_TEMPER           = 0 C
    EXP_REF_RELHUM           = 60 %
    THAW_BEGIN               = 0
    FREEZE_BEGIN             = 0.01 ---

  [GRIDS]

    [OUTPUT_GRID]
      NAME                     = Hourly
      INTERVAL                 = 0 d            1 h

    [OUTPUT_GRID]
      NAME                     = Daily
      INTERVAL                 = 0 d            1 d

    [OUTPUT_GRID]
      NAME                     = Variable (1 s ... 1 h)
      INTERVAL                 = 1 min          1 s
      INTERVAL                 = 10 min         10 s
      INTERVAL                 = 1 h            1 min
      INTERVAL                 = 0 d            1 h

    [OUTPUT_GRID]
      NAME                     = 2.5 years - Last year Hourly
      INTERVAL                 = 549 d          7 d
      INTERVAL                 = 365 d          1 h

    [OUTPUT_GRID]
      NAME                     = 2.5 years - Last year Daily
      INTERVAL                 = 549 d          7 d
      INTERVAL                 = 365 d          1 d

    [OUTPUT_GRID]
      NAME                     = 2.5 years - Last year Monthly
      INTERVAL                 = 549 d          549 d
      INTERVAL                 = 31 d           1 h
      INTERVAL                 = 28 d           1 h
```

```
    INTERVAL                 = 31 d          1 h
    INTERVAL                 = 30 d          1 h
    INTERVAL                 = 31 d          1 h
    INTERVAL                 = 30 d          1 h
    INTERVAL                 = 31 d          1 h
    INTERVAL                 = 31 d          1 h
    INTERVAL                 = 30 d          1 h
    INTERVAL                 = 31 d          1 h
    INTERVAL                 = 30 d          1 h
    INTERVAL                 = 31 d          1 h
    INTERVAL                 = 1 d           1 h

[FORMATS]

  [OUTPUT_FORMAT]
    NAME                     = Temperature field
    TYPE                     = FIELD
    FIELD_TYPE               = TEMPER
    SPACE_TYPE               = SINGLE
    TIME_TYPE                = NONE
    TIME_UNIT                = d
    VALUE_UNIT               = C
    PRECISION                = 9
    WIDTH                    = 12
    FORMAT                   = DEFAULT
    BINARY                   = yes

  [OUTPUT_FORMAT]
    NAME                     = Relative humidity field
    TYPE                     = FIELD
    FIELD_TYPE               = RELHUM
    SPACE_TYPE               = SINGLE
    TIME_TYPE                = NONE
    TIME_UNIT                = d
    VALUE_UNIT               = %
    PRECISION                = 9
    WIDTH                    = 12
    FORMAT                   = DEFAULT
    BINARY                   = yes

  [OUTPUT_FORMAT]
    NAME                     = Moisture mass
    TYPE                     = FIELD
    FIELD_TYPE               = MOISTURE
    SPACE_TYPE               = SINGLE
    TIME_TYPE                = NONE
    TIME_UNIT                = d
    VALUE_UNIT               = kg/m3
    PRECISION                = 9
    WIDTH                    = 12
    FORMAT                   = DEFAULT
    BINARY                   = no

  [OUTPUT_FORMAT]
    NAME                     = Moisture mass - Integral
    TYPE                     = FIELD
    FIELD_TYPE               = MOISTURE
    SPACE_TYPE               = INTEGRAL
    TIME_TYPE                = NONE
    TIME_UNIT                = d
    VALUE_UNIT               = kg
    PRECISION                = 9
```

```
    WIDTH                        = 12
    FORMAT                       = DEFAULT
    BINARY                       = no

  [OUTPUT_FORMAT]
    NAME                         = Overhygroscopic water- Integral
    TYPE                         = FIELD
    FIELD_TYPE                   = OVHWATMASS
    SPACE_TYPE                   = INTEGRAL
    TIME_TYPE                    = NONE
    TIME_UNIT                    = d
    VALUE_UNIT                   = kg
    PRECISION                    = 9
    WIDTH                        = 12
    FORMAT                       = DEFAULT
    BINARY                       = no

[FILES]

  [OUTPUT_FILE]
    NAME                         = 01_temperature_plaster.out
    OUTPUT_GRID                  = 2.5 years - Last year Hourly
    OUTPUT_FORMAT                = Temperature field

  [OUTPUT_FILE]
    NAME                         = 03_temperature_cavity.out
    OUTPUT_GRID                  = 2.5 years - Last year Hourly
    OUTPUT_FORMAT                = Temperature field

  [OUTPUT_FILE]
    NAME                         = 04_temperature_innergranite.out
    OUTPUT_GRID                  = 2.5 years - Last year Hourly
    OUTPUT_FORMAT                = Temperature field

  [OUTPUT_FILE]
    NAME                         = 05_temperature_mortar.out
    OUTPUT_GRID                  = 2.5 years - Last year Hourly
    OUTPUT_FORMAT                = Temperature field

  [OUTPUT_FILE]
    NAME                         = 11_relhum_plaster.out
    OUTPUT_GRID                  = 2.5 years - Last year Hourly
    OUTPUT_FORMAT                = Relative humidity field

  [OUTPUT_FILE]
    NAME                         = 13_relhum_cavity.out
    OUTPUT_GRID                  = 2.5 years - Last year Hourly
    OUTPUT_FORMAT                = Relative humidity field

  [OUTPUT_FILE]
    NAME                         = 14_relhum_innergranite.out
    OUTPUT_GRID                  = 2.5 years - Last year Hourly
    OUTPUT_FORMAT                = Relative humidity field

  [OUTPUT_FILE]
    NAME                         = 15_relhum_mortar.out
    OUTPUT_GRID                  = 2.5 years - Last year Hourly
    OUTPUT_FORMAT                = Relative humidity field

  [OUTPUT_FILE]
    NAME                         = 41_cavity_moist_mass_integral.out
    OUTPUT_GRID                  = 2.5 years - Last year Daily
```

```
      OUTPUT_FORMAT            = Moisture mass - Integral

    [OUTPUT_FILE]
      NAME                     = 42_cavity_ovh_wat_mass_integral.out
      OUTPUT_GRID              = 2.5 years - Last year Daily
      OUTPUT_FORMAT            = Overhygroscopic water- Integral

    [OUTPUT_FILE]
      NAME                     = 51_temperature_total.out
      OUTPUT_GRID              = 2.5 years - Last year Monthly
      OUTPUT_FORMAT            = Temperature field

    [OUTPUT_FILE]
      NAME                     = 52_relhum_total.out
      OUTPUT_GRID              = 2.5 years - Last year Monthly
      OUTPUT_FORMAT            = Relative humidity field

; *********************************************************************


[ASSIGNMENTS]

  [SELECTION]
    TYPE                       = MATERIAL
    RANGE                      = 0 0 8 78
    NAME                       = Lime Plaster (historical)
    LOCATION                   = ELEMENT

  [SELECTION]
    TYPE                       = MATERIAL
    RANGE                      = 9 0 16 78
    NAME                       = Spruce SW Longitudinal
    LOCATION                   = ELEMENT

  [SELECTION]
    TYPE                       = MATERIAL
    RANGE                      = 34 47 59 78
    NAME                       = Granite boulder
    LOCATION                   = ELEMENT

  [SELECTION]
    TYPE                       = MATERIAL
    RANGE                      = 77 47 86 72
    NAME                       = Granite boulder
    LOCATION                   = ELEMENT

  [SELECTION]
    TYPE                       = MATERIAL
    RANGE                      = 34 7 86 30
    NAME                       = Granite boulder
    LOCATION                   = ELEMENT

  [SELECTION]
    TYPE                       = MATERIAL
    RANGE                      = 34 0 86 6
    NAME                       = Clay Mortar (historical)
    LOCATION                   = ELEMENT

  [SELECTION]
    TYPE                       = MATERIAL
    RANGE                      = 34 31 86 46
    NAME                       = Clay Mortar (historical)
```

```
    LOCATION                  = ELEMENT

  [SELECTION]
    TYPE                      = MATERIAL
    RANGE                     = 60 47 76 78
    NAME                      = Clay Mortar (historical)
    LOCATION                  = ELEMENT

  [SELECTION]
    TYPE                      = MATERIAL
    RANGE                     = 77 73 86 78
    NAME                      = Clay Mortar (historical)
    LOCATION                  = ELEMENT

  [SELECTION]
    TYPE                      = MATERIAL
    RANGE                     = 87 0 98 78
    NAME                      = Clay Mortar (historical)
    LOCATION                  = ELEMENT

  [SELECTION]
    TYPE                      = MATERIAL
    RANGE                     = 99 0 112 41
    NAME                      = Granite (weathered)
    LOCATION                  = ELEMENT

  [SELECTION]
    TYPE                      = MATERIAL
    RANGE                     = 99 47 112 78
    NAME                      = Granite (weathered)
    LOCATION                  = ELEMENT

  [SELECTION]
    TYPE                      = MATERIAL
    RANGE                     = 99 42 112 46
    NAME                      = Lime Cement Mortar
    LOCATION                  = ELEMENT

  [SELECTION]
    TYPE                      = MATERIAL
    RANGE                     = 17 0 33 78
    NAME                      = Blown-in Cellulose
    LOCATION                  = ELEMENT

  [SELECTION]
    TYPE                      = BOUNDARYCOND
    RANGE                     = 0 0 0 78
    NAME                      = Inside Heat Conduction
    LOCATION                  = LEFT
    CONDITION_TYPE            = HEATCOND

  [SELECTION]
    TYPE                      = BOUNDARYCOND
    RANGE                     = 0 0 0 78
    NAME                      = Inside Vapor Diffusion
    LOCATION                  = LEFT
    CONDITION_TYPE            = VAPDIFF

  [SELECTION]
    TYPE                      = BOUNDARYCOND
    RANGE                     = 112 0 112 78
    NAME                      = Outside Heat Conduction
```

```
  LOCATION                  = RIGHT
  CONDITION_TYPE            = HEATCOND

[SELECTION]
  TYPE                      = BOUNDARYCOND
  RANGE                     = 112 0 112 78
  NAME                      = Outside Vapor Diffusion
  LOCATION                  = RIGHT
  CONDITION_TYPE            = VAPDIFF

[SELECTION]
  TYPE                      = BOUNDARYCOND
  RANGE                     = 112 0 112 78
  NAME                      = Sun radiation
  LOCATION                  = RIGHT
  CONDITION_TYPE            = SHWRAD

[SELECTION]
  TYPE                      = INITIALCOND
  RANGE                     = 0 0 16 78
  NAME                      = 17C
  LOCATION                  = ELEMENT
  CONDITION_TYPE            = TEMPER

[SELECTION]
  TYPE                      = INITIALCOND
  RANGE                     = 34 0 59 78
  NAME                      = 11C
  LOCATION                  = ELEMENT
  CONDITION_TYPE            = TEMPER

[SELECTION]
  TYPE                      = INITIALCOND
  RANGE                     = 34 0 59 78
  NAME                      = 73%
  LOCATION                  = ELEMENT
  CONDITION_TYPE            = RELHUM

[SELECTION]
  TYPE                      = INITIALCOND
  RANGE                     = 60 0 112 78
  NAME                      = 7C
  LOCATION                  = ELEMENT
  CONDITION_TYPE            = TEMPER

[SELECTION]
  TYPE                      = INITIALCOND
  RANGE                     = 60 0 112 78
  NAME                      = 78%
  LOCATION                  = ELEMENT
  CONDITION_TYPE            = RELHUM

[SELECTION]
  TYPE                      = INITIALCOND
  RANGE                     = 0 0 16 78
  NAME                      = 60%
  LOCATION                  = ELEMENT
  CONDITION_TYPE            = RELHUM

[SELECTION]
  TYPE                      = FIELDOUTPUT
  RANGE                     = 25 44 25 44
```

```
    NAME                         = 03_temperature_cavity.out
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    LOCATION                     = ELEMENT
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APPENDIX 8 – NUMERICAL SIMULATION: RESULTS OF THE EXPLORATORY STUDIES

The first aspect explored in the preliminary calculations was the time needed to reach moisture balance in the wall after the insulation. Determining the time before equilibrium was crucial to define the duration of final simulations that were much more detailed and required more computational resources.

In the exploratory study, moisture equilibrium was understood to be reached when the annual gradient, i.e. increase or decrease of calculated moisture related parameters, was close to zero.

The sample was formed by two-dimensional models of the front wall. The simulations duration was set to 10 years and the external boundary was characterised using the synthetic Design Reference Year for Aberdeen Dyce (from the IWEC database). The internal climate was simulated using the three different classes resulted from this research plus a constant climate with fixed values of temperature and humidity (20 °C, 50 %). Four different configurations of the cavity were simulated:

- Cavity. Non-retrofitted wall. Space between masonry and lath and plaster was simulated as a vertical air gap of 50 mm.
- Cellulose. Retrofitted wall. Cavity filled with blow-in-cellulose.
- PURclosed. Retrofitted wall. Cavity filled with closed-cell polyurethane foam.
- PURopen. Retrofitted wall. Cavity filled with open-cell polyurethane foam.

Since the conditions in the cavity were not known, the initial conditions of all materials were set to 20 °C and 80 %. A total of 16 different scenarios were simulated. The results are summarised in Table 10-3, Table 10-4 and Table 10-5.

Table 10-3 Results of exploratory investigation on moisture equilibrium in walls insulated with Cellulose

Cellulose	Average Moisture Content (kg/m³)				Time @ RH > 95% (d)				Maximum Condensate (g/m³)				Time at Risk of Mould Growth (d)			
	Constant	Class I	Class II	Class III	Constant	Class I	Class II	Class III	Constant	Class I	Class II	Class III	Constant	Class I	Class II	Class III
Year 1	4.78	4.66	5.62	7.32	64	0	53	183	37.4	0.0	52.0	2490.5	179	90	225	308
Year 2	4.82	4.64	5.74	8.15	68	0	91	218	109.5	0.0	188.3	2962.4	180	92	241	365
Year 3	4.82	4.64	5.75	8.23	68	0	91	221	110.0	0.0	201.3	3054.5	180	91	242	365
Year 4	4.82	4.64	5.76	8.28	68	0	91	224	109.5	0.0	206.4	3099.1	180	90	242	365
Year 5	4.82	4.63	5.76	8.31	68	0	91	226	109.0	0.0	209.0	3128.0	180	90	242	365
Year 6	4.81	4.63	5.76	8.33	68	0	91	227	108.6	0.0	211.2	3150.8	180	90	242	365
Year 7	4.81	4.63	5.76	8.35	68	0	91	229	108.1	0.0	212.4	3169.6	180	90	242	365
Year 8	4.81	4.63	5.77	8.37	68	0	91	230	107.9	0.0	213.5	3185.2	180	90	242	365
Year 9	4.81	4.63	5.77	8.39	68	0	91	230	107.8	0.0	214.2	3198.5	180	90	242	365
Year 10	4.81	4.63	5.77	8.40	68	0	91	231	107.4	0.0	215.1	3210.0	180	90	242	365

Table 10-4 Results of exploratory investigation on moisture equilibrium in walls insulated with PURclosed

PUR Closed	**Average Moisture Content (kg/m^3)**				**Time @ RH > 95% (d)**				**Maximum Condensate (g/m^3)**				**Time at Risk of Mould Growth (d)**			
	Constant	Class I	Class II	Class III	Constant	Class I	Class II	Class III	Constant	Class I	Class II	Class III	Constant	Class I	Class II	Class III
Year 1	0.79	0.78	0.89	1.05	0	0	0	0	0.0	0.0	0.0	0.0	96	0	127	334
Year 2	0.80	0.79	0.92	1.17	0	0	0	0	0.0	0.0	0.0	0.0	136	0	233	365
Year 3	0.80	0.78	0.92	1.21	0	0	0	0	0.0	0.0	0.0	0.0	134	0	240	365
Year 4	0.79	0.78	0.92	1.23	0	0	0	0	0.0	0.0	0.0	0.0	130	0	241	365
Year 5	0.79	0.78	0.92	1.24	0	0	0	0	0.0	0.0	0.0	0.0	125	0	239	365
Year 6	0.79	0.78	0.92	1.26	0	0	0	0	0.0	0.0	0.0	0.0	121	0	238	365
Year 7	0.79	0.77	0.92	1.27	0	0	0	0	0.0	0.0	0.0	0.0	120	0	238	365
Year 8	0.79	0.77	0.92	1.27	0	0	0	0	0.0	0.0	0.0	0.0	117	0	238	365
Year 9	0.79	0.77	0.92	1.28	0	0	0	0	0.0	0.0	0.0	0.0	116	0	236	365
Year 10	0.79	0.77	0.92	1.29	0	0	0	0	0.0	0.0	0.0	0.0	115	0	236	365

Table 10-5 Results of exploratory investigation on moisture equilibrium in walls insulated with PURopen

PUR Open	**Average Moisture Content (kg/m^3)**				**Time @ RH > 95% (d)**				**Maximum Condensate (g/m^3)**				**Time at Risk of Mould Growth (d)**			
	Constant	Class I	Class II	Class III	Constant	Class I	Class II	Class III	Constant	Class I	Class II	Class III	Constant	Class I	Class II	Class III
Year 1	1.02	0.81	1.19	4.28	89	0	87	226	404.4	0.0	565.7	8306.6	182	130	242	350
Year 2	1.24	0.81	1.61	10.36	114	0	128	273	1306.1	0.0	1547.8	19194.1	183	141	244	365
Year 3	1.25	0.81	1.64	11.05	114	0	130	277	1330.0	0.0	1649.7	20418.1	183	139	244	365
Year 4	1.25	0.81	1.66	11.34	114	0	131	280	1336.8	0.0	1688.8	20911.8	183	137	244	365
Year 5	1.25	0.81	1.67	11.53	114	0	131	281	1336.6	0.0	1711.2	21225.5	183	137	244	365
Year 6	1.25	0.81	1.68	11.68	114	0	132	282	1337.4	0.0	1728.9	21462.9	183	136	244	365
Year 7	1.25	0.81	1.68	11.80	114	0	132	284	1338.2	0.0	1740.3	21658.6	183	136	244	365
Year 8	1.25	0.81	1.68	11.91	114	0	132	285	1339.0	0.0	1750.1	21828.6	183	136	244	365
Year 9	1.25	0.81	1.69	11.99	114	0	132	285	1338.6	0.0	1757.4	21964.8	183	136	244	365
Year 10	1.25	0.81	1.69	12.07	114	0	132	285	1339.9	0.0	1764.0	22083.8	183	135	244	365

The analysis of the results presented below is exclusively based on walls simulated with constant internal climate. Since all the scenarios had identical initial conditions in the cavity (20 °C and 80%), the total moisture content of the insulation only depended on the material physical properties. Thus, the initial moisture content of PURclosed and PURopen was 53.9 g/m^2 (1.08 kg/m^3) while the moisture content in the Blown-in Cellulose was 318.1 g/m^2 (6.36 kg/m^3). Therefore, looking at the absolute gradient of total moisture was the best way of comparing the different scenarios (Figure 10-1).

First year gradient was only positive in walls insulated with PURopen. The insulation moisture content increased 35.5 g/m^2 (0.71 kg/m^3) at the end of the first year. In the other two cases, PURclosed and Cellulose, the insulation moisture content decreased after one year 11.5 g/m^2 (0.23 kg/m^3) and 35.9 g/m^2 (0.72 kg/m^3) respectively. The annual gradient of total moisture content in the cavity was close to zero in the second year for all three scenarios.

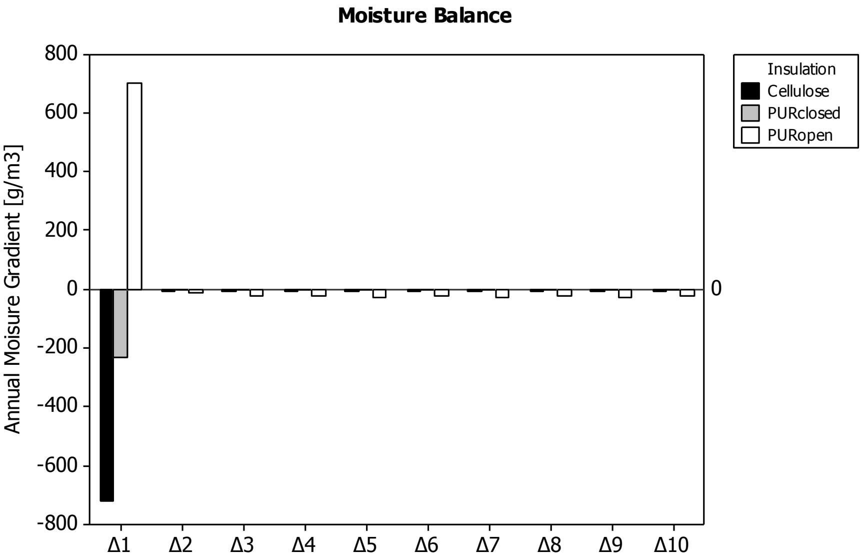

Figure 10-1 Exploratory studies (duration). Moisture balance results.

Risk of interstitial condensation was the next parameter assessed to evaluate the moisture balance in the wall (Figure 10-2). The condensation risk was calculated at the interface between the masonry wall and the insulation. Assuming that condensation occurs when the relative humidity exceeds 95 %, the assessment was done comparing the annual increase, or decrease, in the number of days when the average relative humidity was above that level.

The walls insulated with PURclosed did not registered risk of condensation at any time. In the cases insulated with Cellulose and PURopen, the days at risk of interstitial condensation during the first year were 64 and 89 respectively. In the second year, time at risk increased by 4 and 25 days respectively. After the second year, the time at risk of interstitial condensation remained stable for the rest of the simulation.

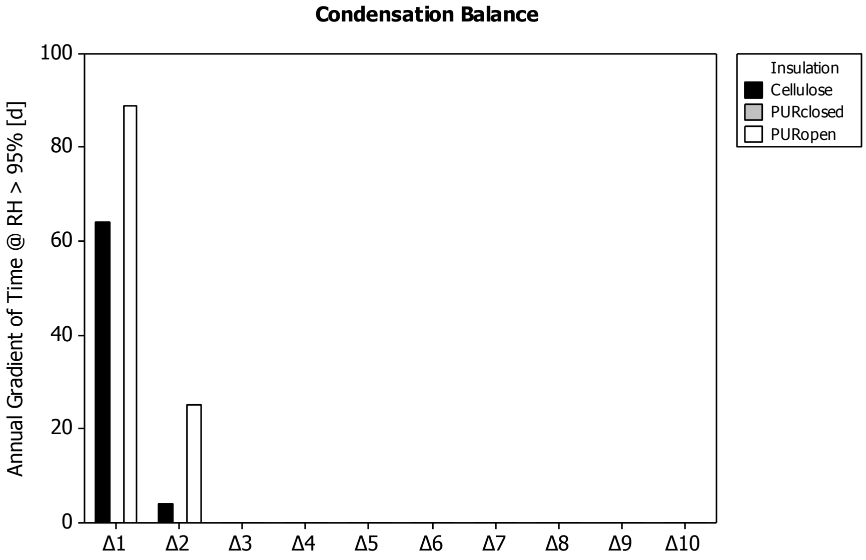

Figure 10-2 Exploratory studies (duration). Condensation balance results.

Additionally, the results of moisture content did not show accumulation at the end of the simulation. That indicated that any condensation occurred in the wall during the cold months dried out in summer and therefore the annual balance always equalled zero. The maximum amount of condensation in the wall, however, did change over time (Figure 10-3).

In the first year, the maxim amount of overhygroscopic water present in the insulation was 1.9 g/m^2 (0.04 kg/m^3) for the Cellulose and 20.2 g/m^2 (0.40 kg/m^3) for the PURopen. In the second year, the peak raised to 5.5 g/m^2 (0.11 kg/m^3) and 65.3 g/m^2 (1.31 kg/m^3) respectively. After the second year, the condensation peaks remained stable in walls insulated with Cellulose and increased slightly for walls with PURopen (1.84 % in the 3rd and 0.45 % in the 4th year).

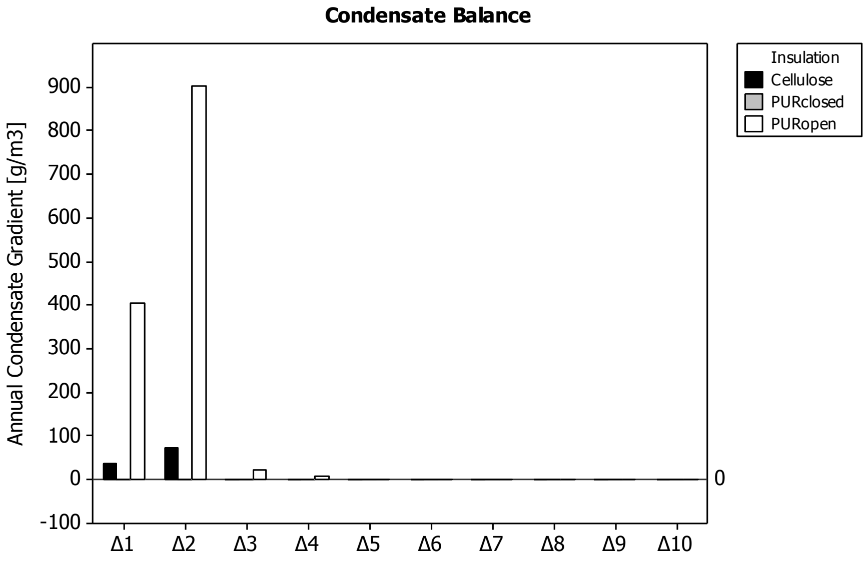

Figure 10-3 Exploratory studies (duration). Condensate balance results.

The last parameter observed to evaluate the wall moisture balance after the insulation was the number of days at which the wall interface conditions were favourable for mould formation. As for the condensation analysis, the assessment was done looking at the annual increase in the number of days at risk of mould growth.

All the scenarios presented conditions favourable for mould growth in the first year (179, 96 and 182 days respectively) (Figure 10-4). During the second year, however, the number of days remained almost stable in cases with Cellulose and PURopen (only 1 day increase) while augmented in 40 days in the case with PURclosed. As of the third year, the risk of mould growth in walls with PURclosed decreased slightly but constantly until the end of the simulation.

Considering the results obtained it can be concluded that the moisture equilibrium was reached after the second year in all the scenarios. As a result, the detailed simulations were configured to start on the 1st of May, lasting 914 days (2.5 years). During the first summer after the insulation, the conditions would be favourable for the initial moisture to dry out. During the first winter, moisture would start to accumulate in the wall due to the vapour diffusion from the internal climate. A portion of this moisture would dry out during the following warm season. The last complete year, when the conditions have proved to be stable, was used to evaluate the impact of the different internal climates.

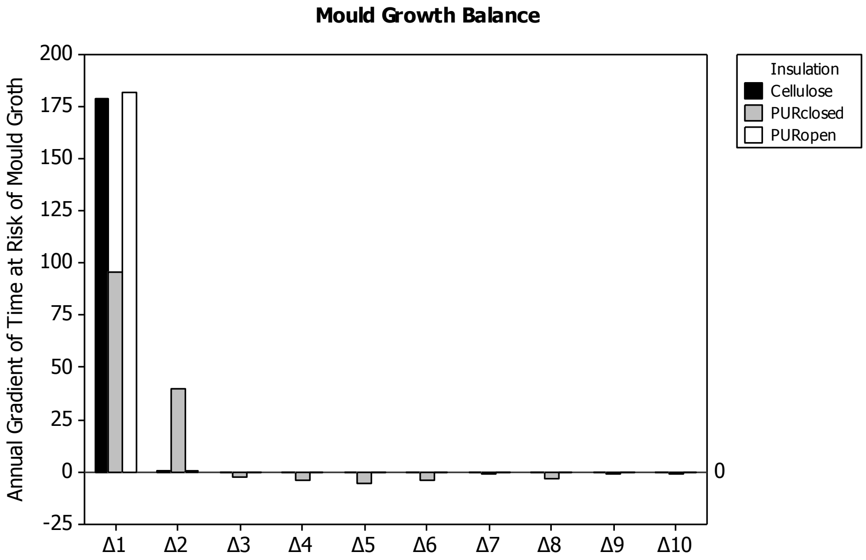

Figure 10-4 Exploratory studies (duration). Mould growth balance results.

After the definition of the simulations optimal duration, based on the moisture equilibrium, it was important to decide the characteristics of the model. In order to calculate the moisture dynamics in the envelope, walls have to be simplified and translated into an abstract model. These models can be represented in one or two dimensions. In a two-dimensional model, the materials are combined trying to reproduce the heterogeneity of an actual wall while in a one-dimensional model the wall is formed by homogenous layers of continuous materials. While two-dimensional models produce more detailed results and provide more information about the moisture migration in the wall, one-dimensional simulations are much less consuming in terms of computational resources.

One-dimensional simulations have been successfully used in previous research looking at internal insulation of sandstone masonry walls. In this case, however, due to the vapour resistant characteristics of granite the accuracy and feasibility of one-dimensional models had to be revised.

Based on a two-dimensional model, three different one-dimensional models were created. Each model represented a different section of the two-dimensional model (Figure 10-5).

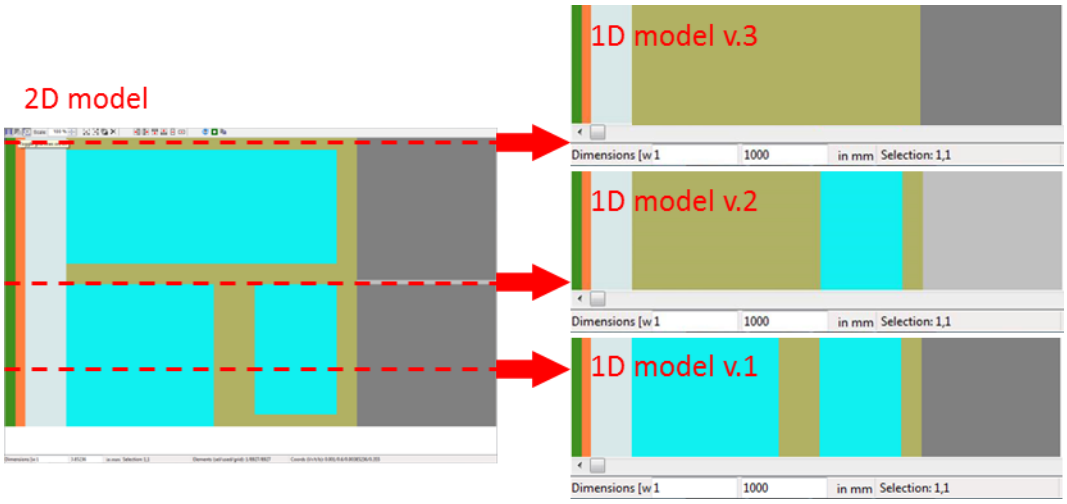

Figure 10-5 Modelling of the wall assembly: Two-dimensional model (left) and simplified one-dimensional models (right).

The simulations used a configuration similar to the previous study. Duration was set to 10 years and the external boundary used the Design Reference Year for Aberdeen Dyce. The internal climate was simulated using the three different classes and a constant climate. The same four configurations of the cavity were simulated: Cavity, Cellulose, PURclosed and PURopen. The initial conditions were set again to 20 °C and 80 %. A total of 64 different scenarios were simulated (Figure 10-6).

Table 10-6 Summary of scenarios simulated for the evaluation of the geometrical representation on the wall

		2D model	1D model v.1	1D model v.2	1D model v.3
Cavity	Constant	2D.1.0	1D1.1.0	1D2.1.0	1D3.1.0
	Class I	2D.1.1	1D1.1.1	1D2.1.1	1D3.1.1
	Class II	2D.1.2	1D1.1.2	1D2.1.2	1D3.1.2
	Class III	2D.1.3	1D1.1.3	1D2.1.3	1D3.1.3
PUR Closed	Constant	2D.2.0	1D1.2.0	1D2.2.0	1D3.2.0
	Class I	2D.2.1	1D1.2.1	1D2.2.1	1D3.2.1
	Class II	2D.2.2	1D1.2.2	1D2.2.2	1D3.2.2
	Class III	2D.2.3	1D1.2.3	1D2.2.3	1D3.2.3
PUR Open	Constant	2D.3.0	1D1.3.0	1D2.3.0	1D3.3.0
	Class I	2D.3.1	1D1.3.1	1D2.3.1	1D3.3.1
	Class II	2D.3.2	1D1.3.2	1D2.3.2	1D3.3.2
	Class III	2D.3.3	1D1.3.3	1D2.3.3	1D3.3.3
Cellulose	Constant	2D.4.0	1D1.4.0	1D2.4.0	1D3.4.0
	Class I	2D.4.1	1D1.4.1	1D2.4.1	1D3.4.1
	Class II	2D.4.2	1D1.4.2	1D2.4.2	1D3.4.2
	Class III	2D.4.3	1D1.4.3	1D2.4.3	1D3.4.3

Table 10-7 Summary of exploratory investigation. Geometrical representation of the wall (Results for 2nd year of the simulation)

		Average Relative Humidity (%)				Average Moisture Content (kg/m^3)				Maximum Condensate (g/m^3)			
		2D	**1D.1**	**1D.2**	**1D.3**	**2D**	**1D.1**	**1D.2**	**1D.3**	**2D**	**1D.1**	**1D.2**	**1D.3**
Cavity	Constant	61.9	61.8	58.4	58.2	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.01
	Class I	66.6	66.6	64.4	64.2	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.01
	Class II	76.4	76.5	73.2	73.2	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.01
	Class III	81.5	81.6	77.5	77.4	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.01
Cellulose	Constant	64.6	64.7	61.7	61.5	1.71	4.85	4.40	4.38	0.04	0.27	0.00	0.00
	Class I	64.1	64.1	61.7	61.6	1.65	4.64	4.37	4.35	0.00	0.00	0.00	0.00
	Class II	73.4	73.7	70.5	70.4	2.04	5.81	5.25	5.23	0.07	0.45	0.00	0.00
	Class III	81.9	83.3	78.5	78.5	2.89	8.74	6.30	6.28	1.05	4.00	0.00	0.00
PURclosed	Constant	63.9	64.3	61.7	61.6	0.28	0.81	0.75	0.75	0.00	0.00	0.00	0.00
	Class I	63.8	64.1	62.3	62.2	0.28	0.79	0.76	0.75	0.00	0.00	0.00	0.00
	Class II	71.5	72.3	62.3	68.5	0.32	0.94	0.76	0.83	0.00	0.00	0.00	0.00
	Class III	79.0	80.2	74.9	74.8	0.41	1.26	0.94	0.94	0.00	0.00	0.00	0.00
PURopen	Constant	64.8	65.0	62.3	62.1	0.44	1.52	0.77	0.77	0.46	2.30	0.00	0.00
	Class I	64.3	64.4	62.2	62.1	0.29	0.82	0.76	0.76	0.00	0.00	0.00	0.00
	Class II	73.6	74.0	70.9	70.8	0.57	2.01	0.91	0.90	0.55	2.83	0.00	0.00
	Class III	82.1	83.5	78.6	78.6	3.67	13.21	1.25	1.24	6.81	24.62	0.00	0.00

The results discussed below are based exclusively on the scenarios simulated with constant internal climates. Furthermore, since walls insulated with PURopen presented the most critical results, the validation of the model was done exclusively based on the analysis of the results for that scenario. The results of models 1D2 and 1D3 were very similar and therefore only one (1D2) was included in the assessment. The validity of the model was assessed based on two main parameters: (i) relative humidity and (ii) moisture content (both total and overhygroscopic).

A one-way analysis of variance (ANOVA), followed by a Tuckey post-hoc test, was performed to investigate the differences in the means of the three samples (2D, 1D1, 1D2).

The first analysis looked at the relative humidity levels in the cavity during the second year of the simulation (Figure 10-6a). There was a statistically significant difference between one and two dimensional models as determined by one-way ANOVA ($F(2,1092) = 29.25$, $p < 0.001$). A Tukey test revealed that the relative humidity in the cavity of model 1D2 was significantly lower (62.25% ± 3.2) than 1D1 (65.02% ± 6.76) and 2D (64.76% ± 5.66). The differences between 1D1 and 2D models were no statistically significant.

The analysis of the relative humidity levels at the interface between the masonry and the insulation showed similar results. In two-dimensional models, the relative humidity was calculated at two different locations: at the interface between the insulation and a granite stone and at the interface between insulation and the mortar joints.

Differences between one and two dimensional models were again significant, as determined by one-way ANOVA ($F(3,1456) = 17.35$, $p < 0.001$). A Tukey test revealed that the humidity measured in the 1D2 model was significantly lower (74.52% ± 8.94) when compared with 1D1 (80.57% ± 15.54) and both locations calculated in the 2D model (mortar: 79.92% ± 13.25; granite: 80.61% ± 15.81).

Cavity moisture content results showed significant differences between all the models ($F(2,1092) = 78.38$, $p < 0.001$) (Figure 10-6b). A Tukey test revealed that the total moisture content measured in the cavity was different in all three models: 1D2 (0.0386 kg/m^3 ± 0.003); 2D (0.0620 kg/m^3 ± 0.0375); 1D1 (0.0759 kg/m^3 ± 0.060)

Similar results were obtained when looking at the maximum overhygroscopic content (Figure 10-6c). In the second year of the simulation, there was a significant difference between all the models (F(2,1092) = 61.24, $p < 0.001$). A Tukey test revealed that the condensate measured in the cavity was different in all three models: 1D2 (0.00003 kg/m^3 ± 0.0005) ; 2D (0.00950 kg/m^3 ± 0.01885); 1D1 (0.01956 kg/m^3 ± 0.03675)

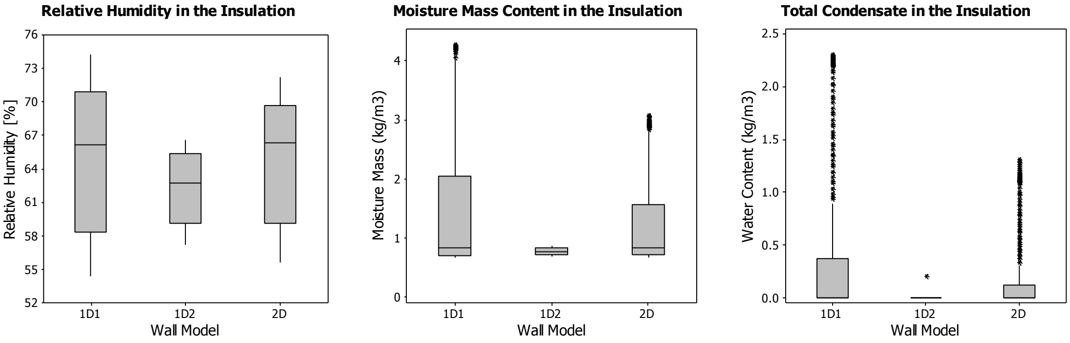

Figure 10-6 Exploratory studies (geometry). Results of (a) relative humidity, (b) moistre content and (c) condensate.

Relative humidity difference between 2D and 1D1 models was not significant. However, there were some important discrepancies in the amount of moisture and condensate accumulated in the cavity of these models (Figure 10-7). That can be explained as an effect of the mortar layers in the wall that were able to absorb and release some moisture.

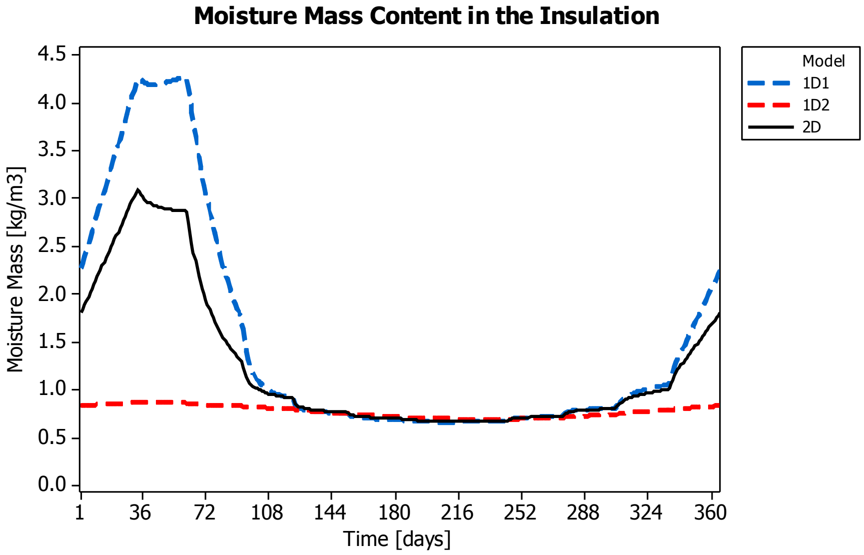

Figure 10-7 Exploratory studies (geometry). Moisture mass content evolution.

Therefore, using one-dimensional models would result in an overestimation of the wall moisture values. Overestimation of results would be especially important on gable walls, where the fraction of mortar is higher and the thickness of the wall is considerably smaller. As a result, simulation of two-dimensional models was adopted in this research. Furthermore, using two-dimensional models allowed the exploration of moisture dynamics in complex scenarios such as the junction between intermediate floors and the external wall.

The last aspect evaluated in the exploratory studies was the configuration of external climate. Most of the climatic parameters (temperature, humidity, solar radiation, wind speed, wind direction, rain, etc.) can be used to define the external boundary. However, the computational resources that are needed to perform the calculations increase with the level of detail used to define the external climate. Therefore, the objective of this study was to define an optimal external boundary that produced accurate results while minimising the computational resources needed.

In order to find the most suitable boundary, four different scenarios of external climate were compared.

- No_Rad. Only external temperature and relative humidity are considered.
- Solar_Rad. The external boundary includes the solar radiation, both diffuse and direct.
- WDR. Besides the solar rations, the external boundary considers the combined effect of wind and rain.
- WDR_South. Same scenario as WDR but with the wall oriented to the South.

The sample was formed by simulations of two-dimensional models of the front wall. The simulation duration was set to 2.5 years and the data collected from the Weather Station were used for the external boundary definition. The simulated walls were insulated with PURopen in the cavity between the masonry wall and the internal lath and plaster. The initial conditions of the insulation were always set to 20 °C and 80 %. Four different internal climates were considered: the proposed internal climates and a constant scenario set to 20 °C and 50 %. A total of 16 scenarios were simulated. The results are summarised in Table 10-8. The discussion presented below is limited to the last year results under humidity classes I, II and III.

Table 10-8 Summary of exploratory investigation. Configuration of the external boundary.

PURopen		Risk of Condensation (h)	Risk of Mould Growth (h)	Maximum Condensate Content (g/m^2)	Total Moisture Content Increase (kg/m^3)	ΔThermal Conductivity (W/mK)
No_Rad	Constant	3178	4729	91.6	0.00	0.000
	Class I	0	5101	0.0	0.00	0.001
	Class II	4418	8761	168.9	0.02	0.003
	Class III	8761	8761	1560.8	5.88	0.019
Solar_Rad	Constant	1834	3732	43.4	0.00	0.000
	Class I	0	2478	0.0	0.00	0.001
	Class II	2805	5313	56.2	0.00	0.002
	Class III	5330	7894	728.5	0.02	0.010
WDR	Constant	2839	4539	226.0	0.05	0.000
	Class I	154	4455	21.8	0.06	0.001
	Class II	3542	7045	321.1	0.27	0.005
	Class III	6222	8761	1327.6	1.21	0.017
WDR_South	Constant	4226	5691	911.2	0.06	0.000
	Class I	0	2887	24.3	0.03	0.001
	Class II	652	5796	126.1	0.08	0.003
	Class III	4494	8605	906.8	0.40	0.012

Time at risk of mould growth was the first parameter assessed to evaluate the feasibility of different external boundaries (Figure 10-8). The scenario that did not consider any form of solar radiation obtained the highest results for risk of mould growth. Results were especially high for humidity classes II and III, where the conditions were permanently favourable for the initiation of mould growth. The other three scenarios (Solar_Rad, WDR and WDR_South) obtained comparable values. Furthermore, the effect of internal climate in all three scenarios was similar.

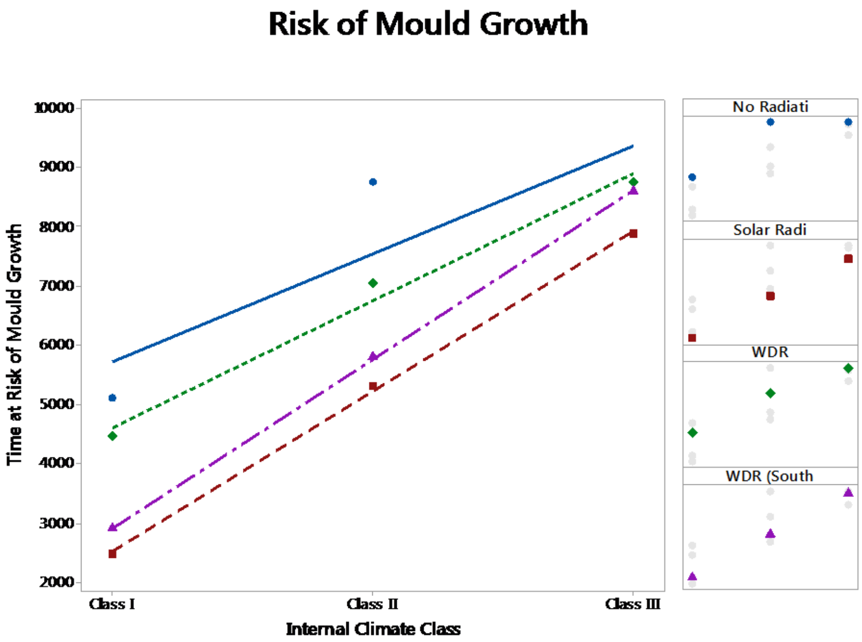

Figure 10-8 Exploratory studies (external climate). Mould growth results.

Looking at the risk of interstitial condensation between the masonry and the insulation (Figure 10-9), the scenario without solar radiation obtained the highest values again. Under the humidity Class III, the risk of condensation was permanent and the relative humidity levels were above 95% for the entire year. The other three scenarios registered comparable values (Solar_Rad = 5330 h; WDR = 622 h; WDR_South = 4494 h).

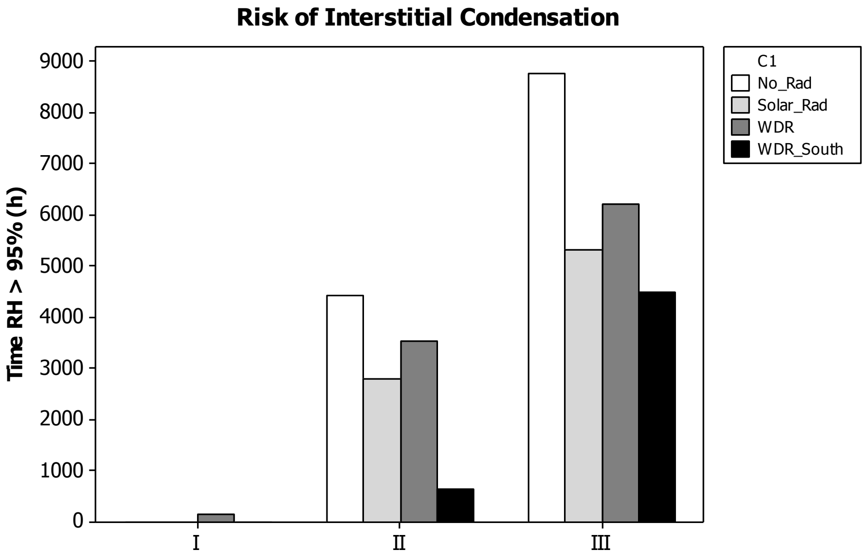

Figure 10-9 Exploratory studies (external climate). Condensation results.

Lastly, the results of moisture balance at the end of the simulation last year showed important discrepancies between the different scenarios (Figure 10-10). Results obtained under class I and II are comparable independent of the external boundary. However, when the internal boundary was simulated with high moisture loads, the model without radiation obtained much higher values.

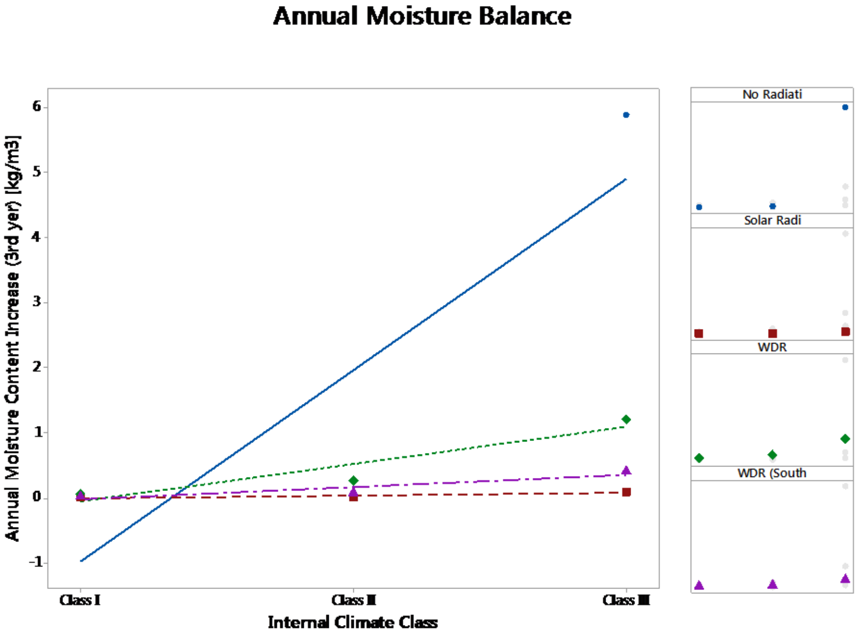

Figure 10-10 Exploratory studies (external climate). Moisture balance results.

Therefore, the simplest external climate (No_Rad) was discarded in order to avoid an overestimation of the internal climate effect. The other three scenarios obtained comparable results but the scenarios that considered wind driven rain (WDR and WDR_South) required intense computing resources and the calculation was very time consuming. An external climate defined by temperature, relative humidity and solar radiation was therefore chosen for the external boundary configuration.

APPENDIX 9 – LIST OF PUBLICATIONS

Published peer-reviewed papers in conference proceedings

Herrera-Gutierrez-Avellanosa D and Bennadji A. *Analysis of indoor climate and occupants' behaviour in traditional Scottish dwellings*. Energy Procedia, Science Direct, Elsevier. 6th International Building Physics Conference, Turin (Italy), June, 2015. [Accessible from : http://www.sciencedirect.com/science/article/pii/S1876610215017786]

Herrera-Gutierrez-Avellanosa D and Bennadji A. *Environmental assessment of energy efficiency improvements in historic buildings: solid wall insulation*. 2014 International Conference of Architectural Technology (ICAT) Conference, Aberdeen (UK), November, 2014. [Accessible from :https://openair.rgu.ac.uk/bitstream/handle/10059/1153/Bennadji%20ICAT2014%20environmental.pdf?sequence=1&isAllowed=y]

Herrera-Gutierrez-Avellanosa D and Bennadji A. *A risk based methodology to assess the energy efficiency improvements in traditionally constructed buildings*. XXIV International CIPA 2013 Symposium Recording, Documentation and Cooperation for Cultural Heritage, Strasbourg (France), September, 2013. [Accessible from : http://cipa.icomos.org/fileadmin/template/doc/STRASBOURG/ARCHIVES/isprsarchives-XL-5-W2-337-2013.pdf]

Conference papers

Herrera-Gutierrez-Avellanosa D and Bennadji A. *Exploring the indoor climate of traditional dwellings following energy efficient refurbishments*. 2nd IDEAS Symposium on Innovation, Design and Sustainability Research, Aberdeen (UK), May, 2015.

Herrera-Gutierrez-Avellanosa D. and Bennadji A. *A decision making analysis of the energy efficiency improvements in Scottish traditional buildings*. BEHAVE Behaviour and Energy Efficiency Conference, Oxford (UK), September, 2014.

Herrera-Gutierrez-Avellanosa D. Understanding the influence of occupants' behaviour on the hygrothermal performance of insulated solid walls in traditional housing. New researchers' colloquium ENHR 2014, Edinburgh (UK), July, 2014.

Herrera-Gutierrez-Avellanosa D. *Analysis of indoor climate measurements in traditional Scottish buildings*. 1st IDEAS Symposium on Innovation, Design and Sustainability Research, Aberdeen (UK), March, 2014.

Herrera-Gutierrez-Avellanosa D and Bennadji A. *Energy efficiency improvements in historic buildings. Developing an assessment methodology for the Scottish built heritage*. Conference on Reuse of Architectural Heritage, Madrid (Spain), June, 2013.

Poster presentations

Herrera-Gutierrez-Avellanosa D. *Exploring the influence of occupants' behaviour on the hygrothermal performance of solid walls*. [Best poster presentation award]. IDEAS 2015 Poster Lunch Event. Faculty of Design and Technology, Aberdeen (UK), December, 2015.

Herrera-Gutierrez-Avellanosa D. *Understanding the influence of occupants' behaviour on the hygrothermal performance of solid walls*. [Best poster presentation award]. RSA student led conference in applied research, Aberdeen (UK), April, 2014.

Herrera-Gutierrez-Avellanosa D and Bennadji A. *Energy efficiency improvements in traditional constructed buildings*. Heritage Research: Showcasing the Future. Historic Scotland & RCAHMS, Edinburgh (UK), February, 2014.

Herrera-Gutierrez-Avellanosa D and Bennadji A. *Combining retrofit and renewable energies to meet current building standards*. Energetica. Perspectives on placemaking conference, Aberdeen (UK), June, 2013.

Bennadji A and Herrera-Gutierrez-Avellanosa D. *Renewable energies ambiguities and selection criteria*. Energetica. Perspectives on placemaking conference, Aberdeen (UK), June, 2013.

Herrera-Gutierrez-Avellanosa D and Bennadji A. *Energy efficient homes: Implementation of renewable energies in retrofitted buildings*. All-Energy conference, Aberdeen (UK), May, 2013.

Bennadji A and Herrera-Gutierrez-Avellanosa D. *Decision making criteria in adopting renewable energies in the built environment*. All-Energy conference, Aberdeen (UK), May, 2013.