THE DISTRIBUTION OF HISTORIC TIMBER-FRAMED BUILDINGS IN THE UK AND THE IMPACTS OF THEIR LOW ENERGY RETROFIT

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

Welsh School of Architecture, Cardiff University

Christopher J. Whitman 2017

Cover: C15th timber framing, The Manor House (left) and 53 Church Street (right), Lavenham, Suffolk. Source: (Author's own, 2017)

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This work has not been submitted in substance for any other degree or award at this or any other university or place of learning, nor is being submitted concurrently in candidature for any degree or other award.

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Summary

This thesis has quantified that approximately 68,000 examples of timber-framed buildings, built pre-1850, survive to this day. By mapping their geographic location, it becomes apparent that they are predominantly concentrated in the East and Southeast of England, and to a lesser extent in the West Midlands and Welsh Marches, their distribution showing correlation to the historic availability of building materials, climatic conditions and socio-economic factors.

As we aim to improve the energy efficiency of our historic buildings, care must be taken to minimize any negative impacts on the existing building fabric. A balance must be achieved between conservation and improved efficiency to avoid damage to their significance, character and historic fabric. Research to date has focused on the retrofit of solid masonry wall construction, with little investigation into timber-framed buildings. Although guidance on the subject exists, there is minimal academic research to validate the approaches proposed. This thesis aims to begin to address this previously under-researched area.

In situ monitoring and digital simulation of five case studies allowed the analysis of current approaches to the retrofit of timber-framed properties. The results suggest that improving airtightness should be prioritised over improvements to the thermal performance of walls. It also indicates that monitoring and simulation should form part of any retrofit decision making process, to ensure the greatest improvements in performance with the minimum loss or risk to historic fabric.

Concurrently, the use of interstitial hygrothermal simulation software WUFI®Pro 5.3 was used to simulate proposed replacement panel infill details. Whilst no substantial risk of biological attack has been identified, further physical testing is recommended to corroborate these findings, and simulations should be repeated for specific climates and orientations prior to their use.

Together with future research, it is hoped that this thesis will begin to inform guidance that will enable these buildings that have stood for hundreds of years to survive for many more to come.

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1 INTRODUCTION

1.0 Introduction

Heritage buildings have often been considered as being "off-limits" when considering energy refurbishment projects, however rising energy prices, stricter legislation (Todorović, 2012) and increasing expectations of thermal comfort mean that they can no longer be ignored. Centuries-old walls are now being thermally upgraded with the aim of reducing greenhouse-gas[1] emissions, lowering energy bills, and improving hygrothermal[2] comfort. However, in the case of historic and heritage properties any refurbishment is a complex issue, involving aesthetic considerations in addition to technical issues (English Historic England, 2012, British Standards Institution, 2015a). The hygrothermal behaviour of wall build-ups in buildings of traditional materials must also be fully understood in order to avoid problems of interstitial moisture, long-term decay and overheating. Research to date has focused mainly on solid-walled masonry construction (Scott and Rye, 2014, Mohammadpourkarbasi and Sharples, 2013, Gandhi et al., 2012), with little work being conducted on timber-framed construction. Although guidance does exist on the retrofit of historic timber-framed buildings, there is little academic research to validate the approaches proposed. This research therefore aims to explore this previously under-researched area.

1.1 Scope

The subject matter of this thesis is the domestic, commercial, agricultural and public buildings built in the UK prior to 1850, where timber framing forms all or part of the external building envelope. It is acknowledged that many buildings hide timber-frame structures behind masonry façades (Alcock, 1981 p79, Brunskill, 1985 p.47), however for

[1] Gases contributing to climate change, including carbon dioxide, methane, nitrous oxide, hydroflurocarbons, perfluorocarbons and sulphur hexafluroride (2008a p.44). Of these carbon dioxide is the most linked to building energy retrofit due to it arising from the combustion of fossil fuels (Nichol et al., 2012 p.160)

[2] Relating to both temperature and moisture

the purpose of this research, such buildings encased within a continuous masonry envelope will not be considered, nor will those where the timber framing is applied as decoration and does not form an integral part of the building structure. This is due to the fundamental differences between the hygrothermal performance of timber-framed and solid masonry construction. Unlike their counterparts in Scandinavia and North America, historic timber-framed buildings in the UK predominantly consist of an exposed structural timber frame with solid infill panels (Figure 1). These panels can be typically of wattle-and-daub[3], fired brick or lath[4] and plaster, with other regional variations (Reid, 1989).

Figure 1. Church Lane, Ledbury, Herefordshire. A collection of C15th and C17th timber-framed buildings. Source: (Author's own, 2016)

Whilst representing only a small percentage of the national pre-1850 housing stock, 7.25% in England (Nicol et al., 2014), 1.6% in Wales and almost non-existent in Scotland (Naismith, 1985) and Northern Ireland (Gailey, 1984), many of these 68,000 buildings (Historic England, 2014, RCAHMW, 2014) have stood for over 500 years and form an important

[3] A traditional panel infill consisting of clay render (daub) supported by a network of woven thin timber members (wattlework) (Brunskill, 1985 p.185)
[4] A thin flat strip of wood, especially one of a series forming a foundation for the plaster of a wall (Soanes and Stevenson, 2005).

element of UK heritage. Timber has been used as a construction material in the UK since ancient times (Coles, 2006), with the Early English verb “to timber” being synonymous with “to build” (Addy, 1905). The oldest standing timber building in the UK is believed to date back to the 9th Century (Historic England, 2014) and timber framing continued to be a common construction technique, reaching its height in the 1600s, before coming to an abrupt halt in the late 18th or early 19th century (Harris, 2010). Even after timber framing ceased to be a common structural solution, its aesthetics continued to be replicated (Eastlake and Crook, 1970, Ballantyne and Law, 2011a) from the Olde English Style, through inter-war *Metroland*, to contemporary suburbia. This black and white aesthetic continues to form a quintessential part of the British, or more specifically English, cultural identity and as such its continuing survival is of national importance. As recognised by Viollet-le-Duc “the best of all ways of preserving a building is to find a use for it” (Viollet-le-Duc, 1990 p.222), however as noted by Historic England in its Conservation Principles, the utility of a building can be beneficial, by ensuring its maintenance, but can also be the source of conflict (Historic England, 2008 p.27). In the case of historic timber-framed buildings, in order to ensure their ongoing use, the thermal comfort they provide their occupants must meet 21st century expectations. Research is therefore required to determine if, when and how thermal retrofits should be undertaken.

Work to any historic building in the UK must take place following a set of ethical principles as set out by each of the four national governmental bodies related to heritage, Historic England, Cadw, Historic Environment Scotland and the Northern Ireland Department for Communities, Historic Environment Division (Historic England, 2008, Cadw, 2011, Historic Environment Scotland, 2016b, Historic Environment Division, 2017). In general, it is expected that where possible every effort will be made to retain existing historic fabric, and where replacement is required that this normally takes place on a basis “like-for-like” basis (Historic England, 2008 p.52, Cadw, 2011 p.24). It is however accepted that this is not

always possible or the best option (ibid). For example, where the complete renewal of timber-frame infill panels is required due to extensive damage, decay, repair of surrounding timbers or the removal of inappropriate modern materials, there exists the opportunity to retrofit an alternative panel with a higher thermal resistance (Historic England, 2016 p.13). At the same time, all conservation work must assess if sufficient information is available to fully understand the implications of any change (Historic England, 2008 p.44). Therefore, it is important to study the hygrothermal impact of the introduction of modern infill materials in order to avoid increased moisture content, interstitial condensation[5], differential movement, greater risk of frost damage and the creation of ideal conditions for fungal decay and insect infestation. Given that even with further research, these problems may arise in the long-term, it is essential that any intervention is reversible (ibid, p.46), another key principle of modern conservation philosophy.

1.2 Aims

The aim of this research is to evaluate the positive and negative impacts of the addition of thermal insulation to historic timber-framed buildings in the UK and by doing so beginning the process of informing best practice and developing a methodology for the selection of appropriate solutions. It is hoped that by doing so, these buildings that have already stood for hundreds of years, might continue providing comfortable accommodation for the following centuries, whilst avoiding interventions that could put their continuing survival at risk.

[5] The introduction of moisture within a structure due to the internal temperature dropping below the dew point temperature causing water vapour to condense (British Standards Institution, 2012)

1.3 Objectives

The historic timber framed buildings in the UK have been quantified and geographically located, noting their age, use and panel infill material. This information has been correlated with geological, topographical, climatic and socio-economic factors to understand the factors influencing their survival. In addition to this information, the history of the origins, development and eventual decline of the construction technique has been studied to understand the significance of these buildings with regards to their historic, architectural, rarity and cultural values.

Past and present advice on the energy retrofit[6] of these properties has been evaluated through the monitoring of case studies, measuring the buildings' hygrothermal performance, internal comfort conditions and impact on the buildings historic fabric and heritage value. Digital energy simulation has been used to examine the resulting energy demand provided by retrofit solutions.

Finally, the interstitial hygrothermal performance of existing and potential replacement infill panels has been assessed, including their thermal transmitance, temperature and humidity gradients, moisture content and risk of interstitial condensation.

The outcomes of this research are a series of findings and recommendations that should inform future guidance on the low energy retrofit of historic timber-framed buildings in the UK. In addition, areas for further research are highlighted and discussed.

[6] The alteration of a building with the purpose of improving its energy efficiency.

2 LITERATURE REVIEW

2.0 Introduction

This chapter presents a review of the existing literature on the energy retrofit of existing buildings, focusing on the information currently available concerning the retrofit of historic and traditional buildings, and more specifically those of timber-framed construction. The review begins with an overview of the literature consulted, before outlining relevant current EU and UK legislation, existing research on the retrofit of historic building stock, research specific to timber-framed buildings and finally the current guidance available to those about to embark on retrofit projects. By doing so, it is possible to see that although guidance does exist, there is little academic research to validate the approaches currently proposed. As such, the research presented in this thesis aims to begin to provide some of the required information to inform future guidance and practice.

A literature review of historic timber-framed buildings is covered in chapters 4-6.

2.1 Overview of literature

A total of 81 sources were reviewed ranging from those dealing with retrofit at a strategic level, to those specifically aimed at timber-framed buildings. Of these 20 were reports, 29 journal articles, 25 books, 5 book chapters and 2 websites. There follow four tables presenting the literature consulted, noting if four specific topics were covered by the author(s), these being; (1) the specific challenges faced by retrofitting historic and traditional buildings; (2) solid masonry construction; (3) timber-frame construction (mention only); (4) timber-frame construction in detail.

Table 1 presents those sources concerned with energy retrofit at a strategic level, Table 2 presents literature concerned with energy fit in general, that is to say for all buildings, Table 3 focuses specifically on the energy retrofit of historic and traditional buildings and Table 4 sets

out the literature that deals exclusively with the energy retrofit of historic timber-framed buildings.

Table 1. Overview of literature consulted that reviews energy retrofit of existing buildings at a strategic level.

Report (R) Article (A) Book (B) Chapter (C)	Title	Citation	Mention of historic and traditional buildings	Mention of solid masonry solid walls	Mention of historic timber-frame	Detailed discussion of historic timber-frame
R	Deep Energy Retrofits: An Emerging Opportunity	(AIA. and Rocky Mountain Institute., 2014)				
R	Each Home Counts	(Bonfield, 2016)				
R	Meeting Carbon Budgets- 2014 Progress Report to Parliament, Chapter 3	(Committee on Climate Change., 2014)				
R	Report From the Commission to the European Parliament and the Council: Progress by Member States towards Nearly Zero-Energy Buildings	(European Commission, 2013)				
R	New Tricks with Old Bricks: How reusing old buildings can cut carbon emissions	(Empty Homes Agency, 2008)		x		
R	The Retrofit Challenge: Delivering Low Carbon Buildings	(Stafford, 2011)		x		
R	Implementing the Energy Performance of Buildings Directive (EPBD) Featuring Country Reports 2012	(Sutherland, 2013)	x			
A	Anticipating the Unintended Consequences of the Decarbonisation of the Historic Built Environment in the UK	(Agbota, 2014)	x	x		
A	Sustaining Our Heritage: The Way Forward for Energy-Efficient Historic Housing Stock	(Crockford, 2014)	x	x		
A	EFFESUS Methodology for Assessing the Impacts of Energy-Related Retrofit Measures on Heritage Significance	(Eriksson et al., 2014)	x			
A	Refurbishment decision support tools review—Energy and life cycle as key aspects to sustainable refurbishment projects	(Ferreira, 2013)				
A	Energy Efficiency in Heritage Buildings — Future Challenges and Research Needs	(Fouseki and Cassar, 2014)	x			
A	Retrofitting the existing UK building stock	(Kelly, 2009)				

Table 1. (Cont.) Overview of literature consulted that reviews energy retrofit of existing buildings at a strategic level.

Report (R) Article (A) Book (B) Chapter (C)	Title	Citation	Mention of historic and traditional buildings	Mention of solid masonry solid walls	Mention of historic timber-frame	Detailed discussion of historic timber-frame
A	Technical options and strategies for decarbonizing UK housing	(Lowe, 2007)				
A	Alternative scenarios for energy conservation in the building stock	(Kohler, 2012)				
A	Does Demolition or Refurbishment of Old and Inefficient Homes Help to Increase Our Environmental, Social and Economic Viability	(Power, 2008)	x	x		
A	Sustainable Renovation of Buildings	(Staniaszek, 2014)				
A	In Search of a Holistic, Sustainable and Replicable Model for Complete Energy Refurbishment in Historic Buildings	(Todorović, 2012)				
B	40% house	(Boardman, 2005)	x	x		
C	Thermal retrofit and building regulations for dwellings in the UK	(Todd, 2013)	x			

From the overview presented in Table 1 it can be seen that only 40% of the sources reviewed dealing with energy retrofit at a strategic level refer to the specific challenges faced in retrofitting historic and traditional buildings. In general, most of these sources refer only to "existing buildings" making no distinction between buildings built in the last 50 years and those that have stood for centuries. The omission of any reference to historic, listed or traditionally constructed buildings, is particularly notable in the report "Each Home Counts: An Independent Review of Consumer Advice, Protection, Standards and Enforcement for Energy Efficiency and Renewable Energy" (Bonfield, 2016). This report was undertaken for the Department for Business, Energy & Industrial Strategy to specifically review the problems

facing the energy retrofit of the UKs existing housing stock. Given that approximately 25% of the domestic building stock of the UK was built pre-1919 (Revell and Leather, 2000 p.16, Nicol et al., 2014 p.8) it would be reasonable to expect some coverage of the potential challenges faced when considering their retrofit. Where reference is made by other authors to historic buildings this tends to be restricted to those that are listed[7] or in conservation areas[8], focusing on aesthetical and philosophical issues rather than technical ones. In addition it has been estimated that only 25% of the pre-1919 housing stock is listed or covered by conservation areas (Boardman, 2005 p.86-87) and so 75% of traditionally constructed buildings are not protected by such legislation.

When looking at a strategic level, no mention is made of historic timber-framed buildings, which might be expected, however 30% of the sources consulted do make reference to solid masonry wall construction, often assuming this to be the external envelope of all pre-1919 buildings. This assumption continues in most of the literature concerning the practical application of energy retrofit to existing buildings (Table 2).

[7] Buildings of special architectural or historic interest, listed as such under the Planning (Listed Buildings and Conservation Areas) Act 1990 for England and Wales (1990 p.1) and the Scottish Act of 1997.
[8] Areas of special architectural or historic interest the character or appearance of which it is desirable to preserve or enhance (1990)

Table 2. Overview of literature consulted that covers the practical application of energy retrofit to existing buildings in general

Report (R) Article (A) Book (B) Chapter (C) Website (W)	Title	Citation	Mention of historic and traditional buildings	Mention of solid masonry solid walls	Mention of historic timber-frame	Detailed discussion of historic timber-frame
R	A Guide to Energy Refurbishment: Maintenance and Renewal in Educational Buildings. Building Bulletin 73	(DES, 1991)		x		
R	Energy Efficiency Best Practice in Housing: Advanced insulation in housing refurbishment	(Energy Saving Trust, 2005)		x		
A	Multi-objective optimization for building retrofit strategies: A model and an application.	(Asadi, 2012)				
A	Low carbon housing refurbishment challenges and incentives: Architects' perspectives	(Davies and Osmani, 2011)	x			
A	Systematic method for the sustainability analysis of refurbishment concepts of exterior walls. final	(Häkkinen, 2012)				
A	Early stage decision support for sustainable building renovation – A review	(Nielsen et al., 2016)	x			
A	Sustainable refurbishment of exterior walls and building facades: final Report Part C-Specific refurbishment concepts	(Peuhkuri et al., 2012)	x	x		
B	Sustainable retrofit and facilities management	(Appleby, 2013)				
B	Residential Retrofit: Residential Retrofit	(Baeli, 2013)	x	x		
B	The handbook of sustainable refurbishment : non-domestic buildings	(Baker, 2009)	x	x	x	
B	The eco-home design guide : principles and practice for new-build and retrofit	(Day, 2016)				
B	Eco-renovation : the ecological home improvement guide	(Harland and Roberts, 2002)				
B	The environmental design pocketbook	(Pelsmakers, 2015)	x	x		
B	The sustainable building bible : an insider's guide to eco-renovation & newbuilding	(Pullen, 2011)				
B	Sustainable Refurbishment	(Shah, 2012)				

Table 2. (cont.). Overview of literature consulted that covers the practical application of energy retrofit to existing buildings in general

Report (R) Article (A) Book (B) Chapter (C) Website (W)	Title	Citation	Mention of historic and traditional buildings	Mention of solid masonry solid walls	Mention of historic timber-frame	Detailed discussion of historic timber-frame
B	Sustainable home refurbishment : the Earthscan expert guide to retrofitting homes for efficiency	(Thorpe, 2010)	x			
B	Renovations : an inspirational design primer	(Wilcock, 2016)	x	x		
C	Barriers to domestic retrofit: Learning from past home improvement experiences	(Mallaband et al., 2013)	x	x		
W	Home Insulation: Solid Wall	(Energy Saving Trust, 2017)	x	x		

It is concerning to see that 47% of the sources relating to the practical application of energy retrofits to buildings in general (Table 2) make no reference to historic and traditionally constructed buildings. Just as the literature dealing with the issue at a strategic level (Table 1), even when historic buildings are mentioned, is often limited to the legal constraints imposed on listed buildings and conservation areas, rather than any technical issues. Again, as previously mentioned, 25% of the domestic building stock in the UK was built pre-1919 (Revell and Leather, 2000 p.16, Nicol et al., 2014 p.8) yet only 25% of these have statutory protection (Boardman, 2005 p.86-87). As such, the failure of much of the guidance offered to address the

potential negative impact of inappropriate retrofit solutions on the historic built fabric increases the risk of serious damage being caused and money wasted.

Those sources (Table 2) that do make reference to the technical issues specific to historic and traditional buildings, again focus on the insulation of solid masonry walling (Baeli, 2013, Baker, 2009, Pelsmakers, 2015, Peuhkuri et al., 2012, Energy Saving Trust, 2017), with the need for vapour permeable solutions only mentioned by four authors (Pelsmakers, 2015 p.258, Peuhkuri et al., 2012 p.181, Thorpe, 2010 p.69-70, Energy Saving Trust, 2017).

With regard to the energy retrofit of historic timber-framed buildings, only one of the nineteen sources looking at the retrofit of buildings in general makes any reference to this construction typology (Baker, 2009), noting that for timber-framed walls with solid infill and cob[9] or rammed earth buildings "*solutions are highly specific to the technical details of the construction, and are not dealt with here*." (ibid, p.31). Although this is only a brief mention, it does at least highlight to the reader that specialist advice should be sought, unlike the rest, which through omission may imply that timber-framed buildings may be approached in the same way as any other wall construction.

There follows a summary of those sources consulted that specifically address the energy retrofit of historic and traditional buildings (Table 3).

[9] Earth construction of mud and straw (and possibly other aggregates) where the mixture is applied wet in layers (Clifton-Taylor, 1987 p.272, Innocent, 1971 p.136).

Table 3. Overview of literature consulted that covers energy retrofit of historic and traditional buildings

Report (R) Article (A) Book (B) Chapter (C) Website (W)	Title	Citation	Mention of historic and traditional buildings	Mention of solid masonry solid walls	Mention of historic timber-frame	Detailed discussion of historic timber-frame
R	U-values and traditional buildings—in situ measurements and their comparisons to calculated values, Historic Scotland technical paper 10	(Baker, 2011)	x	x		
R	Hygrothermal Modelling of Shrewsbury Flax Mill Maltings	(Baker, 2015)	x	x		
R	A Bristolian's Guide to Solid Wall Insulation: a guide to the responsible retrofit of traditional homes in Bristol	(Bristol City Council., 2015)	x	x		
R	BS EN 16883 Conservation of Cultural Heritage - Guidelines for improving energy performance of historic buildings	(British Standards Institution, 2015a)	x			
R	Historic Environment Scotland Technical Paper 19: Monitoring thermal upgrades to ten traditional properties	(Currie et al., 2013)	x	x		
R	Energy Efficiency and Historic Buildings: Application of Part L of the Building Regulations to historic and traditionally constructed buildings (Revised 2012)	(Historic England, 2012)	x	x		
R	Improving Energy Efficiency in Traditional Buildings	(Jenkins, 2010)	x	x		
R	Responsible Retrofit of Traditional Buildings	(May and Rye, 2012)	x	x	x	
R	The SPAB Research Report 1. U-Value Report.	(Rye et al., 2012a)	x	x	x	
R	Performance and Energy Efficiency of Traditional Buildings: Gap Analysis Study	(STBA, 2012)	x	x	x	
A	Energy retrofit of historical buildings: theoretical and experimental investigations for the modelling of reliable performance scenarios	(Ascione et al., 2011)	x	x		
A	A Retrofit of a Victorian Terrace House in New Bolsover a Whole House Thermal Performance Assessment	(Baker, 2016)	x	x		
A	Testing of a method for insulation of masonry and lath walls in existing domestic Scottish construction	(Bennadji and Levie, 2012)	x	x		

Table 3. (cont.). Overview of literature consulted that covers energy retrofit of historic and traditional buildings

Report (R) Article (A) Book (B) Chapter (C) Website (W)	Title	Citation	Mention of historic and traditional buildings	Mention of solid masonry solid walls	Mention of historic timber-frame	Detailed discussion of historic timber-frame
A	Field Testing of Existing Stone Wall in North Wales Climate	(Gandhi et al., 2012)	x	x		
A	Moisture Control and problem analysis of heritage constructions	(Künzel and Holm, 2009)	x	x	x	
A	Energy retrofit and conservation of a historic building using multi-objective optimization and an analytic hierarchy process	(Roberti et al., 2017)	x	x		
A	Balancing Heritage and Environmental Policies for Sustainable Refurbishment of Historic Buildings: The Case of New Court, Trinity College, Cambridge	(Smith, 2014)	x	x		
B	Energy efficiency in old houses	(Cook, 2009)	x	x	x	x
B	Care for old houses	(Cunnington, 1984)	x	x	x	x
B	Practical Building Conservation: Building Environment	(Pender et al., 2013)	x	x	x	
B	The green guide for historic buildings: how to improve the environmental performance of listed and historic buildings	(Prince's Regeneration Trust, 2010)	x	x	x	x
B	Sustainable building conservation : theory and practice of responsive design in the heritage environment	(Prizeman, 2015b)	x	x	x	x
B	SPAB Briefing: Energy efficiency in old buildings	(SPAB, 2014)	x	x	x	
B	Old house eco handbook: a practical guide to retrofitting for energy-efficiency & sustainability.	(Suhr and Hunt, 2013)	x	x	x	x
C	Retrofitting heritage buildings	(Cox, 2015)	x	x		
C	The energy context of domestic traditional buildings in the UK	(Lannon et al., 2015)	x	x		
W	Responsible Retrofit Guidance Wheel	(STBA, 2017)	x	x	x	x

In these sources, the omission of timber-framed buildings begins to be addressed. Thirty percent of these sources do make specific mention of historic timber-framed construction, although only half of these go on to provide any detailed discussion of how the retrofit of these properties may be approached. The five sources that do provide more detailed information (Cook, 2009, Cunnington, 1984, Suhr and Hunt, 2013, Prince's Regeneration Trust, 2010, Prizeman, 2015a, STBA, 2017) are reviewed in greater depth later in this chapter, as are those sources presented in Table 4 that deal specifically with the energy retrofit of historic timber-framed buildings. It should be noted that research into timber-clad timber-framed buildings were no infill panel exist, such as those found in Scandinavia (Sveipe et al., 2011, Vinha, 2007) have not been included in this review due the difference in construction techniques and the associated challenges.

Table 4. Overview of literature consulted that covers energy retrofit of historic timber-framed buildings

Report (R) Article (A) Book (B) Chapter (C)	**Title**	**Citation**	Mention of historic and traditional buildings	Mention of solid masonry solid walls	Mention of historic timber-frame	Detailed discussion of historic timber-frame
R	Energy Efficiency and Historic Buildings: Insulating Timber-Framed Walls	(Historic England, 2016a)	x		x	x
A	Insulation in Timber-framed Buildings	(Demaus, 2017)	x		x	x
A	The issue of thermal performance and protection and modernisation of traditional half-timbered (*bondruk*) style houses in Serbia	(Radivojević et al., 2014)	x		x	x
A	The renovation of period timber-frame buildings in Southwest France: An environmental assessment of insulation materials and techniques for exterior timber-frame walls	(Valkhoff, 2010)	x		x	x
A	An environmental assessment of insulation materials and techniques for exterior period timber-frame walls	(Valkhoff, 2011)	x		x	x
B	Timber-framed buildings of England	(Brown, 1986)	x		x	x

B	Conservation of timber buildings	(Charles, 1984)	x		x	x
B	Erneuerung von Fachwerkbauten	(Dederich et al., 2004)	x		x	x

Table 4 (cont.).Overview of literature consulted that covers energy retrofit of historic timber-framed buildings

Report (R) Article (A) Book (B) Chapter (C)	**Title**	**Citation**	Mention of historic and traditional buildings	Mention of solid masonry solid walls	Mention of historic timber-frame	Detailed discussion of historic timber-frame
B	Wärmedämmung von Fachwerkbauten	(Gerner, 2000)	x		x	x
B	Practical Building Conservation- Timber	(McCaig and Ridout, 2012)	x		x	x
B	Panel Infillings to timber-framed buildings	(Reid, 1989)	x		x	x
B	The Hempcrete Book Designing and Building with Hemp-Lime	(Stanwix and Sparrow, 2014)	x		x	x

2.2 EU and UK legislation relating to the energy retrofit of existing buildings

The drive to improve the energy efficiency of existing buildings in the UK and across the European Union is currently governed by the EU 2010 Energy Performance of Buildings Directive (OJEU, 2010) as updated by the EU 2012 Energy Efficiency Directive (OJEU, 2012). These directives set out the legal framework for how the member states are to achieve a 20% increase in energy efficiency by 2020 against a 1990 baseline (ibid, p.2), and reduce greenhouse gas emissions by 80-95 % by 2050 compared to 1990 (ibid, p.3). Identifying buildings as representing 40% of the EU's final energy consumption (ibid), the directives call upon member states to establish long-term strategies for the "deep renovation[10]" of the existing building stock (ibid). In response, the UK government introduced regulations requiring the energy rating of existing buildings through the use of Energy Performance Certificates (EPCs), which together with schemes such as The Green Deal (Gov.UK, 2012), aimed to incentivise the energy retrofit of existing properties. Although The Green Deal has since been abandoned, the Energy Performance of Buildings Regulations (England and Wales 2012, Scotland 2008 and Northern Ireland 2008) and their subsequent amendments have the ambition of promoting retrofit by turning energy efficiency into a marketable commodity. In addition, The Energy Efficiency (Private Rented Property) (England and Wales) Regulations (2015) introduces minimum energy efficiency standards for private rented property as of 2018, making it illegal as of 2018 to let a property with an EPC lower than E.

[10] defined by the EU Energy Efficiency Directive as "refurbishment that reduces both the delivered and the final energy consumption of a building by a significant percentage compared with the pre-renovation levels leading to a very high energy performance" (OJEU, 2012 p.315/3)

2.2.1 EU and UK energy retrofit legislation and the historic built environment

With regard to historic buildings, article 4 of the 2010 directive includes the exemption of "*buildings officially protected as part of a designated environment or because of their special architectural or historical merit, in so far as compliance with certain minimum energy performance requirements would unacceptably alter their character or appearance*" (OJEU, 2010 art.4.2a p.19). The exact same text appears again in 2012 directive (OJEU, 2012 art.5.2a p.14) and is adopted word for word in the Energy Performance of Buildings (England and Wales) Regulations 2012[11] (2012 p.5). There therefore remains a degree of ambiguity as to the exemption of listed buildings from both EPCs and the drive for energy retrofit in England and Wales, as it could be argued that the exemption only applies when "*minimum*" energy retrofit actions would "*unacceptably alter their character or appearance*" (ibid), a statement which in itself is subjective (Sharples, 2016). What is "*minimum*" and what is "*unacceptable*"? This in turn leads to a degree of uncertainty as to the application of the minimum energy efficiency standards of the Energy Efficiency (Private Rented Property) (England and Wales) Regulations 2015 (2015). Whilst it is generally accepted that listed buildings are exempt from EPCs, this may well be legally challenged by tenants when the 2015 regulations come into effect next year (Sharples, 2016). The impact of this could be considerable for historic and traditional buildings in England and Wales.

Within the Building Regulations for England and Wales, the approved document parts L1B and L2B for *Conservation of Fuel and Power in existing dwellings and existing buildings other than dwellings* respectively, both state that listed buildings, buildings in conservation areas, and scheduled monuments are exempt from the regulations where "*compliance would unacceptably alter the character or appearance of the building*" (HM Government, 2016a p8, HM Government, 2016b p8). Again "*unacceptable*" is subjective. Further special considerations

[11] No comparable texts exists in the legislations Scottish and Northern Irish counterparts (2008b. The Energy Performace of Buildings (Scotland)Regulations 2008. Scotland.) (2008c. The Energy Performance of Buildings (Northern Ireland). Northern Ireland.)

are also granted to buildings of "*architectural and historical merit*" (ibid) referred to in local authority's development plans or in registered landscapes, and "*buildings of traditional construction with permeable fabric that both absorbs and readily allows the evaporation of moisture*" (ibid). For such buildings, and for listed buildings, the approved documents state, "*the aim should be to improve energy efficiency as far as is reasonably practicable*[12]" (ibid). Just as with "*unacceptable*", "*reasonably practicable*" is equally ambiguous. As such, the targets for the energy retrofit of historic and traditional buildings are left open to interpretation by the architect, home owner, building professional in discussion with the Conservation Officer and Building Control. Given the falling number of historic advice specialists within local authorities, down 36% since 2006 (Historic England et al., 2017), the level of advice available will vary leading to regional discrepancies across England. Both approved documents (L1B & L2B) do however include that advice should be sought on "*enabling the fabric of historic buildings to 'breathe' to control moisture*" (ibid) and suggest that further guidance is sought from Historic England's publication "Energy Efficiency and Historic Buildings: Application of Part L of the Building Regulations to historic and traditionally constructed buildings" (ibid). This in turn states, "*an informed approach can achieve significant energy efficiency improvements in most cases although not always to the standards recommended in the regulations*" (Historic England, 2012 p.4). The balance would therefore appear to hang in favour of trying to improve energy efficiency, rather than leaving the buildings as they are. This is also noted in the Northern Irish guidance, which concludes, "*While it is important that the character of our historic buildings is maintained for the appreciation of this and future generations it is also important to maximise energy efficiency… Historic buildings however, function differently from modern construction. A full understanding of the processes at work is necessary to avoid problems.*" (Northern Ireland Environment Agency, 2006 p.19). A similar, but more emphatic approach is given in the handbook for applying the Scottish Building Energy Standard (Scottish

[12] "*Practical*" is used in place of "*practicable*" in Part L2B (HM Government 2016b) opening up a wider interpretation of the regulation.

Government, 2017) which accepts a degree of flexibility but states "*in all cases the 'do nothing' approach should not be considered initially*" (ibid, p.21).

2.3 Energy Retrofit of Historic and Traditional Buildings

The British Standard BS 7913:2013 Guide to the conservation of historic buildings (British Standards Institution, 2013), advocates maintenance as the most effective method of ensuring energy efficiency and sustainability (ibid p10). Minimal interventions such as improving heating systems, increasing air-tightness and installing low-energy lighting, are accepted as appropriate methods of improving the building's performance (ibid p26). However, measures requiring higher levels of intervention such as new windows to improve daylighting, roof and wall insulation, and micro-generation of electricity are given the proviso that their "*potential impact… …on the historic building's significance should be investigated*" (ibid). This is reinforced by BS EN 16883 Conservation of Cultural Heritage - Guidelines for improving energy performance of historic buildings (British Standards Institution, 2015a), which sets out the methodology for assessing this potential impact and acknowledges that "every historic building should be considered as a particular case" (ibid p.16). The standard is however a procedural document, and not prescriptive, and as such it gives no specific advice on historic timber-framed buildings.

The report "Responsible Retrofit of Traditional Buildings" (May and Rye, 2012), prepared by the Sustainable Traditional Building Alliance (STBA) on behalf of the Department of Energy and Climate Change (DECC), undertook a review and gap analysis of the existing research into the area. It identified that there was "*a general absence of literature on the energy behaviour and performance of traditional buildings*" (ibid p.21). This was true for both retrofitted properties and baseline data. The deficiencies of software for modelling both energy performance and moisture conditions were also highlighted and directly attributed to the aforesaid lack of

baseline and material data (ibid p.22-23). In addition the tendency to generalise all pre-1919 buildings was noted with a call for greater typological analysis of the buildings that make up the traditional and historic building stock (ibid p.23), yet no specific mention is made in the report of timber-framed construction.

The academic article "Eco-Retrofitting Very Old Dwellings" (Mohammadpourkarbasi and Sharples, 2013) unfortunately does not deliver on its title, presenting instead the energy retrofit of a 19th century red-brick terrace. The paper shows that a 76% reduction in energy demand can be achieved through the use of internal insulation but highlights that potential overheating in summer may occur (ibid). The results of the paper are unfortunately based only on simulation, and whilst post-retrofit demand has been validated through two years of monitoring, it is unclear as to the existence of any pre-retrofit measured baseline.

A more comprehensive paper covering properties of a similar age is "Pre and post retrofit measurements of a Victorian terraced house with solid brick walls in New Bolsover" (Baker, 2016) prepared for Historic England. In this research in situ U-value monitoring in 14 locations, pressure testing and co-heating tests were undertaken both pre and post-retrofit. The results indicate a 38% saving in energy use, considerably lower than those quoted by the previously discussed paper (Mohammadpourkarbasi and Sharples, 2013). One key finding was that the pre-retrofit in situ U-values were better than expected, thereby reducing the assumed savings, a phenomenon that has been termed "pre-bound effect" (Sunikka-Blank and Galvin, 2012). As such, the paper recommends that measured in situ values should be used for future predictions of energy use for traditional building retrofits (Baker, 2016 p.37).

Further research into the retrofit of solid masonry wall construction has also been conducted on behalf of Historic Environment Scotland (Currie et al., 2013) and Historic England (Baker, 2015) and the European Union funded SusRef project (Häkkinen, 2012). This latter project also included the retrofit of timber-framed constructions, however this research was conducted by

its Scandinavian participants and focuses on timber framing without solid infill and as such is not directly applicable to those buildings under review in this thesis.

2.4 Energy Retrofit of Historic Timber Framed Buildings

2.4.1 International research on retrofit of historic timber-framed buildings with solid infill panels

An article on the thermal performance and potential retrofit of timber-frame houses in Serbia known as *bondruk*, focuses principally on the need for conserving these buildings (Radivojević et al., 2014). The *bodruk* are very similar to UK historic timber-frame in terms of construction, although stylistically they differ appearance (ibid, p.213-215) (Figure 2 & Figure 3).

Figure 2. Serbian half-timbered bodruk. Source: (Radivojević et al., 2014)

Figure 3. Serbian half-timbered bodruk. Source: (Radivojević et al., 2014)

The need for improving the thermal performance of these buildings is acknowledged and secondary glazing, roof and floor insulation are all advocated (Ibid, p.221). The article mentions the possibility of replacing infill panels with thermal insulation or installing internal wall insulation, although the need for caution is highlighted with regard to how wall insulation can affect authenticity, aesthetics and interstitial moisture behaviour (Ibid, p.222). These issues are not however developed in further detail.

A Master's Thesis on the retrofit of timber-framed buildings in SW France (Valkhoff, 2010) uses Life Cycle Assessment (LCA) to assess different insulation solutions for the external walls. The need for the vapour resistance (MNs/gm) of the external finish to be lower than that of the internal finishes, as stated by BS 5250 (British Standards Institution, 2016 p.67), is mentioned but no further study of the interstitial hygrothermal conditions is undertaken (Valkhoff, 2010 p.65). This is cited as an area for future research (ibid, p.74). The thesis concludes with a call for case studies of whole buildings and field measurements in order to prove the potential damage that inappropriate thermal wall insulation can potentially have on historic timber-framed buildings (ibid, p.73). Research into other locations where timber-frame construction is common, such as Alsace, Normandy, Germany and the UK is also called for (ibid). Information from the same thesis was also presented in the conference paper "An environmental assessment of insulation materials and techniques for exterior period timber-frame walls" (Valkhoff, 2011).

In Germany the application of internal insulation to timber-framed buildings appears to be the favoured retrofit solution (Gerner, 2000, Dederich et al., 2004). However, even with this, it has been acknowledged that the German Energy Performance targets are hard to achieve and that retrofit of individual properties must go hand in hand with low carbon energy generation for timber-framed neighbourhoods (Gerner, 2017). Not all are in favour of the application of insulation to these buildings, not only from a technical viewpoint but also from a cultural one. The German author Cora Stephan, in an impassioned article in Die Welt entitled "Insulation is the death sentence for half-timbered houses (*Dämmung ist das Todesurteil für Fachwerkhäuser)"* (Stephan, 2014), denounces the race to insulate these old buildings as "prosaic", and laments the loss of the internal character both visual and climatic (ibid). To her insulation threatens to "kill" these houses and her only hope is that areas such as where she lives are too poor to afford energy retrofits (ibid).

2.4.2 UK research on retrofit of historic timber-framed buildings

In the UK there would appear to be almost no research into the retrofitting of historic timber-framed buildings. Whilst the international research is still relevant, little specific research involving the UK climate and local materials and construction techniques appears to exist.

The Prince's Regeneration Trust's book "The Green Guide for Historic Buildings," (Prince's Regeneration Trust, 2010) and Martin Godfrey Cook's book, "Energy Efficiency in Old Houses" (Cook, 2009) both contain the same case study, Berg Cottage, Barkway, Hertfordshire (Prince's Regeneration Trust, 2010 p.27-28, Cook, 2009 p.42-45). This cottage is one of the few case studies of the retrofit of a historic timber-framed building in the UK where monitoring has been undertaken post-retrofit. The same cottage appears again briefly in the Energy Savings Trust's "Energy Efficiency Best Practice in Housing Advanced insulation in housing refurbishment" (Energy Saving Trust, 2005 p.22) and photos of it are featured in Historic England's guidance on insulating timber-framed walls (Historic England, 2016a). Although the description in all sources is quite brief, the case study does include details of pressure testing, with measurements showing 24 air changes per hour at fifty pascals(ac/hr@50 Pa) pre retrofit (Cook, 2009 p.44) and 16 ac/hr @ 50 Pa post-retrofit (Energy Saving Trust, 2005 p.22). The case study includes the introduction of external sheep's wool insulation behind weatherboarding, which achieves a reduction in gas consumption of 27% (Prince's Regeneration Trust, 2010 p.28) and an reduction in overall fuel consumption by 50% (Cook, 2009 p.42).

Another case study using sheep's wool insulation is presented by Prizeman, in a chapter covering the retrofit of four traditionally constructed domestic buildings (Prizeman, 2015a p.193-218), in a book on sustainable building conservation edited by the same author (Prizeman, 2015b). The detail of the infill is shown in Figure 4. A thorough description is provided and many of the key issues relating to the retrofit of timber-framed buildings are

discussed (vapour permeability[13], damage to internal/external finishes, reversibility). An estimated energy saving of 21% is predicted (ibid, p.203). Although no pre or post-retrofit monitoring has taken place, as supervisor of this thesis Dr Prizeman has been able to share her knowledge and experience gained through her involvement as architect on this project.

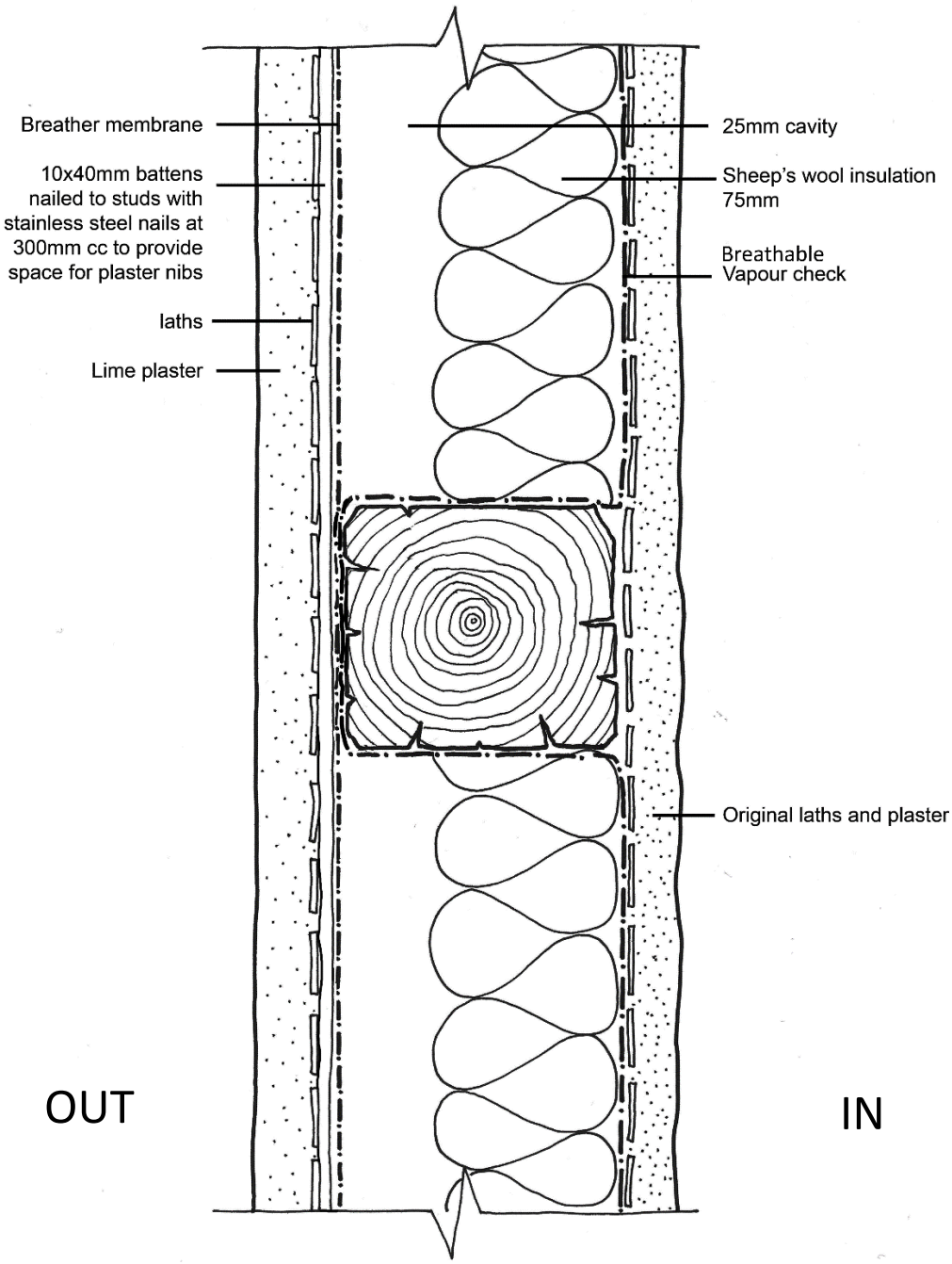

Figure 4. Detail of sheep's wool insulation applied as infill from outside to retained internal lath and plaster. Source: (Author's own based on detail by O.Prizeman ©)

[13] The ability of a material to allow the passage of water vapour, often referred to as "breathability" (Hughes, 1986 p.1)

In the first SPAB U-Value report (Rye et al., 2012a), the research undertaken by Archimetrics did include a two timber framed-buildings, however neither went on to be retrofitted and covered by the subsequent "SPAB Building Performance Survey" (Rye et al., 2012b, Rye et al., 2013, Archimetrics Ltd, 2014, Archimetrics Ltd, 2015, Archimetrics Ltd, 2017).

2.4.3 UK guidance and best-practice for the retrofit of historic timber-framed buildings

Although little exists with regard to academic research, there does exist best practice guidance from Historic England, SPAB and individual authors. There follows a review of this guidance.

An early example of guidance for energy retrofitting of historic timber-framed building in the UK can be found in F.W.B. Charles's "Conservation of Timber Buildings" (Charles, 1984 p.131). With wattle-and-daub and its annual maintenance deemed "impractical", a sandwich panel with expanded polystyrene insulation and rendered wood wool board is proposed (Figure 5 and Appendix A).

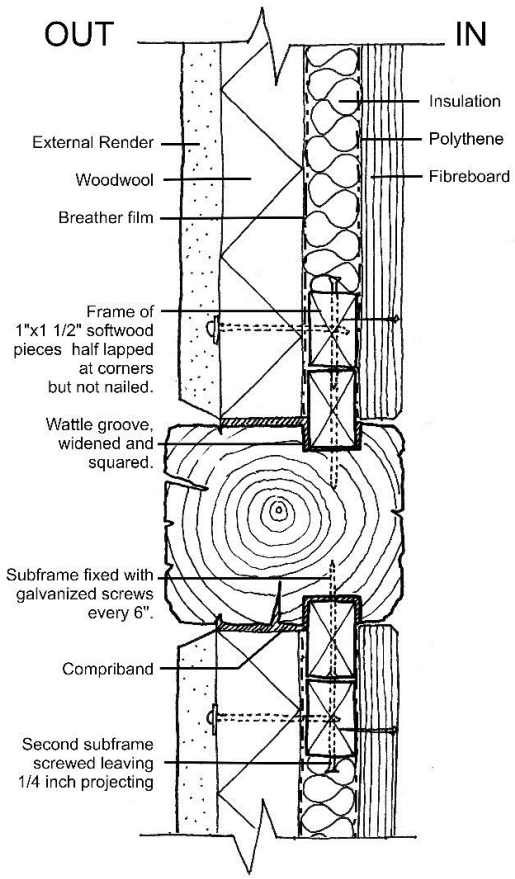

Figure 5. Replacement infill detail as suggested by FWB Charles. Source: (Author's own based on (Charles, 1984))

At the junction with the timber frame, a detail with two sub-frames is proposed, one embedded in the historic frame and the other "*floating*" (ibid), along with the use of compriband elastic sealant. As such, the difficult junction between the infill and frame is addressed and problems of shrinkage and movement are resolved. This same detail was reprinted with no modification in the reprint of the book in 1998.

Similar advice is given by R.J. Brown (Brown, 1986 p.352), although without the use of a second floating sub-frame, and wood wool features again as the preferred option in P. Cunninton's "Care for Old Houses" (Cunnington, 1984 p.111). According to Brown the use of wood wool had "*long been used as a replacement for wattle-and-daub*" (ibid p.353). Exactly how long is not clear, although machines for the production of the wood strips for wood wool, known as *excelsior* in the USA are listed as far back as 1876 (Knight, 1876 p.2214) and the production of cement and wood wool boards was common across Europe by the 1930s (Botting, 1997). In addition to wood wool, Brown suggests alternatives such as compressed

mineral fibre and polyurethane insulation, and the use of lightweight cement blocks is noted but discouraged due to problems with differential movement (Brown, 1986 p.352).

The most recently published[14] technical pamphlet from SPAB, Technical Pamphlet 11 (Reid, 1989), dates from around the same time as Charles, Brown and Cunnington's books. In the technical pamphlet, there exist a number of details, similar in nature to those presented by Charles and Brown, containing synthetic non-vapour permeable materials that would appear to go against the current advice from SPAB. These materials include foil backed plasterboard, polythene sheeting, injected polyurethane foam and closed cell foam insulation (ibid p.9). These details are shown in Figure 6, Figure 7 and Appendix A. An attempt to contact the authors of the individual details was made but no response was obtained or the authorship of the details was denied. It is understood that a new revised edition is currently in progress (Kent, 2014) and a first draft has been seen by the author, although its contents are confidential and as such cannot be discussed in this thesis.

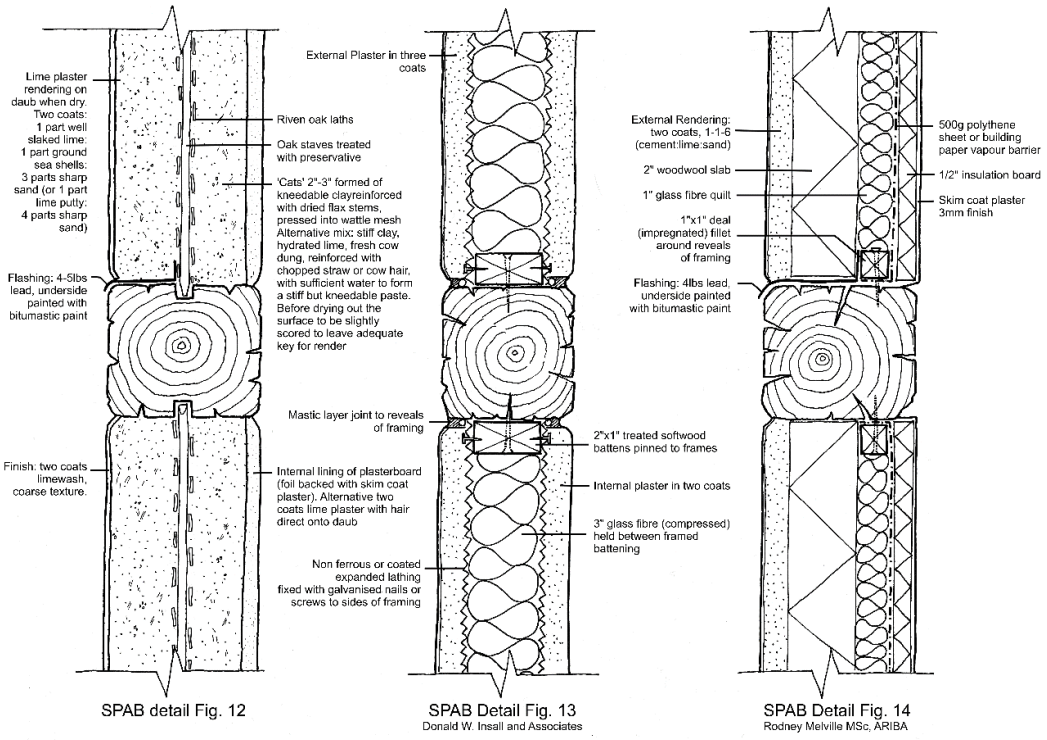

Figure 6. Replacement infill details as featured in the SPAB technical pamphlet 11. Figures 12-14 as labelled in the pamphlet. Source: (Author's own based on (Reid, 1989)). See Appendix A for larger images.

[14] This pamphlet was still available at the beginning of the research for this thesis but has subsequently been removed from the SPAB website some time since 2014

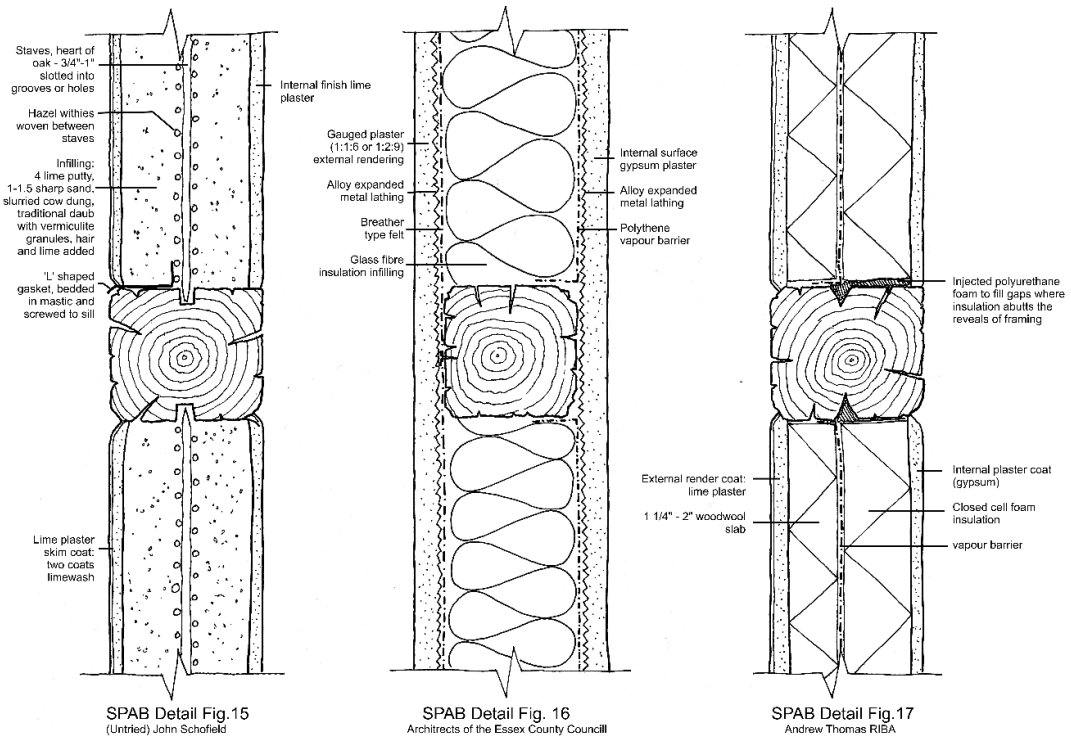

Figure 7. Replacement infill details as featured in the SPAB technical pamphlet 11. Figures 15-17 as labelled in the pamphlet. Source: (Author's own based on (Reid, 1989)). See Appendix A for larger images.

In collaboration with SPAB, M. Suhr and R. Hunt have published the "Old House Eco Handbook" (Suhr and Hunt, 2013) which contains more up-to-date advice on improving the energy efficiency of timber-framed buildings. The authors note that timber-framed buildings are some of the worst performing traditional buildings and as such are a prime target for inappropriate retrofit (ibid, p.117). In the general section on wall insulation they note that external insulation is not suitable for buildings with exposed timber frames (ibid, p.101) and also that internal insulation is to be minimised or avoided in thin walls such as those found in timber-framed buildings (ibid, p.108). Later on, internal insulation is suggested as a possible solution if vapour permeable (such as reed board) and care is taken over possible historic linings and wall paintings (ibid, p119). The preservation of original wattle-and-daub is stressed as "paramount", however, where modern infill is to be replaced, hempcrete or hemp-lime is suggested as a modern equivalent (ibid). A simpler less invasive retrofit action proposed is the plugging of gaps between panel infill and frame, and within frame elements, with a breathable fibre such as hemp, finishing this with a lime plaster (ibid, p.118). A similar detail, although advocating the use of sheep's wool and haired lime plaster is proposed by R. Demaus as the

"*most effective method of improving hygrothermal performance*" (Demaus, 2017 p.36). Demaus also supports the use of hemp-lime (ibid, p.38).

More detailed advice can be found from Historic England, both in their Practical Building Conservation series (McCaig and Ridout, 2012 p.324-5, Pender et al., 2013 p.183) and in a separate pamphlet, first issued in 2010 (Ogley, 2010) and last issued in 2016 (Historic England, 2016a). In the Practical Building Conservation book on Timber (McCaig and Ridout, 2012), two potential retrofit details are provided along with the suggestion of new wattle-and-daub or brick nogging[15]. The first retrofit detail involves the use of wood fibre insulation and a wood wool as a carrier board for the external lime render (Figure 8a). This in many ways is an updated version of that proposed by F.W.B. Charles. The second proposed infill is hemp-lime, and although no detail is given, this would be similar to that illustrated by (Stanwix and Sparrow, 2014 p.276) (Figure 8b).

[15] The use of masonry as panel infill. Most commonly brick nogging, although stone and flint nogging can also be found (Brunskill, 1985 p.152)

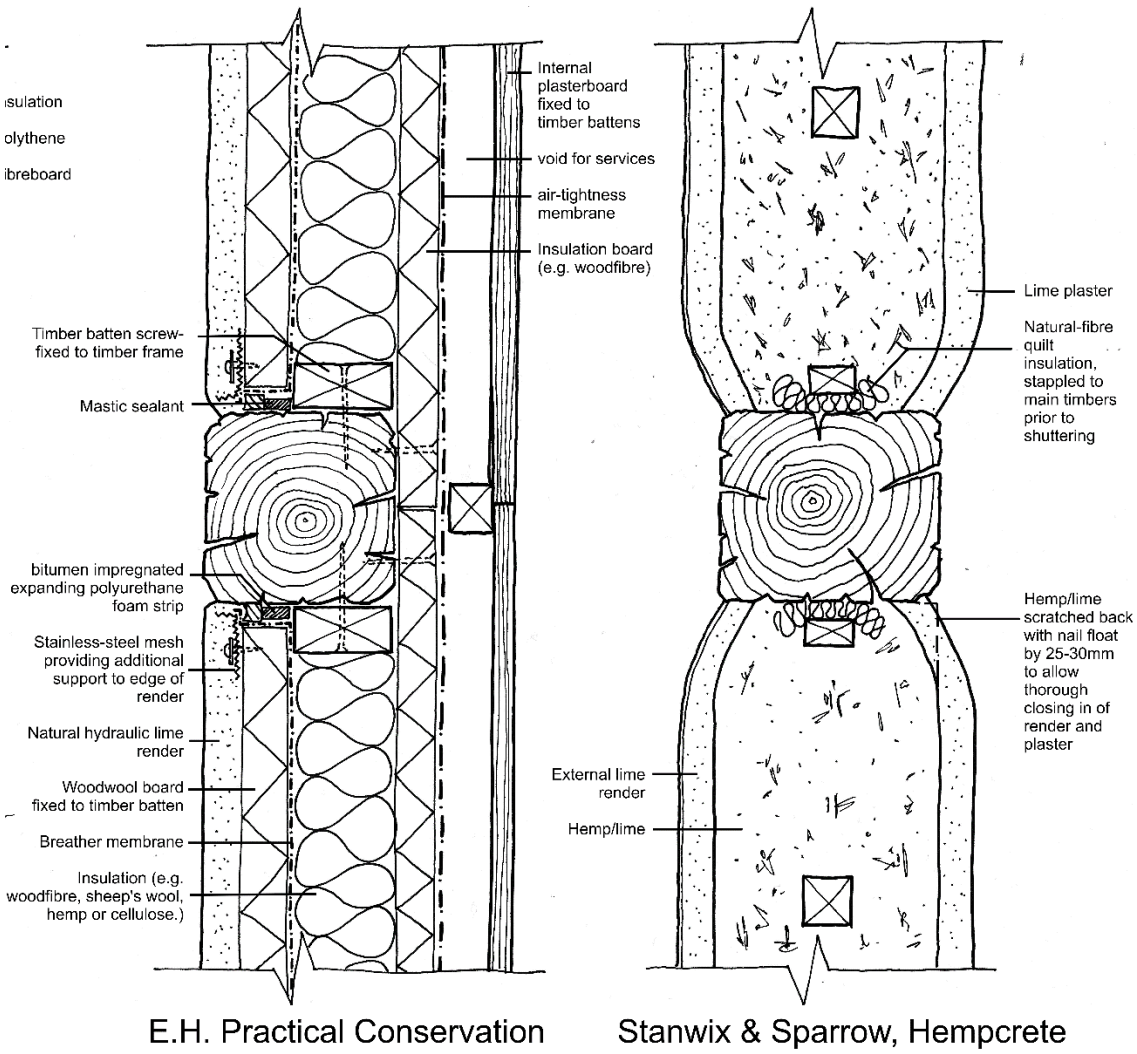

Figure 8. Replacement infill details as proposed by Historic England. Source: (Author's own based on (McCaig and Ridout, 2012) and (Stanwix and Sparrow, 2014))

In the pamphlet "Energy Efficiency and Historic Buildings: Insulating Timber-Framed Walls" (Historic England, 2016a) hemp-lime is again advocated (ibid, p.11), as are other vapour permeable, hygroscopic[16] insulation materials such as wood-fibre and sheep's wool (ibid, p.14). An additional detail showing the use of internal insulation to existing wattle-and-daub is also included both with the option of either the use of a vapour barrier (ibid, p.17) or the use of a ventilated cavity (ibid, p.18) (Figure 9 & Appendix A).

[16] Tending to absorb moisture from the air (Soanes and Stevenson, 2005)

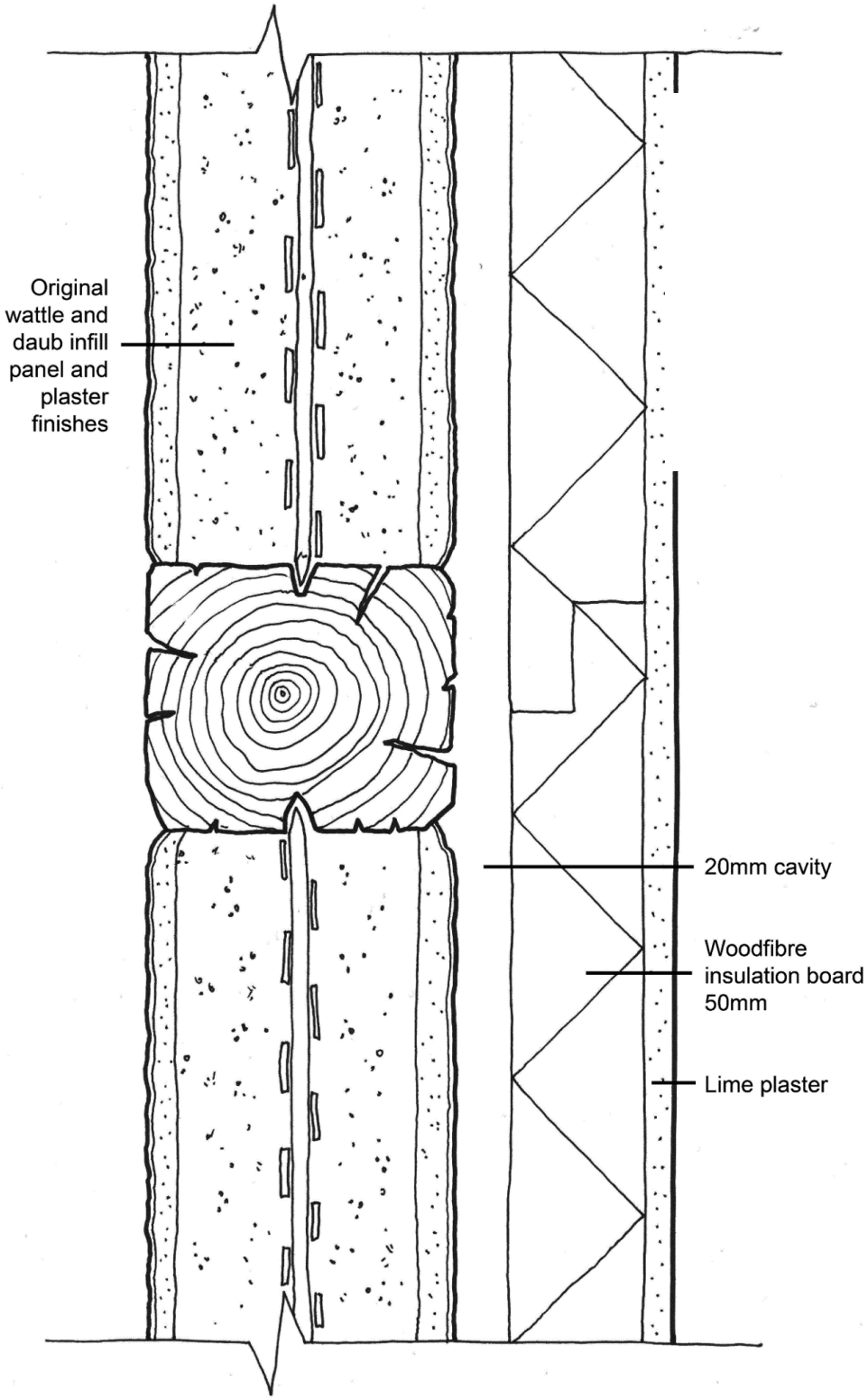

Figure 9. Internal wall insulation to existing wattle-and-daub. Source: (Author's own based on (Historic England, 2016a)

The Sustainable Traditional Buildings Alliance (STBA) has developed a "Responsible Retrofit Guidance Wheel" to provide building owners and building professionals with advice on retrofitting traditional buildings [see http://www.responsible-retrofit.org/wheel/]. The wheel includes guidance on "Frame Infill Insulation" and highlights the advantages and concerns

associated with this retrofit action. The advantages given are reduced heat loss, improved comfort, reduced energy costs and lower CO2 emissions, and depending on the materials used potential improvement in moisture buffering[17] (STBA, 2017). The concerns are divided into technical concerns, heritage concerns and energy concerns, as detailed in Table 5, with cold bridging and increased moisture content being two of the primary concerns.

Table 5. Concerns cited by STBA's Responsible Retrofit Guidance Wheel for Frame Infill Insulation

Category	Concern	Risk category
Technical	Thermal Bridges	Major
	Interstitial/surface condensation	High
	Trapped/accumulated moisture	High
	Personal capacity/right opportunity	High
	Overheating	Medium
	Building control/Warrant	Medium
	Rain and Drains (liquid moisture penetration)	Medium
	Monitoring and Feedback	Medium
Heritage	Use of sympathetic materials	High
	Planning consent within conservation area	High
	Original internal detail lost	Medium
	Original external detail lost	Medium
Energy	Insulation quality	High
	Actual U-value	Medium
	Rebound effects	Medium

In addition to written guidance, advice was also sought from the principal supplier in South Wales of traditional and ecological building materials, Ty Mawr Lime Ltd. (Ty Mawr Lime Ltd., 2017), who are also the authors of technical information on the use of lime (Gervis and Gervis, 2014). Through discussion with the co-owner Nigel Gervis and his technical team, further replacement infill details using expanded natural cork insulation were developed Figure 10.

[17] The ability of internal surface materials to control the internal relative humidity through the absorption and desorption of airborne moisture (El Diasty et al., 1992).

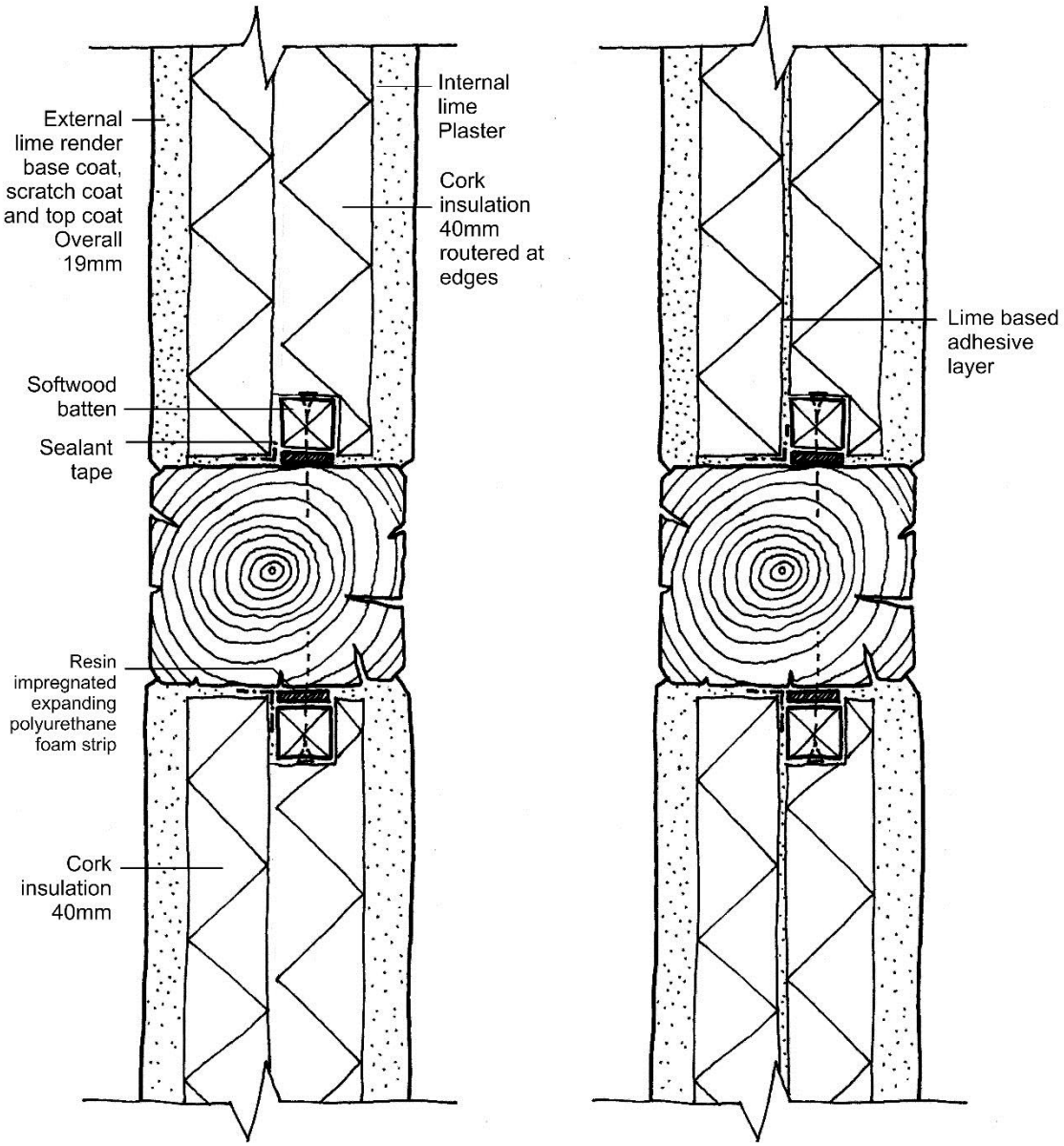

Figure 10. Replacement infill detail using expanded natural cork insulation. Source: (Author's own, developed in association with Ty Mawr Lime Ltd.)

Table 6 presents the hygrothermal performance of the constituent materials and overall thermal transmittance or U-value of the replacement infill panels so far presented in this chapter. It can be seen that overall the panel with the best thermal performance is that suggested by Historic England (McCaig and Ridout, 2012 p.325), with a U-value of 0.42 W/m^{2}K. The traditional wattle-and-daub has the worst thermal performance, with a U-value of 2.83W/m^{2}K.

Table 6. Technical information for replacement infill panels currently suggested for historic timber framing

Code	Source	Materials	Thickness (mm)	Coefficient of Thermal Conductivity (W/mK)	Vapour Diffusion Thickness – sd-value (m)	U-Value (W/m²K)
S1a	SPAB[1] fig.12	External lime render	11	0.7	0.007	2.83
		Earth daub	2x45	0.59	0.011	
		Wattlework (non-continuous)	10	0.19	0.140	
		Internal lime render	14	0.7	0.007	
S1b	SPAB[1] fig.12	External lime render.	11	0.7	0.007	2.53
		Earth daub	2x45	0.59	0.011	
		Wattlework	10	0.19	0.140	
		Foil backed plasterboard	12.5	0.2	1500.000	
S2	SPAB[1] fig.13	External lime render.	19	0.7	0.007	0.67
		Glass wool	50	0.04	0.001	
		Internal lime plaster	22	0.7	0.007	
S3	SPAB[1] fig.14	External lime render	19	0.7	0.007	0.63
		Wood wool	50	0.08	0.009	
		Glass wool	25	0.04	0.001	
		Vapour barrier	-	-	1500.000	
		Wood-fibre	25	0.042	0.003	
		Internal lime plaster	22	0.7	0.007	
S4	SPAB[1] fig.17	External lime render	19	0.7	0.007	0.62
		Wood wool	50	0.08	0.009	
		Extruded polyurethane	25	0.025	0.050	
		Vapour barrier	-	-	1500.000	
		Internal lime plaster	15	0.7	0.007	
S5	SPAB[1] fig.18	Half brick nogging	102.5	0.4	0.016	1.14
		Expanded polystyrene	12.5	0.036	0.073	
		Internal lime plaster		0.7	0.007	
E1a	EH-1[2] pg325	External lime render		0.7		0.42
		Wood wool	15	0.08	0.009	
		Breather membrane (BM)	-	-	0.1	
		Cellulose fibre	54	0.04	0.0015	
		Wood-fibre board	20	0.042	0.003	
		Vapour barrier (VB)	-	-	1500.000	
		Gypsum Plasterboard	12.5		0.007	
E1b	EH-1[2] pg325	As E1a but with no BM or VB	-	-	-	0.42
E2	EH-2[3] Fig.18	Historic infill retained	130	-	unknown	approx. 0.64
		Breather membrane (BM)	-	-	0.1	
		Wood-fibre insulation	50	0.042	0.003	
		Internal lime plaster		0.7	0.007	
E3	EH-2[3] Fig.19	As E2 but with 20mm air-gap in place of BM + plasterboard	-	-	-	0.59
HC1	Stanwix & Sparrow[4]	External lime render	22	0.7	0.007	0.84
		Hemp lime	115	0.115	0.005	
		Internal lime plaster	19	0.7	0.007	
T1a	Tŷ-Mawr[5]	External lime render		0.7	0.007	0.48
		Cork board	2x40	0.04	0.030	
		Internal lime plaster		0.7	0.007	
T1b	Tŷ-Mawr[5]	As T2 but with 2mm lime plaster between cork boards.	-	-	-	0.48

1 SPAB (Reid, 1989)
2 EH-1 (McCaig and Ridout, 2012)
3 EH-2 (Ogley, 2010)
4 (Stanwix and Sparrow, 2014)
5 Tŷ-Mawr- developed by author

With regard to the vapour permeability of the individual layers of construction, the material with the highest vapour diffusion thickness[18], or sd-value, is the vapour control layers with an sd-value of 1500m followed by the breather membrane with an sd-value of 0.1m. These materials are obviously designed to retard the movement of water vapour; however, some of the insulation materials also have relatively high sd-values, such as the expanded polystyrene (0.073m), the extruded polyurethane (0.05m) and to a lesser extent the cork (0.03m). This raises the concern over the potential for trapping moisture within the construction, especially at the junction with the timber frame. The high sd-value of the wattlework is misleading as this value is for the timber itself and does not take into account that the building layer is non-continuous.

2.4.4 Current practice for new-build traditional timber-framed buildings in the UK

Although the focus of this thesis is the retrofit of historic timber-framed buildings, the resurgence of traditional green-oak new-build construction in the UK may offer some potential technical solutions. Over the past few decades, there has been a renewed interest in this construction technique with one of the most iconic new buildings being the reconstruction of Shakespeare's Globe Theatre on London's Southbank (TRADA, 2015a). The infill panels of this building, that opened in 1997, are of lath and plaster with a core of a fire board developed by Rockwool® (Mulryne et al., 1997). This detail reflects the buildings need to comply with Building Regulations with regard to fire escape but not with regard to thermal performance due to the open-air nature of the performance space. Perhaps more relevant to this thesis is the re-emergence of companies offering the construction of new timber-framed houses. The Carpenters Fellowship currently lists 64 timber-frame companies on its database (Carpenters Fellowship., 2018). These companies are predominately located in the South of England, and the Welsh Marches, however the most northerly can be found to the north of Dundee (Figure 11).

[18] The equivalent thickness of stagnant air (m) need in order to have the same vapour diffusion resistance. The higher the sd-value, the less vapour permeable.

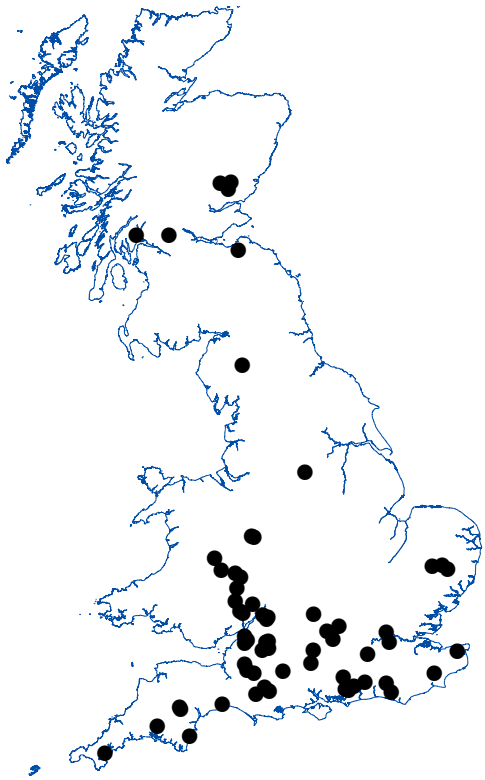

Figure 11. Distribution of timber-frame companies as listed on the database of the Carpenters Fellowship (Carpenters Fellowship., 2018).

Many of these companies work exclusively on the design and construction of only the timber-frame itself and offer no information on potential infill details. However, of the seven companies that do provide advice on completing the building envelope, it is interesting to note that five strongly recommend the use of continuous exterior insulation, in addition to any insulation within the frame (Crossley, 2018, Castle Ring Oak Frame, 2014, Carpenter Oak & Woodland, no date p.16, Oak Frame Carpentry Company, no date, The Green Oak Carpentry Co Ltd, 2018). The material recommended for this continuous external insulation varies from polyisocyanurate (PIR) (The Green Oak Carpentry Co Ltd, 2018) to woodfibre insulation (Crossley, 2018). Of the remaining two companies, Carpenter Oak & Woodland (Carpenter Oak & Woodland, no date) offers an option with continuous external PIR insulation or an option to expose the frame on both sides with the use of an infill detail similar to the previously mentioned detail 17 from the SPAB technical pamphlet (Reid, 1989 p.9), with the principle difference being the replacement of the wood wool board with plywood (Carpenter Oak &

Woodland, no date). A similar detail was developed in 1970 by the final company, Border Oak, which instead of plywood uses a glass fibre mesh to carry the lime render (Border Oak., 2018). Whilst these details meet the requirements of current Building Regulations, the application of them to historic timber-framed buildings is questionable. The use of rigid panel materials is appropriate for new-build constructions with right-angled joints and straight edges but is unsuitable for the complex three-dimensional distortions found in most of the buildings covered by this thesis. Equally, the use of non-vapour permeable insulation materials raises concerns over the potential for increasing moisture content within the historic timber frame, concerns that will be studied further in sections 9.6.4 and 11.

2.5 Conclusions

From the review of the available literature, it appears that many of the reports, research and guidance on the energy retrofit of existing buildings, both at a strategic level and regarding its practical application, fail to acknowledge the specific challenges that need to be addressed in order to retrofit the 25% of the building stock that is traditionally constructed. Where historic buildings are recognised, the issues tend to revolve around the restrictions imposed by the statutory protection of approximately 25% of the pre-1919 buildings and do not engage with the vapour-permeable, hygroscopic nature of their built fabric. Those authors who do specifically tackle the technical challenges faced by traditional buildings tend to focus on the more common solid masonry wall construction, with little academic research being undertaken into the potential impacts of energy retrofitting historic timber-framed buildings. Some limited international research does exist in this area, as does practical guidance. Whilst this guidance comes from trusted sources, empirical research is still need to verify and support its claims and assumptions.

3 METHODOLOGY AND STRUCTURE

3.0 Introduction

There is currently much talk of the need for interdisciplinary teams both in research and in practice. What is perhaps less often discussed is the benefit of the interdisciplinary individual, one whose knowledge spans the boundary of disciplines, enabling a problem to be viewed from multiple perspectives. The energy retrofit of historic timber-framed buildings is such a case. Issues involving history, architectural theory, conservation philosophy, construction, biology, building physics, human comfort and socio-economic factors must all be considered to ensure that the best balance is achieved between user, building and planet. As such, this thesis has taken a mixed methodological approach, choosing an appropriate methodology for each section of the research and at times combining them. It has been acknowledged that this approach has the advantage of different methodologies complementing each other (Groat and Wang, 2013 p.446) and is perhaps best suited to a multi-faceted problem such as the energy retrofit of historic timber-framed buildings.

The details of each methodology are described in detail at the beginning of each chapter. There follows an outline structure of this thesis and a brief summary of the methodologies undertaken and the justification of their choice.

3.1 Structure

The structure of this thesis is divided into two main parts. The first is focused on understanding the context, reviewing the history and development of historic timber-framed buildings, considering their architectural, historical and cultural significance and quantifying the number and location of those buildings in question. The second section then goes on to review the potential for retrofit through the use of case studies, monitoring and simulation. The thesis concludes with findings, recommendations and overall conclusions.

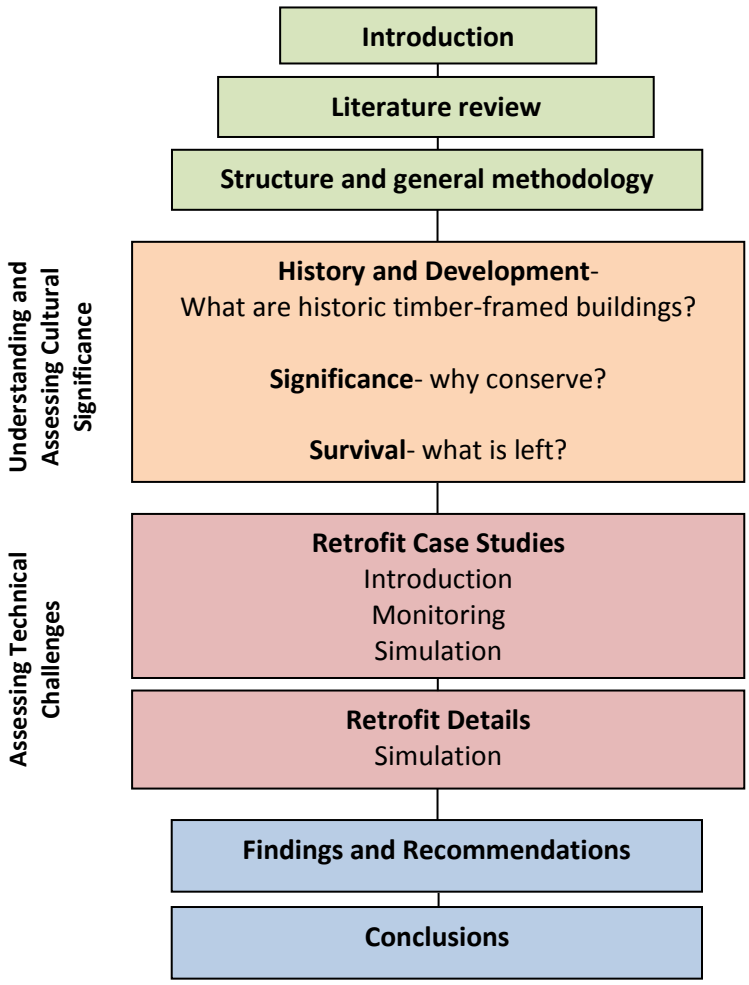

Figure 12. Diagram of overall thesis structure.

3.2 Conservation and the Burra Charter

The methodology of this thesis is informed by the conceptual process set in place by the International Council on Monuments and Sites (ICOMOS) in their Burra Charter (ICOMOS, 2013)[19] (Figure 13) and upheld in the latest draft of the "Principles for the conservation of Wooden Built Heritage" of the same organisation (ICOMOS, 2017).

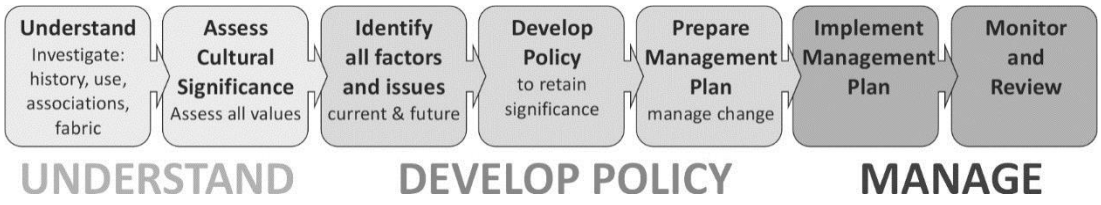

Figure 13. The conservation of places of cultural significance adapted from The Burra Charter. Source: (Author's own based on(ICOMOS, 2013 p.10)).

The charter states that in order to conserve places of cultural significance, it is essential first to understand its significance (ICOMOS, 2013 p.4), especially when its conservation requires a degree of change (ibid, p.6). To achieve this, a detailed study of a place or subject must precede any work in order to understand its setting, its location, the various cultural values placed upon it and the participation of those who hold these cultural values (ibid, p.5). Once this understanding of cultural significance has been gained, all influencing factors arising from it, both current and future, should be identified (ibid, p.10) and policies developed to retain this significance and manage change (ibid). This thesis sits at the beginning of this process and does not pretend to result in a fully-developed policy. Instead, it is hoped that it begins to create the necessary knowledge to allow the formation of guidance. As part of this, it also engages in the final stage of the process, monitoring and reviewing actions already implemented by others, to help inform the decisions of the future.

[19] The Burra Charter was first adopted in 1979 with minor amendments in 1981, 1988 and more substantial changes in 1999. The version cited here is the charter as adopted by Australia ICOMOS in 2013

3.3 Historical research

In order to understand the origins, development and eventual decline of timber framing as a construction technique, a review has been undertaken of secondary, and where possible primary historical sources. Through a mixture of historical accounts (Moxon, 1695, King, 1696, Neve, 1736, Wood, 1788), the theories of those who have previously studied the subject (Addy, 1905, Braun, 1940, Brunskill, 1985, Harris, 2010, Hewett, 1967, Innocent, 1971, Rackham, 1972, Salzman, 1992, Smith, 1965) and the study of the surviving examples, a narrative is created, setting the historic timber-framed building in context. This work is presented in chapter 4. This methodology is further expanded in the following chapter, which discusses the cultural significance of these buildings by studying the endurance of half-timbering as a style even following the decline of its use as a common structural system. Theories are formed as to the reason for this endurance in the hope that the essential nature of remaining examples can be understood and not diminished by any potential interventions.

3.4 Correlational Research

To assess the scope for this research and understand the key factors at play, the percentage of surviving historic timber-framed buildings in the UK has been quantified and geographically located. Using geographic information system (GIS) mapping techniques, secondary data from the national designation lists for England, Wales, Scotland and Northern Ireland has been cross referenced with secondary data covering topographic, geological, climatic and socio-economic factors and the correlations between the data has been analysed. As such, it is possible to begin to understand the conditions that led to their construction, success and survival, and to identify those factors that could in time lead to their failure and disappearance. This work is presented in chapters 6 and 7.

3.5 Case studies

The use of five case studies has allowed the study and comparison of real historic timber-frame buildings and the challenges involved in seeking to improve their energy efficiency. The case studies include buildings where no retrofit has been undertaken, where minimal or moderate interventions have been made and one where major changes have occurred, substantially altering the external envelope. For each case study, historical research has been undertaken to understand their development from construction to their present condition. In addition to the use of archival material, interviews have been undertaken with owners, occupiers, custodians and those directly involved in any retrofit actions.

3.5.1 Quantitative measurement

The data collected on the case studies is primarily quantitative data using scientific research monitoring methodologies for assessing thermal transmittance[20], airtightness[21], internal hygrothermal conditions and moisture content. Detailed methodologies for each of these is contained in chapter 9. The data from each case study was analysed and compared to the others in addition to normative guidance. In a number of cases, it was possible to compare measurements from the same building at different stages of the retrofit process. As such, the buildings are assessed both against each other and against current building standards.

3.5.2 Qualitative measurement

In addition to the quantitative data collected on the buildings performance, in three of the case studies it was possible to obtain qualitative data on the internal hygrothermal comfort

[20] The rate of heat transfer across a building element. Heat flow rate in the steady state divided by area and by the temperature difference between the surroundings on each side of a System: SI units W/m2K (British Standards Institution, 1996)

[21] A building's resistance to uncontrolled air flow through cracks, permeable materials, unintentional openings and unions within the construction of the external building envelope (British Standards Institution, 2015b p.1)

as experienced by the buildings occupants. Although limited in scope, this information helps to form a more comprehensive understanding of the hygrothermal performance of the specific case studies and timber-framed buildings in general.

3.6 Digital simulation

The information gathered from each of the case studies was used to undertake digital simulation of their past, current and potential future heating energy demand. By doing so, it was possible to evaluate the efficacy of individual retrofit actions and combined scenarios, and set these against the associated impact on the historic built fabric. A detailed methodology of this process is presented in chapter 10.

Digital simulation was also utilised to review the interstitial hygrothermal performance of the replacement infill panel details obtained during the literature review, thereby allowing an appraisal of the potential risk posed to the historic timber frame from increased moisture content and associated insect attack and fungal decay. A detailed methodology is covered in chapter 11.

3.7 Analysis and synthesis of results

The analysis and synthesis of the results is dealt with at the end of each chapter, building on, and referring to the work that has been presented in preceding chapters. The final conclusions draw these discussions together, summarising the recommendations that have been made throughout and collating the areas for future research identified.

4 HISTORY

4.0 Introduction

As previously stated, prior to embarking on the conservation of any historic building or group of historic buildings, it is essential to understand their cultural significance (ICOMOS, 2013 p.4, ICOMOS, 2017 p.1) and associated values. The various established methods for defining significance will be discussed in more detail in the next chapter, however two key values are the historic and aesthetic value of the building. It is therefore necessary to study the history and development of timber-framed construction in the UK, from its origins, to its eventual decline. To assist in this, the works of Innocent (1971), Salzman (1992) and Davey (1961) set timber framing within the wider context of the history of English construction, as do the studies that arose from the interest in British vernacular and domestic architecture in general that began in the late 19th century (Addy, 1905)[22] and continued throughout the 20th century (Oliver, 1929, Braun, 1940, Brunskill, 1978, Smith, 1988, Oliver, 1997). Those books where timber-frame construction is the main focus, were invaluable, specifically Brunskill's "Timber Building in Britain" (1985), the works of members of the Vernacular Architecture Group (Smith, 1965, Hewett, 1967, Alcock, 1981), that of F.W.B. Charles (1967) and most recently Harris's compact but informative "Discovering Timber-Framed Buildings" (Harris, 2010). Where possible, contemporary accounts were sought (Bede and Giles, 1843, Giraldus et al., 1863, King, 1696), although the carpentry manuals of the late 17th and early 18th centuries (Moxon, 1695, Neve, 1736, Wood, 1788) were written too late (once timber-framing was no longer a common wall construction technique) to be of much relevance. Archaeological evidence was also considered (Bulleid, 1894, Historic England, 2016b), as were visits to the case study buildings and some other iconic examples of surviving timber-framed buildings, including St Andrew's Church, Greensted; Fyfield Hall; Cressing Temple barns; Paycocke's, Coggeshall; Lavenham Guildhall; and The Market House, Ledbury.

[22] Originally published 1898

This chapter begins with an account of timber-framed buildings, presented from their early beginnings (Innocent, 1971, Braun, 1940), through their rise to become one of Britain's most common construction techniques (Harris, 2010, Brunskill, 1985). Evidence is presented for its historic use in England and Wales where surviving examples may still be found, in addition to Scotland and Ireland (Glendinning et al., 1996, O'Curry and Sullivan, 1873), areas now not known for their timber construction (Gailey, 1984). There follows an overview of the basic typologies and construction methods, outlining the principal schools (Mason, 1974, Smith, 1965, Fox, 1959), styles and materials (Clifton-Taylor, 1987), and concludes with a study of its decline and in some places prohibition (Reddaway, 1940). Yet as the risk of fire led to its replacement with inflammable brick, the British attachment to these half-timbered buildings remained (Ballantyne and Law, 2011a). In chapter 5, this argument will be developed and the cultural significance of historic timber framing explored.

4.1 Early beginnings

The architectural historian C.F. Innocent surmises that primitive dwellings developed from piles of brushwood, forming screens to protect from weather and wild beasts (Innocent, 1971 p.7). In time, these developed into "*hurdles*" or "*flakes*" formed of woven brushwood, thin branches or "*wattlework*" (ibid). He infers that these woven panels moved from forming simple vertical elements, to being used horizontal or as simple propped shelters such as that depicted in J.F. Millet's 'Le Cantonnier,' (drawn 1895) (Figure 14) (ibid). He goes on to note that a German theory proposes that the full enclosure of the living space was later developed principally to protect the fire (ibid).

Figure 14. Piles of brushwood and J.F Millet's 'Le Cantonnier' illustrating Innocent's theory of the development of timber construction (Innocent, 1971 p.7). Sources: (Wolton, 2009, Viard, 2007)

Some of the earliest evidence of timber-framed constructions in the UK are not buildings but raised walkways such as the "Sweet Track" discovered in the peat bogs of the Somerset Levels (Coles, 2006) (Figure 15). This structure, which includes both round posts and squared planks, has been dated to the Neolithic period, with dendrochronology[23] showing that the trees were felled in the winter of 3806/3807BC (Hillam et al., 1990 p.214) with

[23] The science of dating of timbers by study of the tree-ring numbers and widths (Harris, 2010 p.94)

construction following shortly after (ibid, p.215) . Although not buildings, these archaeological remains clearly display the sophistication and woodworking ability of Neolithic Man. The timbers are not the crude, unfinished lumber we might have imaged but are in fact as carefully shaped and worked as many timbers from the height of mediaeval carpentry.

Figure 15. Neolithic Timbers from The Sweet Track raised walkway, Somerset levels. Source: (Coles, 2006)

Archaeological evidence would suggest that dwellings from the period directly preceding the Roman conquest were conical and built of timber poles (Braun, 1940 p.2). The remains of a Late Iron Age (250BC) village near Glastonbury, discovered in 1892, show circular huts built on timber and brushwood platforms (Bulleid, 1894 p.141).

> "*The hut walls were constructed of upright posts placed about one foot apart, the spaces between them being filled in with wattle-and-daub. This is shewn not only by the quantity of baked clay bearing wattle and timber marks but also by the stumps of actual wall-posts in situ*" (ibid, p145).

Braun describes how a central pole or set of poles would form the principal support to a ring of angled perimeter poles, their bases set in the earth (Braun, 1940 p.2), with the diameter of these constructions varying from 10 to 25 feet (3-7.6m) (ibid). Bracken, heather and turf would be used to cover the primary structure as Braun surmises that the straw produced by these early agriculturists would be too short to be used as a thatch (ibid). The existence of similar conical huts can be found until recently in the indigenous architectures of tribes from other cold temperate, forested regions of the world such as Siberia (Evenki) (Oliver, 1997 p.841), North America (Pre-Navajo and Assiniboin) (Oliver, 1997 p.1934) and Patagonia (Selk'nam (Figure 16), Alacalufes and Yagánes) (Emperaire, 2002 p.157). Even in England this method of construction was used up until the mid-19th Century by shepherds and goatherds (Innocent, 1971 p.8) and in 1916 Innocent claims that these structures were commonly used by charcoal burners (Figure 17) and were in widespread use across Europe, especially in Germany and Sweden[24] (ibid.). Their ongoing use in the UK was recorded in England in 1905 (Addy, 1905 p.3) and was still common in 1940 (Braun, 1940 p.2).

[24] This is interesting as archaeological evidence suggests that early houses in continental Europe tended to be rectangular in plan rather than round HARDING, A. F. 2000. *European Societies in the Bronze Age*, Cambridge University Press.p.36

Figure 16. "Fuegian" or Selk'nam, Tierra del Fuego, as depicted by Fitzroy 1826-1836. Source: (FitzRoy, 1893)

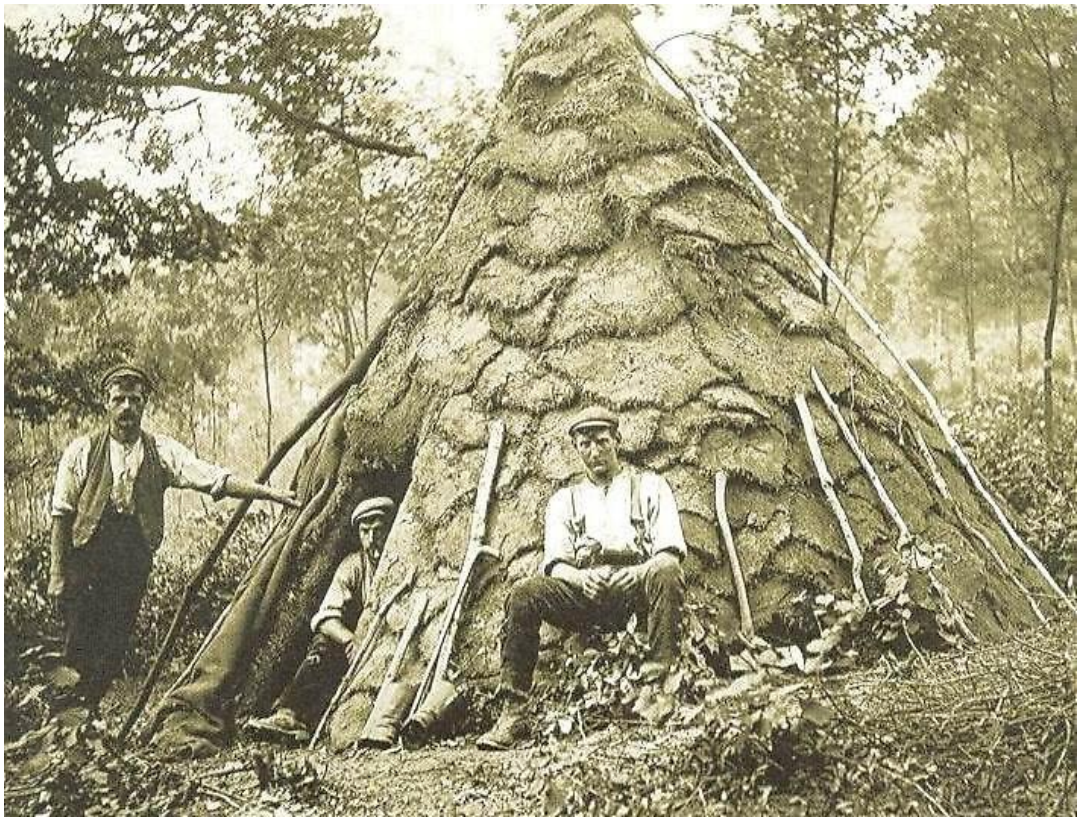

Figure 17. Charcoal Burners and hut, Backbarrow, Cumbria, UK 1930 Source: (Massicks, 2010)

These simple tepee-type structures were most probably superseded by the introduction of vertical wall elements to increase the head-height and usable floor area. Evidence of vertical walls were present in recent discoveries of a Bronze Age settlement at Must Farm, Cambridgeshire (Historic England, 2016b). The floor and walls were of wicker-work held by a wooden frame, itself set on stilts (ibid.) The houses were capped with conical roofs covered with turf, clay and thatch (ibid.), essentially the same as the earlier constructions but raised above the floor on walls. The next development in the early British dwelling is thought to be the invention of the ridge beam, thereby allowing the expansion of the plan form from circular to oval and eventually rectangular (Braun, 1940 p.7).

4.1.1 Early surviving timber-framed buildings in the UK

The oldest surviving timber building in the UK is believed to be the Church of St. Andrews, Greensted-juxta-Ongar, Essex (Prizeman, 1975 p.42, Innocent, 1971 p.108).

Figure 18. The church of St. Andrews, Greensted- juxta-Ongar, Essex. Source: (Author's own, 2017.)

In its listing description it is claimed that the walls of the nave have been dated to 845 AD (Historic England, 2014) however others set this date between 1063 and 1103 (Walker, 1999a p.24). Either way, it still predates any other timber structure still standing. The walls of the nave are built of half oak trunks, set upright, with the split faces inwards (Innocent, 1971 p.109). As such, the building perhaps bears some resemblance to Irish and Scottish oratories as described by O'Curry and Sullivan (1873 vol iii p.35-38) and the Venerable Bede (Bede and Giles, 1843 p360). Equally it is similar to surviving “Stave Churches” found in Norway, perhaps suggesting evidence of a Scandinavian influence (Braun, 1940 p.14). Unfortunately the building suffered a thorough “restoration” in 1849 and the original overall form of the building that is believed to have survived intact until this time has been lost (Hewett, 1982). What survives are the aforementioned north and south walls of the nave. The base of the walls sat originally in the earth, a technique known as “earthfast”, but a dwarf wall and sill plate were inserted at a later date (Brunskill, 1985 p.189). The corners of the nave are completed with three-quarter trunks (Innocent, 1971 p.109) and loose vertical fillets are set in grooves to join each timber member (Brunskill, 1985 p.189, Hewett, 1982 p.1) (Figure 19). These fillets or tongues could be argued to be the first precursors of the infill panel, however, with its solid walls, the construction of the church cannot be truly considered as timber-framed.

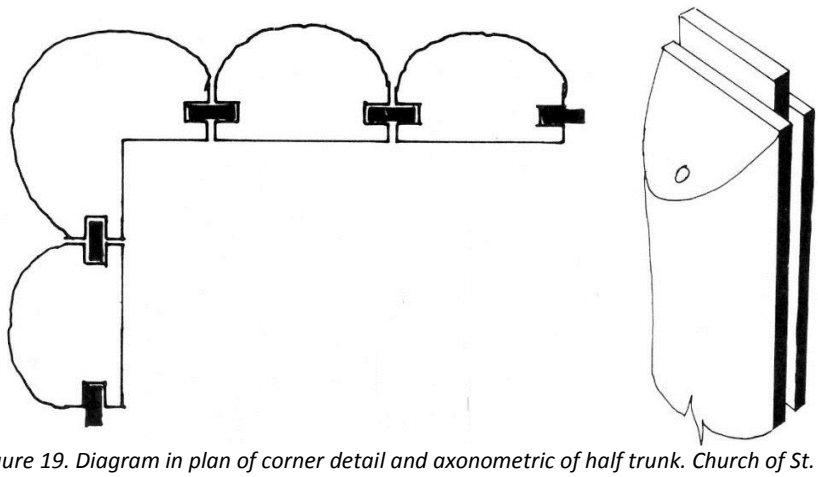

Figure 19. Diagram in plan of corner detail and axonometric of half trunk. Church of St. Andrews, Greensted-juxta-Ongar. Source: (Hewett, 1982 p.2)

Fully timber-framed buildings appear to have developed around the late 12th century (Walker, 1999a p.21). Few of these building survive but those that do are aisled halls or barns (ibid). The Bishop's Palace Hereford 1180, is described as "*probably the most complete timber building in England to have survived from the twelfth century*" (Jones and Smith, 1960 p.69), however the building was partly encased in brick by Bishop Bisse in the 18th Century (R.C.H.M., 1931 p.116). Another contender for the title would be Fyfield Hall, Fyfield, Essex (Figure 20 to Figure 22).

Figure 20. North Façade of Fyfield Hall, Fyfield, Essex Source: (Author's own, 2017)

Whilst previously published dendrochronology dates of 785-985 AD have now been called into question (Alcock, 1998 p.136), the original open aisled hall of the building is now accepted to date from 1167-1185 (Walker, 1999a p.21, Bettley and Pevsner, 2007 p.375). The private house, recently on the market for £2.55 million (John Sear Estate Agents, 2016) was remodelled in the late 14th early 15th century (leading Pevsner to originally date it as such (Pevsner, 1954 p.171), extended in 16th and 17th centuries and the south façade re-

fronted in the 18th or 19th century (Walker, 1999b p.127) (Figure 21). As such little of its original appearance remains (Figure 22).

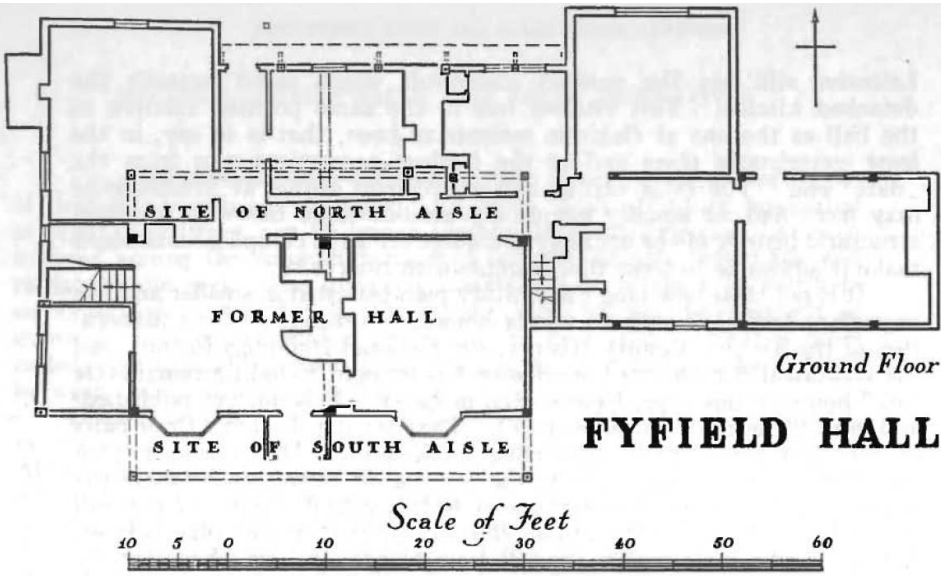

Figure 21. Ground floor plan of Fyfield Hall, Essex. Source: (Smith, 1955)

Figure 22. South Façade of Fyfield Hall, Fyfield, Essex. Source:(John Sear Estate Agents, 2016)

Timbers from the two-bay aisled hall survive, but as with the Bishop's Palace, these are confined to principal posts and roof members. It is therefore difficult to appreciate the wall structure of this early example of timber-framed construction. A study of eight late 12th and early 13th century timber-framed aisled buildings shows evidence of boarded panel infill in half of the study sample but also find the use of wattle-and-daub (Walker, 1999a p.30).

Figure 23. Wheat Barn (left) and Barley Barn (right), Cressing Temple, Essex. Source: (Author's own, 2017)

Two impressive examples of early timber-framed construction are the Wheat Barn and Barley Barn at Cressing Temple, Essex (Figure 23). The site was gifted to the Knights Templars by Matilda, wife of King Stephen in 1137 (Bettley and Pevsner, 2007 p.313) before being passed to the Knights Hospitallers 1312 upon the suppression of the Templar order (Pevsner, 1954 p.138). In the first edition of "The Buildings of England: Essex" (Pevsner, 1954) Pevsner notes that the Wheat Barn was dated by experts *c*. 1450 and the Wheat Barn 1530. However, by the publication of the latest edition of the guide (Bettley and Pevsner, 2007) dendrochronology had shown that in fact the trees used in the Barley Barn were felled between 1205 and 1235 and those of the Wheat Barn 1257 and 1280 (ibid, p313-314). A detailed study of the two barns (Hewett, 1967 p.68) expressed surprise in the relatively short interval between the construction of the two barns due to the large technical advances, especially in the jointing techniques, that are evident in a comparison between the two barns. This rapid development may possibly confirm that timber-frame construction was still in its infancy. The most obvious visual difference between the two

externally is the walling material, with weatherboarding to the Wheat Barn and brick-nogged, close-studding to the Barley Barn. However, both barns have been re-walled at a later date and so yet again we can learn little about their original external walls. That said, the two barns remain imposing examples of early timber framing, with the Wheat Barn measuring 36m long by 14m high and the Barley Barn 40m long by 12m high (ibid).

These early examples mark the beginning of a building technique that was to go on and dominate UK construction for centuries.

4.1.2 Early Timber Buildings in Wales

Although not as many historic timber buildings survive in Wales as they do in England, there still exists evidence of an early tradition of its use. In the 12th century Giraldus Cambrensis recorded simple timber constructions noting that the Welsh:

> "*neither inhabit towns, villages, nor castles, but lead a solitary life in the woods, on the borders of which they do not erect sumptuous palaces, nor lofty stone buildings, but content themselves with small huts made of boughs of trees twisted together, constructed with little labour and expense and sufficient to endure throughout the year*" (Giraldus et al., 1894 p.505).

Although Giraldus appears to assert that all the Welsh lived as such, it has since been argued that the dwellings he describes are shepherds shelters and not permanent dwellings (Wiliam et al., 2011 p.117). This would appear to be confirmed by Benjamin Malkin who writes in 1807 that,

> "*Houses of the like construction for temporary summer residence on mountains, or in woods, are frequently mentioned by poets as late as the commencement of the seventeenth century. Down to the year 1760 or later, they were used in the mountains of Glamorgan and Monmouthshire for summer dancing*" (Malkin, 1807 p.414).

The use of timber and wattling for temporary shelters was however not restricted to the lower echelons of society. In around 945, for the purpose of writing his book of Welsh law, a bower was built for King Hywel Dda (Howell the Good) Prince of all Wales (ibid, p143).

This bower consisting of "*white wattles, interwoven with smaller twigs of various colours, representing the figures of birds, flowers and other natural objects*" (ibid). Malkin goes on to state "*At the same time, there can be no reasonable doubt that the Welsh had buildings of stone and timber in the reign of Howel Dda; since his laws themselves prove it in numerous passages*" (ibid, p414).

4.1.3 Early Timber Buildings in Scotland and Ireland

Evidence of constructions, similar to those previously described at Glastonbury and Must Farm, have also been discovered in Scotland in the form of lake dwellings or *Crannogs* (West, 1967 p.19). The earliest of these date from the Romano-British era, although they remained popular especially in the Highlands until the 16th Century (ibid). Sites included Milton Loch (Kirkcudbright) and Lochlee, near Tarbolton, Ayr (ibid). They consisted of a superstructure of timber resting on a substructure either of stone in the North and West, or elsewhere, especially in the Southwest, of rafts or mounds of peat, timber and brushwood (Glendinning and MacKechnie, 2004 p13).

The tradition of timber construction in Ireland is recorded in the accounts of the life of the 7th century Irish builder Gobban Saer, and specifically his building of the oratory of Saint Moling (O'Curry and Sullivan, 1873 vol iii, p.34). The account shows that the main building materials for the oratory were timber with timber shingles. This is backed up by the account of the building of another oratory, that of Rathain Ua Suanaigh, which tells of the use of one thousand timber boards for its construction (ibid, p38). It is possible that the oratory was similar to the Viking stave churches still found in Norway today, or the previously presented church of St. Andrew's Greensted-juxta-Ongar (Figure 18).

Timber construction in 7th century Ireland appears not to be limited to religious buildings but also the dwellings of high social standing as told in the tale of Cuchulain when referring to Bricriu's house (ibid p.18). Six horses were used to carry home every post or plank of the

walls and it took seven of the stoutest men in Ulster to weave or interlace between the uprights with hazel rods (ibid). This interweaving of hazel rods would appear to be wattling and appears again in the construction of a more humble abode, quoted here by O'Curry from the Gaedhelic Life of Saint Colman Ela, a 7th century Irish saint. Watching a man build his house whilst sheltering from a rainstorm, Saint Colman's student Saint Baoithin states:

"*Of drops a pond is filled;*
Of rods a round-house is built;
The house which is favoured of God;
More and more numerous will be its family.
[It is a] single rod which the man cuts
And which he weaves upon his house:
The house rises pleasantly,
Tho' singly he sets the rod" (ibid, p32)

O'Curry, writing in 1873, notes, "*The plan of this description of house was very simple, and may be seen preserved in the wicker or wattle sheep-cots in many of those parts of Ireland where timber is abundant enough to render its use more economical in raising these simple temporary structures, than either stone or earth*" (ibid, p31). He goes on to describe how the structures, unlike a tent or the previously described charcoal burner's hut, did not have poles tapering to an apex but formed vertical walls. Again, the poles were set in a circle and between them; the interstices were filled with stout hazel and other rods. A central post or *tuireadh* supported the rafters and the roof was thatched with straw or sedge (ibid).

In the 8th century AD the Venerable Bede in his Historia Ecclesiastica, Book III, Chapter XXV (Bede and Giles, 1843) writes of a 7th century timber construction, built by the second bishop of Lindisfarne, Bishop Finan (Powicke et al., 1961).

> "*In the meantime, Bishop Aidan being dead, Finan, who was ordained and sent by the Scots, succeeded him in the bishopric, and built a church in the Isle of Lindisfarne, the episcopal see; nevertheless, after the manner of the Scots, he made it not of stone, but of hewn oak, and covered it with reeds…*" "Interea, Aidano episcopo de hac vita sublato, Finanus pro illo gradum episcopatus a Scotis ordinatus ac missus acceperat; qui in insula Lindisfarnensi fecit eclesiam episcopali sedi congruam, quam tamen, more Scotorum, non de lapide, sed de robore secto, totam composuit atque arundine texit…" (Bede and Giles, 1843 p.360).

It is interesting to note that the term "*more Scotorum*", in the manner of the Scots, is used to distinguish the construction from the stone construction of the Romans. Bede uses "*Scotis",* Scots to refer to those inhabiting Ireland and part of modern day Scotland. Bishop Finan had himself been sent from the Scottish Island of Iona, where he had been trained, but was originally from mainland Ireland (Grattan-Flood, 1909).

In the 12th century, a feudal system similar to that of the Anglo-Norman's in England and Wales began to develop in Scotland (West, 1967 p.52-53). With it came the building of motte and bailey castles, and just as with their English counterparts the first keeps built on these artificial earthen mounds were of timber construction (ibid). West also notes that pre 17th century most rural dwellings in Scotland were of timber, wattle or turf (ibid). Even in 1791 in the first statistical account of Scotland, when talking of the rural dwellings, it was stated, "the greatest number of these were built of earth and are usually raised to the ground one in five or seven years when they were added to the dunghill. Poverty kept them such" (Oliver, 1997 p.1276).

4.2 A common construction technique

It has been noted that there were two expansive periods in British vernacular architecture (Mason, 1974 p.26), the first was seen first in the south-east and in the Welsh Marches from 1400-1500 and later in East Anglia 1450-1600 (ibid). The second was nationwide, taking place from about 1570-1630 (ibid), although there is some question over these exact dates and regional variations do exist (Machin, 1977 p.34). This second period has been christened "*The Great Rebuilding*" (Hoskins, 1953 p.44), with both the building of new dwellings, mostly small cottages, and the renovation and enlargement of existing mediaeval buildings (ibid. p48). Hoskins explains this increase in construction work as a result of the existence of freeholders with relatively fixed expenses or outgoings, and a rapid increase in the price of all agricultural products, resulting in larger incomes (ibid.

p50). He explains that their tenure of land and rents had been fixed often centuries earlier, whilst the products that they were producing steadily increased in price. Their net income therefore increased. In those locations where land tenure was sufficiently stable, farmers would be willing to invest these profits in the construction of new, sturdier houses, replacing previous impermanent dwellings that may have lasted no more than a generation (Machin, 1977 p.55). Hoskins also argues that the increase in population in the latter half of the 16th Century is both cause and effect of this building boom (Hoskins, 1953 p.55). More houses were constructed due to an increasing population, whilst at the same time the population increased due to the improved privacy for couples provided by these larger, less overcrowded dwellings (ibid).

Prior to the 15th century most houses would been of one storey, with at most an attic in the roof (Braun, 1940 p.44). Whilst in the countryside there was land available to increase the size of a property horizontally, the confinement of town and city walls lead to the need for expansion upwards and resulted in the addition of upper floors (ibid). At the same time upper floors could begin to overhang or jetty, thereby further increasing available floor space. 15th century Essex, with its trade with Europe, was "by far the most progressive part of the country", and it is here that the earliest examples of two storied jettied timber yeoman's houses can be found (Braun, 1940 p.48).

By the 16th century, timber framing was the most common construction technique, especially for dwellings. Spanish visitors to England in the reign of Queen Mary (1553-1558) noted that

> "*These English have their houses made of sticks and dirt, but they fare commonly so well as kings*." (Harrison, 1968 p.196).

This short derisive statement is substantiated by the work of the Elizabethan intellectual William Harrison, who writing in his "Description of Britian" in 1587 states

> "*The greatest part of our building in the cities and good towns of England consisteth only of timber, for as yet few of the houses of the commonalty (except here and there in the West Country towns) are made of stone*…" (ibid p195).

He goes on to say that

> "*In old times the houses of the Britons were slightly set up with a few posts and many raddles (wattlework)…, the likes whereof almost is to be seen in the fenny countries and northern parts unto this day, where for lack of wood they are enforced to continue this ancient manner of building*" (ibid).

The flimsy nature of 12th century houses is shown by the Assize of Clarendon 1161, article 21, which enacts that any person who harbours one of the sect of renegades excommunicated at Oxford

> "*shall be at the mercy of the lord king; and the house in which they have been shall be carried without the town and burned*" (Henderson, 1892 p20).

The quality of timber construction varied across the country, Harrison distinguishes between the plain and wood soils. He records that in woody soils houses

> *"…are commonly strong and well-timbered – so that in many places there are not above four, six or nine inches between stud and stud…*"(Harrison, 1968 p.196).

However, in areas with plain (un-wooded) soils the lack of timber for construction is notable.

> *"… In the open and champaign[25] countries they are enforced for want of stuff to use no studs at all…"*(ibid)

In the following chapter of this thesis, it will be shown that there remains a marked distinction between these two regions, with timber-framed buildings surviving in the former but not the latter.

There were also marked differences between the timber framing techniques within those areas where the material was widely used. One of the most cited differences is the divide in

[25] Open level countryside

construction techniques between those areas to the south and east of the Jurassic limestone belt (stretching from Portland Bill, through the Cotswolds to Lincolnshire), an area classed as “lowland” and those to the north and west or “highland” area (Fox, 1959 p.29, Harris, 2010 p.11, Mason, 1974 p.16). The distinction between these two areas lies in their differing early construction techniques where “Aisled” frames develop in the lowland areas and “Cruck” frames in the highlands (Harris, 2010 p.11). It should however be noted that there is some blurring between the two regions and their borders are in reality not clearly defined (Smith, 1965 p.133, Mason, 1974 p.16, Smith, 1981 p.5). At the same time, Smith (1965) identifies three separate schools or traditions of carpentry, the eastern with close studding and tension-bracing, the western with square panelling and angle bracing and the northern with the interrupted sill beam (Smith, 1965 p.156).

The following section will go on to explore in more detail the various construction methods and building materials that developed during the period in which timber framing became the most common construction technique across the country.

4.2.1 Structural Techniques

Timber framed buildings developed along two principle structural methods, that of ‘cruck framing’ and ‘post and truss’, the latter of which can be divided into aisle framing and box framing (Innocent, 1971 p.74). The relationship between the structure and the external envelope differ between the two. There follows a description of each.

4.2.1.1 Cruck Framing

Some argue that cruck construction is a Celtic form, evidenced by the similarity of their distribution to that of Celtic place names (Smith, 1964 p.126). Others suggest that it may have been more widespread, and that the evidence of its use has been obliterated by the Norman-French introduction of box framing in the South East (Mason, 1974 p.23) where no examples of surviving cruck construction have been identified (Alcock, 1981 p.98-171).

Evidence of cruck construction can be found in the British Isles from at least the 12th century and is argued by some to have pre-Roman origins (Smith, 1981 p.5). The Oxford Dictionary of English states that the word is a 16th century variant of the word *crook,* an Middle English word for hooked tool or weapon derived from *Krókr in* old Norse (Soanes and Stevenson, 2005). If so, then it is possible that the construction technique was brought over by invaders from Scandinavia where similar constructions can still be found (Smith, 1981 p.5). The technique differs from other timber-frame constructions in that it utilizes pairs of massive, book-matched timber members, known as cruck blades, cut from the same tree, which rise from low down in the external walls to the apex of the roof (Peate, 2011 p.158-165) (Figure 24 & Figure 25). As such, most of the roof loads are carried by these principal members, and the walls become secondary elements, whose principal role is to enclose the internal space, providing shelter from the elements.

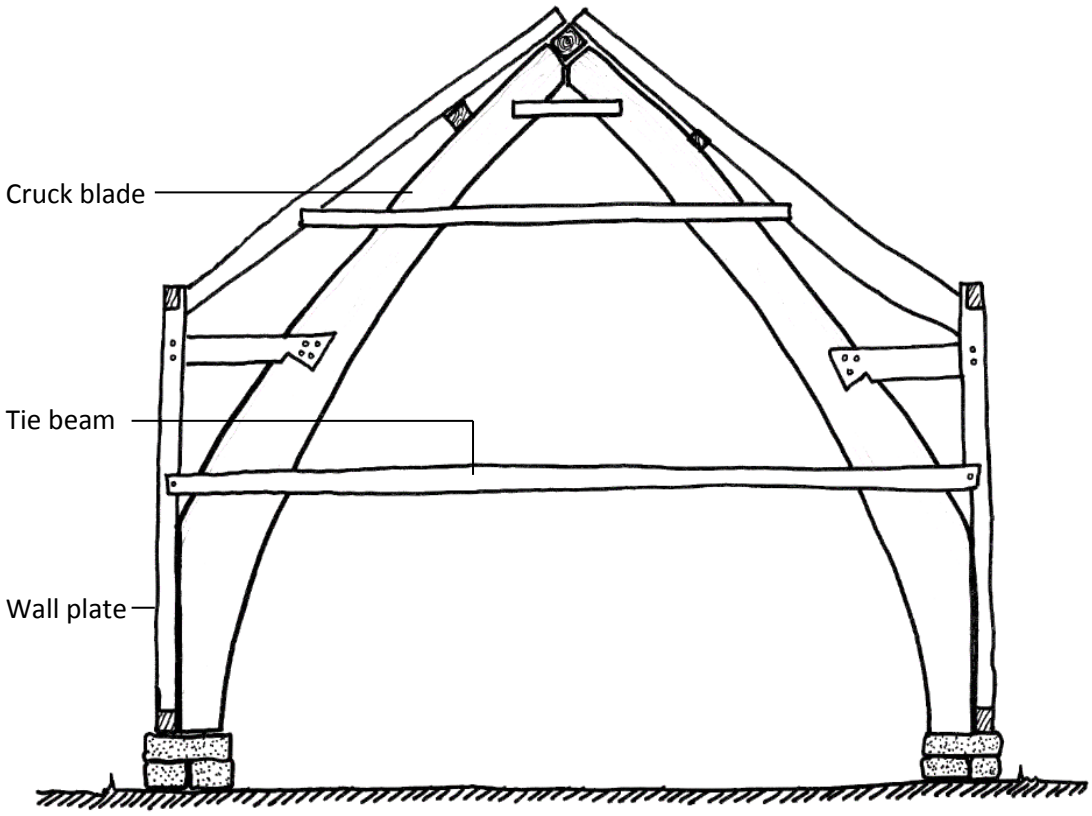

Figure 24. Transverse section through a typical cruck construction showing the principal members. Source: (Author's own)

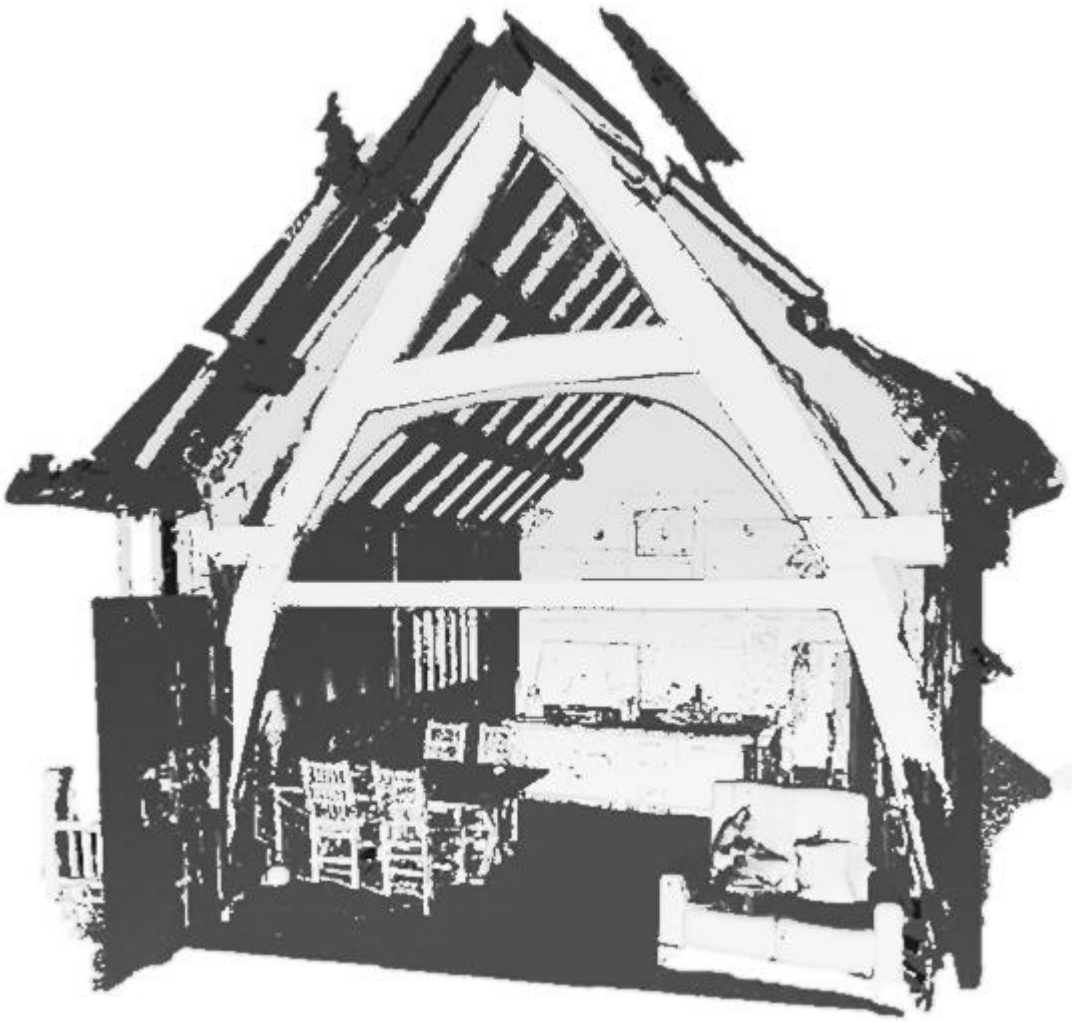

Figure 25. Laser scan section of Hacton Cruck Hall, Preston-on-Wye, Herefordshire. Source (Author's own, 2016)

The external walling material used to create this enclosure varies according to region (Figure 26), with traditional materials including stone, brick, timber-frame and cob. This is most probably due to the influences of climate and availability of local materials. The distribution of external walling materials illustrated in Figure 26 clearly shows the limestone belt, running diagonally from the South-West, dividing the forests of Central and South-East England. The preference for stone or brick walls in the west and north of the country could also be due the harsher climates of these areas. Further issues related to this are discussed in more detail in the chapter on survival chapter 6.

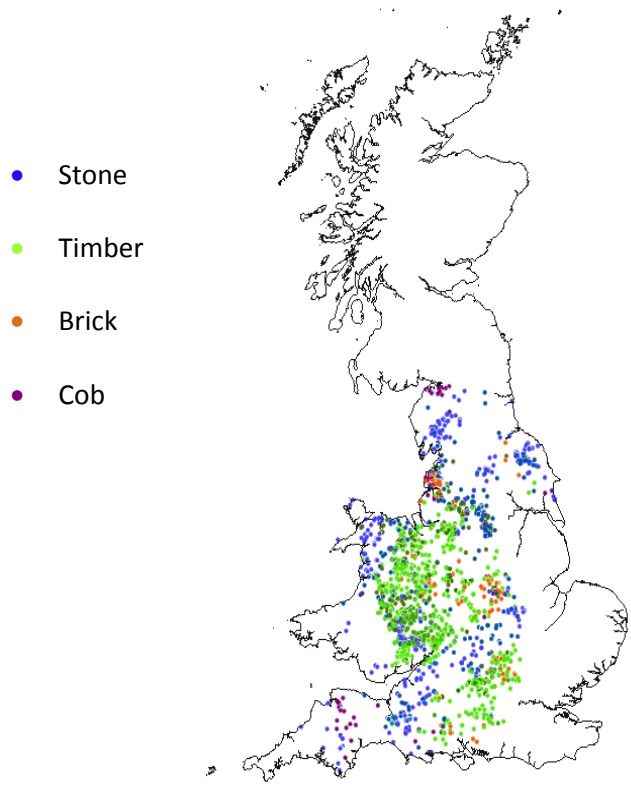

Figure 26 Distribution of cruck framed buildings showing external walling material. Source: (author's own based on (Alcock, 1981))

In the cases where timber framing forms the external envelope, the timber members are often far thinner due to them not carrying the structural load of the roof. The lack of depth therefore prevents an added challenge with regards to retrofit, one that will be studied in more detail in the first case study, Hacton Cruck (see chapter 8.2).

4.2.1.2 Aisled Frames

Another equally early framing technique was that of the aisled hall or barn, the origins of which have been claimed to date back to pre-historic times (Smith, 1955 p.76). Its development has been clearly explained by Harris and Innocent, as follows. The width of a timber post and beam structure was governed by the length of timbers available for the tie beam (Harris, 2010 p.10, Innocent, 1971 p.82). In order to achieve wider spans, one solution was to divide the structure into a central nave with side aisles (ibid). In doing so the tie beams and roof trusses are supported on internal arcade posts, rather than the

posts of the external wall (ibid). Examples of this construction technique include the previously discussed barns at Cressing Temple and Fyfield Hall, both in Essex, representing the Lowland tradition of these structures. By the end of the mediaeval period aisled halls had become obsolete, at least for domestic structures (Smith, 1955 p.76). The restrictions of the plan created with side aisles and nave may have been suitable for agricultural, storage and ecclesiastical functions, however for the open hall of the manor house structures were invented to remove the obstacle of the internal posts (Harris, 2010 p.10). One such structure was the hammer beam (ibid). By cantilevering out from the outside wall, it was possible to start the arcade posts from above head height, as opposed to from the floor. Perhaps one of the most famous examples of this principle is the great roof to Westminster Hall (Figure 27).

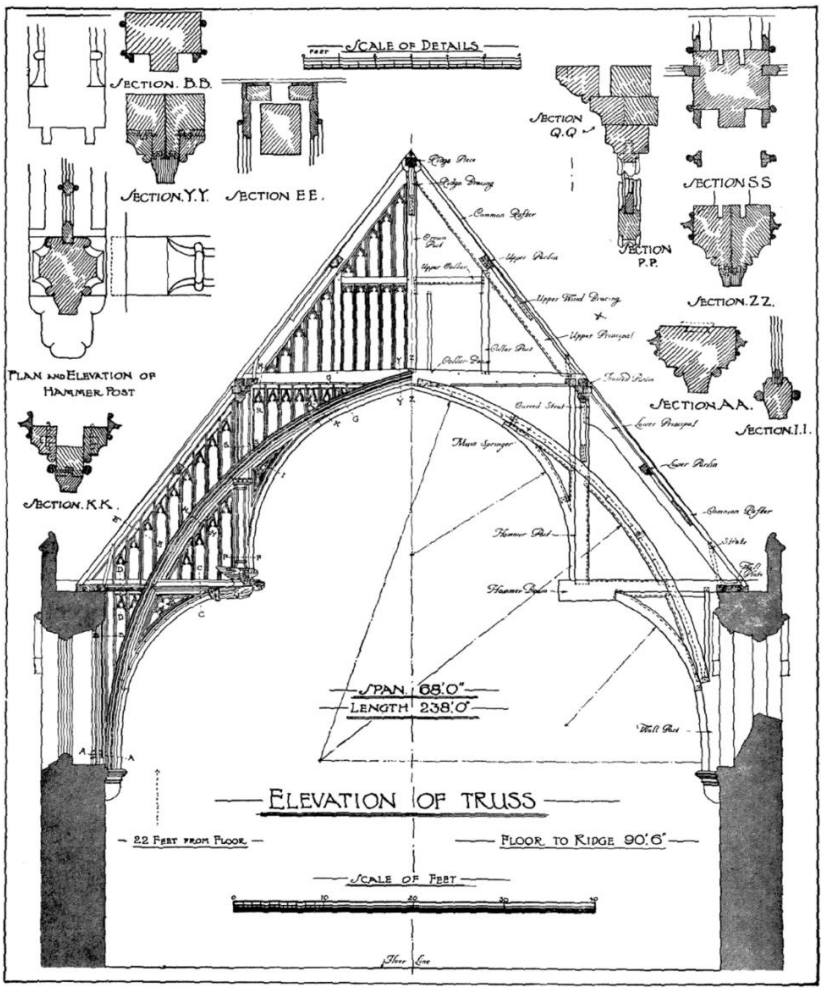

Figure 27. Section through Westminster Hall, London, showing the elevation of the roof truss. Source. ((Cescinsky and Gribble, 1922)

4.2.1.3 Box Framing

Harris defines box framing as "*Timber framing in which post and wall plates carry roof trusses, as opposed to being cruck-built*" (Harris, 2010 p.94). As such, the aisled halls belong to this tradition.

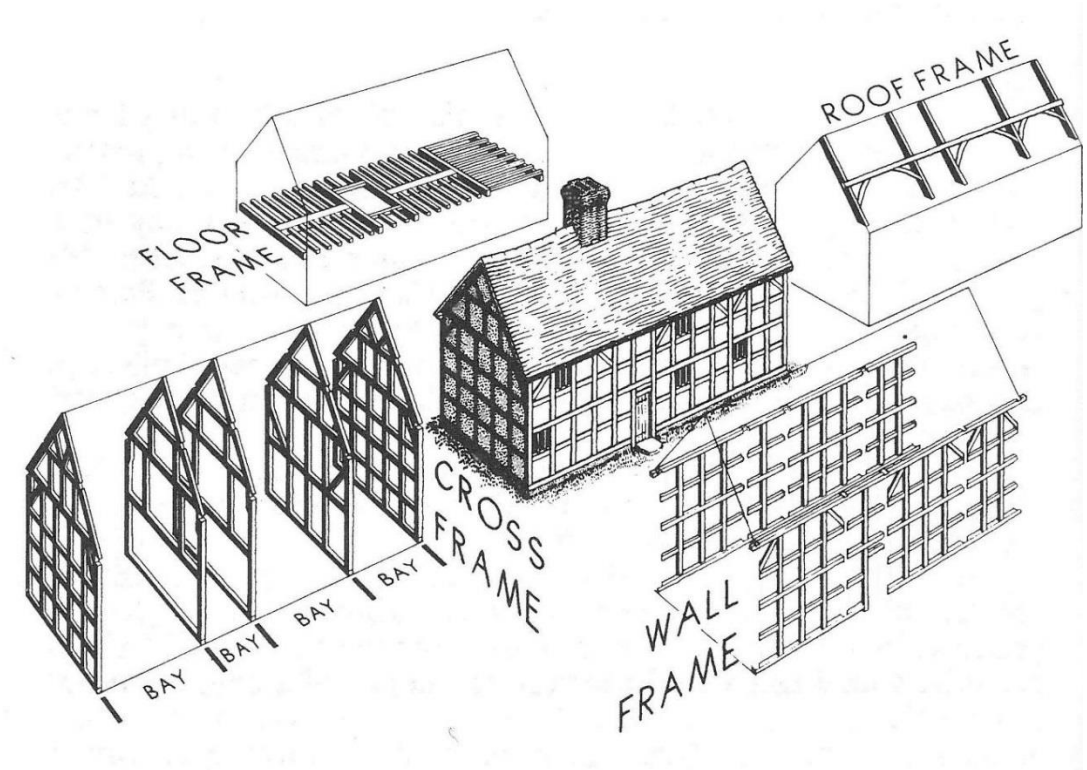

Figure 28 Elements of a box-framed construction showing frames and bays. Source: ((Harris, 2010)

Boxed-framed construction relies on a series of timber frames – wall frames, cross frames, roof frames and floor frames – to form a box (Figure 28) (ibid). As with cruck frames, the cross frames split the building into a series of bays or half-bays. These differ in size across the country but tend to be fairly standard within a particular building type in a particular area of the same period (Brunskill, 1985 p.96). Harris states that bays vary between 5 and 20 feet (1.5 to 6 metres) (Harris, 2010 p.6), with the approximate width of a typical bay being quoted by Braun as 16 feet wide (4.9 metres), a measurement know as a "perch"

(Braun, 1940 p.13)[26]. A perch, Braun surmises, would be sufficient to accommodate a plough team of four oxen (ibid). He also notes that the perch would be a physical pole kept by each village, when it broke a new one would be measured by asking sixteen men, as they entered the parish church on Sunday, to place their right foot one behind the other (ibid)[27]. This may account for the variance, as noted by Brunskill, across the country but not within buildings of the same locality and age.

4.2.2 Wall Framing Styles

So far we have seen that timber-framed buildings in the UK come from two distinct structural concepts, that of cruck framing and box framing. At the same time, overlaying these structural differences but independent from them, there can be found three principle wall framing styles. These are square framing, close-studding and ornamental (Brunskill, 1985 p.154). There follows a brief description of each.

4.2.2.1 Square Framing

Square framing as it name suggests consists of approximately square panels. The sizes of these panels can vary considerably in different buildings and within the same building itself. Common configurations are storeys three panels high (Figure 29), two panels high (Figure 30) (Smith, 1965 p.136) and sometimes even with a single panel spanning the storey height (Figure 31 and Figure 32). Square framing is most common in the Welsh Marches and West Midlands, although there is also a smaller concentration of examples of its use in Kent and Sussex (Smith, 1965 p.136). It would appear that storeys two panels high are more common than those with three (ibid) with the latter having its strongest concentration in Shropshire (Mason, 1974 p.69). A closer study of typical panel sizes is undertaken in chapter 7 of this thesis.

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[26] Although not stated, Braun is in fact quoting ADDY, S. O. 1905. *The Evolution of the English House,* London, Swan Sonnenschein & Co. p67

[27] Again Braun is repeating that stated by Addy, (1905, p68) who in turn cites KOEBEL, J *Geometrei*, Frankfurt 1556

Figure 29. Square framing, three panels high, Bible House, 4 Church Street, Bromyard, Herefordshire. Late 17th Century. Source: (author's own, 2015)

Figure 30 Square framing, two panels high, 1&3 Old Road, Bromyard, Herefordshire. 16th century. Source: (author's own, 2015)

Figure 31. Square framing, one panel high, Little Bursted Farm, Upper Hardres, Kent. Early 16th century. Source: (Canterbury Archaeological Trust Ltd., 2017)

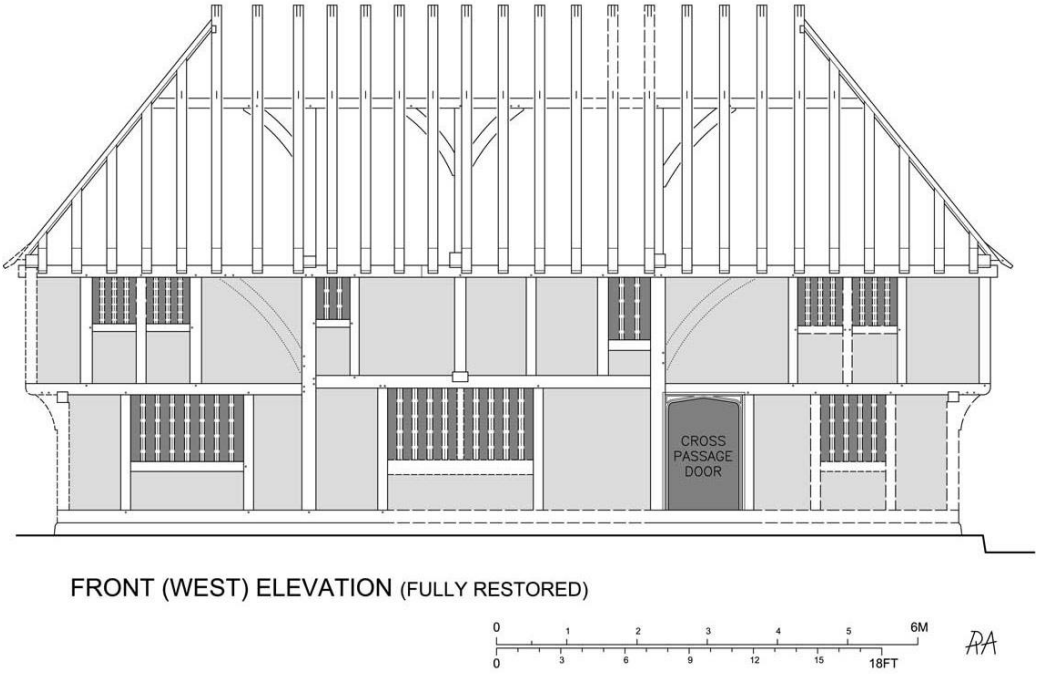

Figure 32. Square framing, one panel high, Little Bursted Farm, Upper Hardres, Kent. Early 16th century. West Elevation. Source: (Canterbury Archaeological Trust Ltd., 2017)

4.2.2.2 Close Studding

The other principle form of wall framing is close studding. Here the vertical studs are placed closer together forming tall rectangular panels either spanning the entire storey or in some cases split by a middle rail (Brunskill, 1985 p.152). The width of stud and panel can often be of a similar dimension (ibid). Harris states that close studding is universal in East Anglia and may have originated there (Harris, 2010 p.23). However, he goes on to note that the technique spread to high status buildings in all the UK by the 15th Century (ibid). This use of close studding for high status buildings would have been a result of the additional timber required for its construction. Mason (Mason, 1974 p.13) estimates that a four-bay, three cell house with open hall would require 720 cubic feet (20.4m^3) of timber if constructed in large quadrilateral panels with curved braces, whereas the same house constructed in close-studding would require 900 cubic feet (25.5m^3), an additional 25%. This illustrates the additional material and cost required for close studding. It has been calculated by Rackham that a house requiring 1,230 cubic feet (34.8m^3) of timber would be the result of 50 years' growth on 5.7 acres of woodland in West Suffolk (Rackham, 1972 p.6), with the timber as a raw material costing between £6 and £10, approximately a tenth of the total cost of the house (ibid, p3).

The introduction of different bracing members to both square-framing and close studding adds an additional layer of complexity, one that varies across the country with strong regional patterns (Smith, 1965 p.145). Variations include the form of the bracing either straight or curved, and its positioning, for example springing from the timber sill to midway up the post, as in Kentish bracing (ibid. p146) or springing from midway up the post to the wall plate, as in arch-bracing (ibid. p148).

4.2.2.3 Ornamental style

The final wall framing style, the ornamental style or decorative framing, is the most elaborate and timber consuming. Here, small square panels are filled with various patterns such as stars, quatrefoils, *fleur de lys*, herringbone and quadrants (Harris, 2010 p.25). At its simplest, this may be a simple pattern such as chevrons as seen at the Market House in Ledbury built 1617-55 (Pevsner, 1963 p.218) (Figure 33).

Figure 33. Simple ornamental framing. The Market House, Ledbury, Herefordshire. 1617-55 Source: (Author's own, 2016)

Or it may be more complex with elaborate panel infills such as that seen at Samlesbury Hall, Preston dating from 1545 (Hartwell and Pevsner, 2009 p.595) (Figure 34) or with a mix of motifs, as used at Churche's Mansion, Nantwich built 1577 (Pevsner and Hubbard, 1971 p.288) (Figure 35).

Figure 34. Ornamental Panelling, Samlesbury Hall, Preston, Lancashire. Source: (www.Samlesburyhall.co.uk)

Figure 35. Complex ornamental framing. Churche's Mansion, Nantwich, Cheshire. 1577 Source: (Summers, 2016)

The main concentration of ornamental or decorative framing can be found in the North West of England in Lancashire and Cheshire, with other examples to be found down into the West Midlands and the Welsh Marches (Smith, 1965 p.137). This distribution has been explained by E.A Ould by "*the natural love of ornament and want of restraint in a less*

civilized people", Cheshire and Lancashire being "*regions which were the last to emerge from the semi-barbarism of the Middle Ages*" (ibid)[28]. However, this derogatory assumption is questioned by Smith as some examples can also be found in Kent and Sussex (ibid) and is more likely to represent the general prejudice of 20th century architectural critics against ornamentation. A similar sentiment is expressed by Maxwell Fry (1934)

> *"…for a long time its material remained unchanged, while the technique of timber construction, growing amazingly clever and complicated, degenerated into tricks, and finally fell away before the onrush of a new civilization which came from Italy into the North*" (Maxwell Fry, 1934).

Before moving on to look at this decline, the following section will present some of the principal materials involved in timber-frame construction.

4.2.3 Materials

4.2.3.1 Timber species

The preferred timber of the timber-framer was oak (Harris, 2010 p.19, Brunskill, 1985 p.27, Mason, 1974 p.12), with over 90% of building timbers estimated to be of this timber (Rackham, 2003 p.46). Writing in 1736, Richard Neve states that oak is "*one of the principal material in building*" (Neve, 1736 p.214), so much so that Neve believed that it required no further description. Other timbers were however used, including elm, ash, chestnut and poplar (Brunskill, 1985 p.27-28, Neve, 1736 p.261-262). Chestnut is noted by Neve to be the most sought after timber after oak (Neve, 1736 p.262), whilst the historian and ecologist of British woodlands O. Rackham notes that elm, ash and aspen were most commonly found in the houses of the relative poor (Rackham, 2003 p.46). The detailed study by Rackham of a medium-sized house built c1500, showed that 18% of the great timbers and 20% of the small timbers could be identified as Elm (Rackham, 1972 p.7). He notes that although largely interchangeable with oak, the use of elm tended to be used in

[28] Smith is quoting from PARKINSON & OULD, 1904 *Old Cottages and Other Half Timber Buildings in Shropshire Herefordshire and Cheshire* London; BT Batsford p3

those parts of the house well protected from the weather (ibid). Writing in the late 16th century the chronicler William Harrison states in his *Description of England* (Harrison, 1968)[29]

> "*In times past men were contented to dwell in houses builded of sallow*[30]*, willow, plum tree, hardbean [hornbeam] and elm, so that the use of oak was in manner dedicated wholly unto churches, religious houses, prince's palaces, noblemen's lodgings, and navigation, but now all these are rejected and nother but oak any whit regarded*" (Harrison, 1968 p.276).

Harrison also reports a saying common in the late 16th Century "*no oak can grow so crooked but it falleth out to some use*," (ibid, 277). The preference for oak was however not new to the 16th century, as can be seen by a court case of 1317 in St Ives, where a carpenter by the name of John of Bythan was sued for using alder and willow in a house that he had been contracted to build of oak (Clifton-Taylor, 1987 p29). Oak was however in great demand for other purposes, namely ship building and charcoal for iron working (Innocent, 1971 p.101) and to a lesser extent salt-making (Crossley, 1951 p.4). As such, the availability of British oak for building construction went into decline (ibid). Even before this scarcity mediaeval carpenters had sourced timbers from abroad due to the restrictions of the length of English oak (Brunskill, 1985 p.28). From as early as the 13th century there are records of fir, known as deal, being imported from the Baltic, however its use did not become commonplace until the late 17th century and it did not replace oak until a century later (ibid).

4.2.3.2 Infill materials

As has been shown there existed a number of different schools and styles of timber-framed buildings across the United Kingdom. However cutting across these styles is the use of a variety of infill materials. These include oak laths and plaster, stone, flint and brick as a later introduction, but perhaps the most widespread was the use of wattle-and-daub

[29] First published 1577
[30] A species of willow

(Brunskill, 1985 p.152, Harris, 2010 p.20-21, Reid, 1989 p.2-4). This technique consists of staves or stakes of riven oak, ash or sometimes beech placed most commonly vertically, although sometimes horizontally, between the timber frame (Reid, 1989 p.2). An auger-bored hole in the underside of the cross rail would take the sharpened top end of the stave, whilst a groove in the lower timber would allow the opposite end of the stave, which would be chisel tapered, to be sprung in place (ibid). Figure 36 shows an early 18th century wattle-and-daub infill panel with the outer layer of daub and plaster removed. One stave remains, whilst the impression of a second in the daub can be seen to the right of the image.

Figure 36. Wattle-and-daub with wattling exposed and in poor condition. Gunn's Mill, Forest of Dean 18th century. Source: (Author's own, 2017)

Around the principal staves were then woven smaller pliable elements, these were most commonly hazel withies or thicker hazel rods (wandys) (ibid), although other materials such as willow (osier), reeds or thin strips of wood were also used (Salzman, 1992 p.188). This is confirmed by Rackham (Rackham, 2003 p.47) who states that hazel and sallow are the commonest, although he has encountered elm, aspen, birch, maple and lime, with the *bast*

(inner bark) fibre being used for string (ibid). The horizontal wattling was sometimes terminated in a vertical groove in the upright post (Reid, 1989 p.2) but could also be held by a final vertical stave, set tight against the timber upright, as was the case for the panel shown in Figure 36.

Balls of daub, known as "cats", would be pressed into the wattle to form a homogenous mass (Reid, 1989 p.2). The daub varied in its constituents with a 1530 source stating that

"*daubing may be with clay onely, with lime plaster, or lome that is tempered with heare or strawe*" (Innocent, 1971 p.142).

Many recipes for modern daub include cow dung as a key ingredient (Reid, 1989 p.8-9, Minke, 2012 p.40), however the deliberate addition of animal dung historically has been questioned (Henry et al., 2015 p.93). It is now thought that that the addition of dung may have been accidental, either as a result of the daub being trodden by oxen or horses to mix it, or through the inclusion of soiled livestock bedding (Pritchett, 2001).

One of the earliest examples of the use of wattle-and-daub can be found at the previously mentioned Iron Age village near Glastonbury (Davey, 1961 p.40, Bulleid, 1894 p.145). Vitruvius also writes of the use of wattle-and-daub in the 1st century BC in his book II, chapter VIII paragraph 20 (Vitruvius, 1960 p.57). However, he is far from complementary,

> "*As for "wattle-and-daub" I could wish that it had never been invented. The more it saves in time and gains in space, the greater and the more general is the disaster that it may cause; for it is made to catch fire, like torches. It seems better, therefore, to spend on walls of burnt brick, and be at expense, than to save with "wattle-and-daub," and be in danger. And, in the stucco covering, too, it makes cracks from the inside by the arrangement of its studs and girts. For these swell with moisture as they are daubed, and then contract as they dry, and, by their shrinking, cause the solid stucco to split. But since some are obliged to use it either to save time or money, or for partitions on an unsupported span, the proper method of construction is as follows. Give it a high foundation so that it may nowhere come in contact with the broken stone-work composing the floor; for if it is sunk in this, it rots in course of time, then settles and sags forward, and so breaks through the surface of the stucco covering*" (ibid).

Despite Vitruvius's misgivings for the material, wattle-and-daub was the most common infilling material in both England and Wales. In Welsh, the name for wattle is *bangorwaith* and the verb to wattle is *bangori* (Wiliam et al., 2011 p.116). The material is commemorated in the several places called Bangor, these being named after the wattle fence that once enclosed them (ibid). Also in Welsh, the word *Adeilad* meaning a building and *adeiladu*, the verb, "to build", come from the root *adail,* which in the Middle Ages specifically referred to wattle walls (ibid).

Wattle-and-daub were not the only infill material used. Examples of the use of masonry can also be found. These include chalk blocks (clunch) (Clifton-Taylor, 1987 p.46), flint (ibid), irregular stone blocks and ashlar (Reid, 1989 p.4), and stone slabs (Harris, 2010 p.21). However, following the latter half of the 16th century brick nogging became a widely used solution (Reid, 1989 p.4). Although many have suggested that brick is an unsuitable material for infilling due to its rigidity, water retention, weight and differential movement between itself and the frame (Reid, 1989 p.4, Ryan, 2011 p.132, Harris, 2010 p.21), many householders must have seen it as an improvement on the maintenance-heavy daub. Brick production in the UK dates back to Roman times, although its production appears to cease with their retreat, with the use of brick in Saxon and Norman buildings generally believed to be salvaged Roman material (Innocent, 1971 p.148). During the 14th century the use of brick began its revival in East Anglia with its arrival as ballast in ships returning from trading wool on the Continent (Braun, 1940 p.33). Later, national production was revived, with one of the earliest records of a British brick maker being William Weysey, who was commissioned to provide bricks for Speen Abbey in 1437 (Innocent, 1971 p.150). The rise of brick as a common building material is intrinsically linked to the demise of the timber frame, with its inflammability being its key property (ibid) as shall be discussed later in section 4.3.

Another infill detail, especially in the east of the country, was the use of lime plaster on split oak laths (Harris, 2010 p.20). The plaster when applied to the closely spaced laths would squeeze through forming protrusions known as “nibs” anchoring the plaster to the substructure (Figure 37).

Figure 37. Lime Plaster on oak lath infill panel with outer face missing showing plaster nibs, Gunn’s Mill, Forest of Dean. Source: (Author’s own, 2017)

With this method, the laths were sometimes placed between the timber-frame uprights in the same way as wattlework, however, commonly in East Anglia (ibid) the laths would be fixed to the face of the frame, with the plaster, pargetting[31] or rough-cast being a continuous coating covering the frame (Salzman, 1992 p.191, Brunskill, 1985 p.110). With pargetting, incised, moulded or pricked patterns could be applied (ibid) including geometric chevrons or fans or even complex sculpted forms built up by hand as shown in Figure 38.

[31] A decorative use of plaster as a cladding (Brunskill, 1985 p.110), applied externally to the timber frame (Harris, 2010 p.95)

Figure 38. Sculpted pargetting on 25-27 Church Street, Saffron Walden, Essex. Source: (Author's own, 2017)

4.2.3.3 Over cladding

4.2.3.3.1 External Cladding

Just as the use of plaster and pargetting evolved to cover the timber frame, other forms of over cladding were also used in various parts of the country. Perhaps the simplest, and one most commonly used on agricultural buildings, was the use of timber planks laid either horizontally or vertically (Brunskill, 1985 p.110). Known as weatherboarding, this technique has been noted to improve the water tightness of the timber frame by covering the gaps between frame and infill panel (Braun, 1940 p.104) and its use is most commonly found in the southern counties of England (Innocent, 1971 p.116-117). In some cases, the weatherboarding completely replaces the need for any infill material, most obviously for barns but also for houses where an interior cladding of lath and plaster complete the wall build-up. This type of construction went on to become one of the most common construction techniques in North America (Braun, 1940 p.103-104) with plastic siding eventually replacing timber. A variant on weatherboarding is the use of wooden shingles,

with typically one third of the shingle being exposed, thus forming an external skin three shingles thick with alternating vertical joints.

In areas where an even greater degree of weather protection was required, timber frames were hung with slates or clay tiles (Brunskill, 1985 p.110). The use of slate-hanging was noted by John Evelyn in 1666 at King Henry VIII's only timber-framed palace, that of Nonsuch in Surrey, shortly before its demolition (Clifton-Taylor, 1987 p.174). However, the technique is more commonly found in the far Southwest of England in South Devon and Cornwall where slate is a local material (ibid). Tile-hanging is conversely found in the South-eastern counties such as Kent, Sussex and Surrey, together with parts of Hampshire and Berkshire, appearing from towards the end of the 17th century (ibid. p265). Both slates and tiles may be square cut or have scalloped or pointed ends, often used in combination to create patterns (Brunskill, 1985 p.110). The use of tiles of different colours may also sometimes be used to decorative effect, which according to Crossley (1951) is "*felicitious* [sic]" unlike weatherboarding, which he considers "*cheap-looking and disagreeable*" (Crossley, 1951 p.120).

One method of tiling that aimed to hide the timber nature of the building completely, was mathematical tiling (Brunskill, 1985 p.110). These tiles were designed to imitate brick and would usually include plaster bedding to complete the deceit (ibid). Their use was a Georgian invention and is concentrated in the South-East of England (Clifton-Taylor, 1987 p.269). Due to their complexity of manufacture and installation, these tiles were not initially introduced to be a cheap alternative to bricks; however, the introduction of the Brick Tax in 1784 altered the economic balance, as mathematical tiles were exempt (ibid). Clifton-Taylor notes that the majority of examples of mathematical tiles date from 1784 until the repeal of the tax in 1850 (ibid).

4.2.3.3.2 Internal Cladding

On the inside of timber-framed buildings, the timbers are often plastered over but may also be exposed. Historically higher status buildings would also have possibly had timber panelling, a custom known as "sealing" (Salzman, 1992 p.258) or lined with tapestries (ibid. p259). By doing so, the problems of drafts through ill-fitting infill could be avoided. Harrison writing in 1587 confirms this by saying,

> "*The walls of our houses on the inner sides in like sort be either hanged with tapestry, arras*[32] *work, or painted cloths…, or else they are ceiled [panelled] with oak… whereby the rooms are not a little commented, made warm, and much more close than otherwise they would be.*" (Harrison, 1968 p.197).

As such, it would appear that the use of internal insulation is not a new phenomenon.

4.2.3.4 Limewash

In addition to the actual panel infill, many timber-framed buildings would have been finished with a thin layer of limewash[33] (Harris, 2010 p.23). On most everyday buildings it is questionable that this would have been carefully applied within the timbers and it is probable that many were completely whitewashed, timbers and all (ibid). This continual coating had the additional benefit of sealing the difficult joint between infill and frame, and with regular applications would repair any minor cracks that occurred over time (ibid). H.P. Wyndham noted that on his visit to Glamorgan in 1774 "*scarcely a cottage to be seen, which is not regularly brushed over every week*" (Wyndham and Lyttelton, 1781 p.151). This seemingly over-frequent application by the fastidious people of Glamorgan is collaborated by John Evan who noted on his visit in 1798 that "*they frequently renew it every Saturday*."(Evans, 1804 p.185). Whether lime washing was a weekly event is questionable, although a touching up may have occurred, however, elsewhere the application of lime-wash was a more common practice once a year in spring before Easter (Wiliam et al., 2011

[32] Wall hangings
[33] A mixture of lime and water used for coating walls (ibid)

p.141). The timing of this application of a fresh coat of lime, preceding Sunday or Easter, has been linked to warding off evil spirits and witches, with superstition holding that: "*White-liming… keeps the witches and their master away*"(Rees, 1936 p.127), however it could equally be a matter of putting on the house's "Sunday best" and making repairs following the passing of the winter storms, or weekly downpours of Glamorganshire. Either way, the regular application of limewash would have both reduced infiltrations and extended the lifespan of the timber-frame and infill, whilst maintaining its vapour permeability.

4.3 Decline and prohibition

Timber framing reached its peak in the 17th century, yet by the early 19th century its common use had almost vanished (Harris, 2010 p.3). Even by the late 17th century, J. Moxon in his "Mechanick Exercises of the Doctrine of Handy-Works" (Moxon, 1695)[34] is offering equal weight to advice on house-carpentry and bricklaying, and by 1788 J. Wood was advising on the use of stone and brick even for labourers cottages (Wood, 1788 p.3). Whilst it has been argued that the decline in the use of timber was down to a dwindling supply of raw materials and the competition from shipbuilders and ironworkers, this is debatable (Harris, 2010 p.83). Examples of utilitarian structures with high quality timbers can be found from both the 18th and 19th centuries (ibid), and as we have seen there was the possibility of using imported timber from the Baltic (Crossley, 1951 p.4). At the same time Rackham (2003) argues that the destruction of forests by industry and shipbuilding is also a myth (Rackham, 2003 p.48-49). It would therefore appear that the principal reason for the demise of timber framing was fire.

The Fitz-Ailwyn's *Assize of Building of Allaying Contentions as to the Assizes of Buildings*, written in 1189, states of London

[34] First published 1678

"*that in ancient times the greater part of the city was built of wood and the houses were covered with straw or stubble and the like*." (City of London et al., 1859 p.xxix).

However, following the first great fire, which occurred in the first year of the reign of King Stephen, (1136), many of the wealthier citizens rebuilt their houses with free-stone partition walls, a practice that the Assize was to make law (Knowles and Pitt, 1972 p.7). Despite this, houses continued to be built from timber and there appears no attempt to replace those already standing (ibid). A lack of any authority to enforce the law, and the sheer scale of the number of timber houses, made the wholesale rebuilding of London economically unviable.

By the early 17th century, London was still a predominantly timber-framed city. James I, comparing himself to the Emperor Augustus in his proclamation 152 of 1615, decreed

> "*that as it was said by the first Emperour of Rome, that he had found the City of Rome of Bricke, and left it of Marble, So that Wee whom GOD hath honoured to be the first king of Great Britaine, might bee able to say in some proportion, That Wee had found Our Citie and Suburbs of London of stickes, and left of Bricke, being a Materiall farre more durable, safe from fire, beautifull and magnificent*" (James I King of England 1566-1625., 1973 p.364).

The use of timber in the capital was a pressing concern for the King. During his reign he issued no less than 6 royal proclamations restricting its use (James I King of England 1566-1625., 1973). His concerns revolved around both the risk of fire and the preservation of timber as a national resource. The first proclamation, no. 51 of 1605, states that due to an over use and resulting shortage of timber

> "*no person shall build or erect a new house… except all the utter [outer] walls and windowes thereof and the forefront of the same be wholly made of Bricke, or Bricke and stone…*" (ibid. p112).

The second, 78 of 1607, calls for the use of stone and brick for new constructions, being a material

> "*lesse subject to the danger of fire, and cause lesse waste of Timber (fitter to be reserved for the shipping of his Realme)*" (ibid. p172),

a call reiterated in proclamation 120 of August 1611 which adds that timber

"*is much wasted and growne very skant within the Realme*" (ibid. p267).

Proclamation 121 of September 1611, just one month later, repeats an identical call (ibid. p269-271) as does that of 1620, proclamation 204 (ibid. 485-488). This latter proclamation refers back to the previously mentioned Assize of Building, lamenting the lack of its observation (ibid. p485).

James I's proclamations appear to have had little impact on London, nor did the following years of Civil War and the Commonwealth. On 16th August 1661, an edict by Charles II was issued noting the frequent fires caused by timber buildings (Knowles and Pitt, 1972 p.26). This law reiterated the call that all new buildings must be of brick or brick and stone (ibid). It is interesting to note that the proclamation states that the building in brick or stone was found to be little more, if not less than building in timber. Whether this is true, or if it was propaganda to promote the use of less combustible materials we cannot tell. Even if new building were being built at this time in accordance with these proclamations, nothing was done about those already standing. This was to prove disastrous when on the 2nd September 1666 a bakers shop in Pudding Lane caught fire (Reddaway, 1940 p.22). The Great fire of London burned for four days destroying nearly four-fifths of the city including St Pauls Cathedral, eighty-seven Parish churches, the Guildhall, the Royal Exchange, The customs House, forty-four halls of the City companies, four prisons, four gates, numerous commercial buildings and thirteen thousand two hundred houses (ibid, p26). Thirteen thousand people were made homeless and the financial loss was estimated at ten million pounds (Knowles and Pitt, 1972 p.28). By the 13th September, a Proclamation was issued by the King covering the reconstruction (ibid, p29). Among other aspects, this proclamation

included that the exterior of all new buildings were to be of brick or stone, save for doors and window frames. This proclamation formed the basis of an Act for rebuilding the city, for which Royal Assent was given on 8th February 1667 (ibid). With much of the old timber-framed city destroyed and the prohibition of new timber-framed buildings, London passed from being the city of sticks, to the city of bricks, just as King James I had intended.

The risk of fire was not confined to the capital. Norwich lost 718 buildings in its fire of 1507, Tiverton 400 in 1598 and Oxford around 300 in 1644 (Borsay, 1989 p.15). Two of the worst provincial fires of the late 17th century were in Northampton in 1675 and in Warwick in 1694 (ibid. p18). The rebuilding of the latter was to take place in classical style abandoning the traditional vernacular architecture (ibid. pVii) and abandoning timber-frames.

The story was repeated in Scotland. Although today little timber framing survives, there is archaeological evidence of wattle and timber buildings (Lynch et al., 1988 p.49) and box-framing (ibid. p73) within the historic centres of Scottish burghs. In the 16th century, stone houses with timber frontages formed a transition from timber to stone (ibid. p74). According to Glendinning,

> "*most Edinburgh High Street houses, although structurally of stone, were faced with wooden galleries and front annexes*" (Glendinning et al., 1996 p.26).

The use of timber on a stone structure had been permitted in Edinburgh following an act of 1508 (ibid). The presence of timber is corroborated by Petzsch who states that

> "*from the 16th century more buildings in the [Scottish] burghs were built in stone but most seem to have incorporated timber for overhanging galleries and extensions, supported on wooden brackets*" (Petzsch, 1971 p.68).

A surviving example is that of Huntly House on the Cannongate in Edinburgh completed in its current form in 1570 (ibid). As noted, timber had been used more widely in many Scottish towns, however legislation introduced by the Deans of Guild of each burgh, from the 12th century onwards, lead to its steady prohibition (Davies et al., 2002 p.20). The first

of these was the requirement for an eavesdrop[35], next was the need for a stone fire-safe for valuables, then the use of a stone core, then the stone infilling of the eavesdrop, followed by the construction of a stone rear wall (ibid). By the late 17th century the construction of all timber façade elements was finally forbidden by council bylaws first in Edinburgh (1674) and three years later in Glasgow (1677) following fires in both cities (Glendinning et al., 1996 p.64). These laws required stone to be compulsory for all new buildings and frontages. The changes wrought by this legislation was noted by Sibbald the Geographer Royal for Scotland. Writing of Edinburgh in 1693 he states

> "*The High Street from the Castle to the Abbey is adorned with stately Buildings, which are of late made of hewen Stone, since that by an Act of the Town-Council it hath been prohibited (for the frequent burnings which happened) to build any more Timber-Houses either in the City or Suburbs*" (Sibbald, 1693 p.1).

The predominance of timber framing had passed, at least for urban construction. Its use in the countryside and villages would continue for another 150 years but even there the increasing use of brick nogging lead to framing timbers reducing in their dimensions and panel sizes increasing. Timber would eventually cease to be a common structural construction system, although its style would continue.

4.4 Conclusion

This chapter has reviewed sources asserting that timber framing has its roots in the very beginnings of construction. It developed in Britain simultaneously through cruck trusses and box framing to become a common construction technique, reaching its peak in the 17th century. The various permutations of framing styles, infill materials and cladding methods have given us a rich and varied vernacular architecture. Yet few true timber framed

[35] An eavesdrop was a space between each building, not wide enough for a passageway but a space for the rain from the eaves to drop. DAVIES, I., WALKER, B. & PENDLBURY, J. 2002. *Timber Cladding in Scotland,* Edinburgh, UK, ARCA Publications Ltd.

buildings have been built since 1850, a fact that only adds to their rarity value and the consequent case for them to be conserved. The following chapters will aim to study their significance, before moving on to quantify the number and location of those that still survive and then look at how this long tradition can continue to be a functional part of 21st Century Britain, as it has been for over 900 years.

5 SIGNIFICANCE

5.0 Introduction

The previous chapter has reviewed the historical, aesthetic and technical values of timber-framed construction. However, in order to understand the cultural significance of historic buildings there are other factors that must be considered. The Burra Charter (ICOMOS, 2013) was possibly one of the first times that the concept of cultural significance was clearly articulated, especially when related to the management of the historic environment (Worthing and Bond, 2008). The charter defines cultural significance as the "aesthetic, historic, scientific, social or spiritual value for past, present or future generations" (ibid, p.2). These values have now been adopted by most heritage bodies both internationally and in the UK (Historic England, 2008 p.27, Cadw, 2011 p.16, Historic Environment Scotland, 2016b p.48). In England and Wales these values are expressed as Evidential Value - the fabric of the asset itself; Historic Value - events, people or lifestyles represented or associated to the asset; Aesthetic Value - the sensory or intellectual pleasure that the asset evokes; and Communal Value- the meaning the asset has for those who relate to it (Historic England, 2008b p.27, Cadw, 2011 p.16). Whereas in Scotland the terms used are Intrinsic, Contextual and Associative values (historic Environment Scotland, 2016b, p.48). This chapter aims to explore the communal or associative values of historic timber-framed buildings in the UK.

Accounting for 6.4% of England's pre-1850 dwellings and only 0.2% of its domestic building stock (Nicol et al., 2014), it could be assumed that these buildings are an insignificant element of our built heritage. However, it has been asserted that there is something quintessentially English about these buildings (Ballantyne and Law, 2011b p.125), something that elevates their place in our national conscience. But just what is it? Even after timber framing ceased to be a common structural solution, its aesthetics continued to be replicated, from the eighteenth century *cottage orné*, to the Victorian Olde English

Style, the inter-war *Metroland*. The enduring influence of timber-framed buildings can be seen to this day, be it implicit, as seen in the applied timber screens of the 2016 RIBA House of the Year award winner (Figure 39), or explicitly reproduced on mass housing (Figure 40). This chapter will first trace the roots of this reproduction and then seek to discover the reasons why its popularity endured. By doing so, the cultural significance of the original timber-framed buildings will be affirmed and the argument for ensuring their continuing survival strengthened.

Figure 39. RIBA House of the Year 2016 by Richard Murphy. Source: ***(Richard Murphy Architects, 2017)***

Figure 40. Heritage Drive, Cardiff c1990. Source: ***(Google, 2016)***

5.1 The Endurance of a Style.

5.1.1 Eighteenth Century Cottage Orné

Following the French revolution in the 1790s and the ensuing wars, an increasing number of architectural pattern books began to appear in England (Ballantyne and Law, 2011a p.138). Between 1790 and 1835 more than 60 such books were published, containing the designs for small to moderately large houses (McMordie, 1975 p.43). As taxes were raised to pay for the wars, architectural commissions diminished and architects turned to publishing (McMordie, 1975 p.47). At the same time, the Board of Agriculture was encouraging landowners to improve[36] the construction of cottages for their tenants (Board of Agriculture, 1796p.LXIII). At the same time the rise in cottage building on country estates was also fuelled by a concern for the conditions of the rural poor, coupled with a fear of revolution crossing the channel from France (Ballantyne and Law, 2011a p.90). If new cottages were not provided then the events of 1789 might be repeated in England. This perceived need for new cottages was taken up by the pattern book designers, with many of them focusing specifically on the design of rural dwellings.

One such designer was the Irish engraver and watercolourist James Malton, who in 1798, published his book "An Essay on British Cottage Architecture: being an attempt to perpetuate, that peculiar mode of Building, which was originally the effect of chance" (Malton, 1798). Drawing on vernacular architecture he presents fourteen of his own designs for dwellings that "*may agree and correspond with the surrounding scenery*" (Malton, 1798 p.2). The designs range from peasant huts (designs 1-5), through residences for tradesmen, small farmers and retired gentlemen of small fortune (6-11), to habitations (12-14) "*worthy of a gentleman of fortune"* (Malton, 1798 p.3). Figure 41 and Figure 42 show his designs number 8 and 10 respectively.

[36] The initial impulse for the improvement of cottage construction was "*more especially to ascertain the means by which the consumption of fuel could be diminished*" (BOARD OF AGRICULTURE 1796)

Figure 41 Malton's Design no.8, Plate 10, which he suggests could be for a retired gentleman Source:(Malton, 1798)

Figure 42 Malton's Design no.10, plate13 "is manifest to every eye, the decided residence of the substantial farmer." Source:(Malton, 1798)

As stated by his title, Malton wished to "*perpetuate*" an architecture that he saw as a natural part of the English countryside, something that had come about "*by chance*" and which he feels is under threat by buildings that are either too *"…fanciful, and sometimes whimsical…*" or *"…neat and convenient…*" (Malton, 1798 p.3). He urges the need for the protection of the cottage style, fearing its loss, with its existence only recorded in paintings (Malton, 1798 p.11). For Malton the key elements of a true cottage are

"*A porch at entrance; irregular breaks in the direction of the walls; one part higher than the other; various roofing of different materials, thatch particularly, boldly projecting; fronts partly built of walls of brick, partly weather boarded, and partly brick-nogging dashed; [and] casement window lights…*" (Malton, 1798 p.5).

This idea of an architecture that has been added to and evolved over time is however not wholly apparent in his designs. Some designs, such as Figure 41 and Figure 42 appear to pre-empt the speculative builders of suburbia rather than true vernacular architecture, with minimal rustic motifs hinting at their rural ancestry, most notably the use of exposed timber framing. Nevertheless, through these designs Malton believed he could promote the continuation of an architecture that he saw as

"*the most pleasing, the most suitable ornaments of art that can be introduced to embellish rural nature*" (Malton, 1798 p.1).

Not all were to agree with Malton with regard the value of vernacular architecture, nor the need for assisting its perpetuation. In his "Essay on Rural Architecture: illustrated with original and œconomical [sic] designs,"(Elsam, 1803) the English Architect and writer, Richard Elsam, writing five years after the publication of Malton's designs, attempts to counteract his arguments. He argues that it is simplicity rather than difference that most befits a cottage, stating that uniformity is the key aspect to be achieved (Elsam, 1803 p.3).

This "uniformity" is clearly that of the Georgian simplified classical language. Referring to Malton's designs, Elsam is of the opinion that

"*he hath suffered his better taste to be overcome by a too zealous partiality for the rusticity of architecture*" (Elsam, 1803 p.4).

He dismisses the vernacular architecture, such as those to be found in "*Kent, Hampshire, Surry [sic] and the southern parts of Wales*" to be buildings, not architecture, and suitable for peasants and farmers, believing that this building tradition will continue unaided and as such will not disappear. He is adamant that they should not form a model for architects, as to do so is "*disagreeable*"(Elsam, 1803 p.5) and instead provides a set of designs, simple in plan, based on classical or gothic precedents (Elsam, 1803 p.6). No half-timbered designs are included.

Almost at the culmination of the trend for pattern books came the best-selling "Encyclopaedia of Cottage, Farm, and Villa Architecture and Furniture" (Loudon, 1834a), first published 1833, with a collection of over 80 designs collated and reviewed by John Claudius Loudon. The encyclopaedia set out to

"*…improve the dwellings of the great mass of society, in the temperate regions of both hemispheres…*"(ibid, p.1)

The encyclopaedia however included very few half-timbered designs, principally designs X, XII, XXIII, XXIV and LIV, with a few other timber-framed agricultural barns. Loudon states that his collection of designs, by others, were aimed at the lower and middle classes of countries with a privileged aristocracy, however in self-governed democracies such as North America or new colonies such as Australia, they would suit the whole rural population (ibid, p.8). As such the construction of these dwellings were to be as economical as possible, constructed in the cheapest materials available locally (ibid, p.87). Loudon elaborates on this, stating,

"*In almost every part of the world the cheapest article of which the walls can be made, will be found to be the earth on which the cottage stands*" (ibid, p.74).

Even when designs are depicted with half-timbering other options are suggested, and as in the case of Design X (Figure 43), the brick-nogged option is discouraged.

"*The cottage is in what is called the old English manner… the introduction into these outer walls of brick nogging, is an inferior mode of construction, undeserving of imitation*" (ibid, p.52).

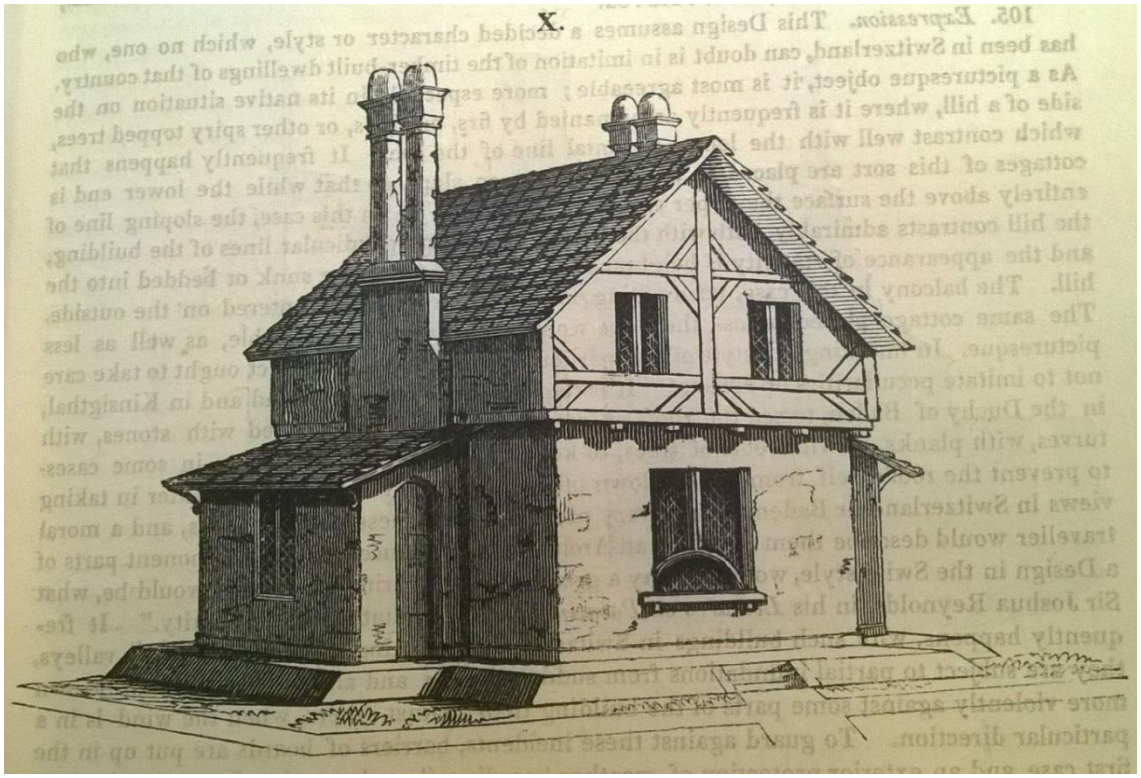

Figure 43 Loudon's Design X, A dwelling for a married couple and one child, with a pigsty. Source:(Loudon, 1834a p.51)

Only in two designs for farms by French designers, specifically for use in France, does Loudon support the use of timber as the main construction material, and yet even here it is clear that he does not think that this will sit well with his British reader. In the description of Design XXIV (Figure 44) he states,

"*A superficial observer, deeply imbued with the prejudices common in Britain, and especially in Scotland and other stone countries, against wooden buildings… … will be apt to despise the simplicity and homeliness of the farm house; but to us, who have entered into all the details of the Design, it appears perfect of its kind*" (ibid, p.504).

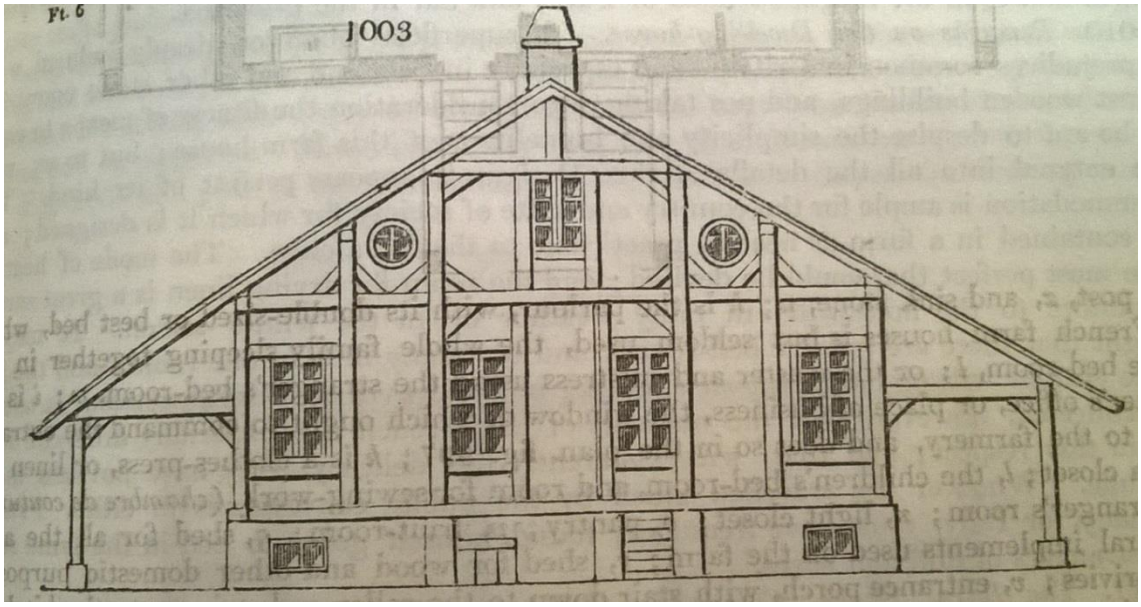

Figure 44 Design XXIV, A Farm House and Farmery suitable for a farm of from three-hundred to five-hundred acres in France. Source:(Loudon, 1834a p.499).

Although, as can be seen from the opinions of Elsam and Loudon, timber framing was not yet seen as a common or desirable style to reproduce, timber-framed designs could still be found in other pattern books, such as that by Samuel H. Brooks. In his "Designs for cottage and Villa Architecture" (Brooks, 1839) presents a couple of half-timbered buildings, including Plate LV (Figure 45) showing a building in "*the old English style of architecture*" (Brooks, 1839 p.74). Brooks describes the proposed construction method as a timber frame with lath and plaster infill panels but suggests the filling of the void between the outer and inner laths to "*be filled with saw-dust or sifted coal ashes, to absorb any moisture that might pass from one surface to the other*" (Brooks, 1839 p.74).

Even with such innovations, these examples are in fact true timber-framed construction. The frame remains the principle, loadbearing structure, with a secondary material completing the infill. Yet, they have begun to move away from the vernacular. These are no longer the result of traditional craftsmen's knowledge but are buildings consciously designed by an architect. Timber framing has already begun its transition from construction technique to stylistic feature.

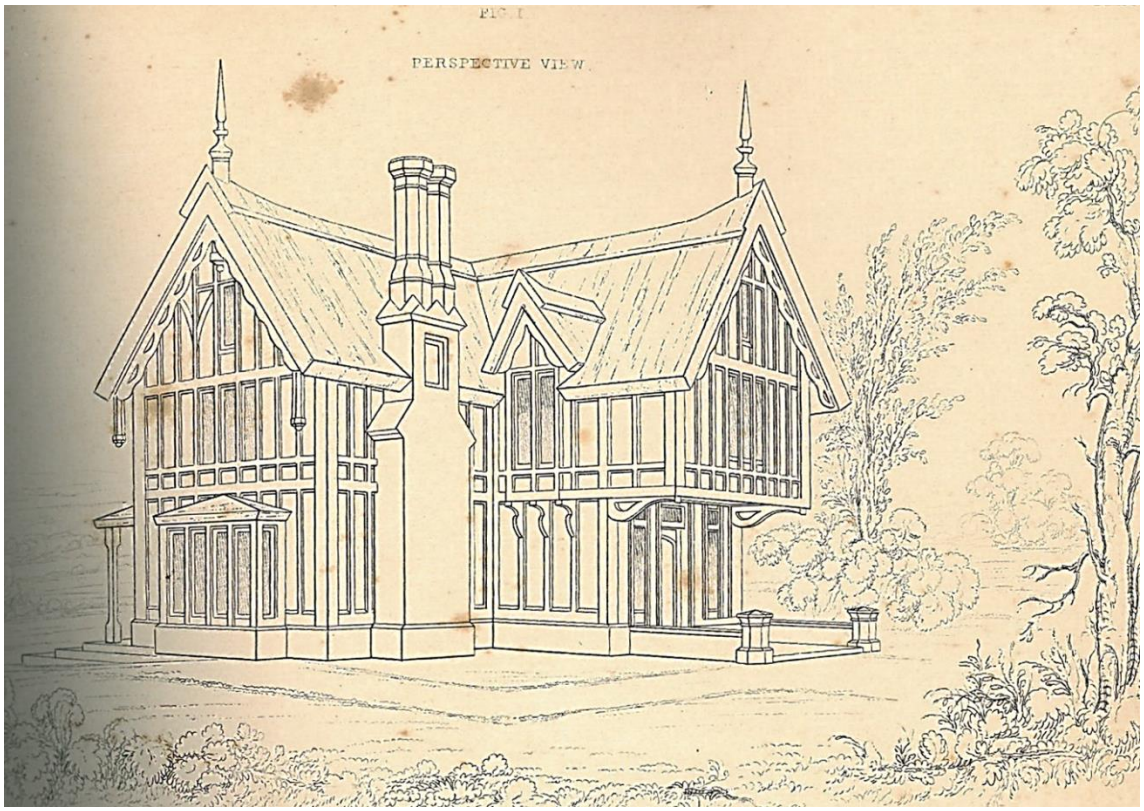

Figure 45 Old English Style cottage by Samuel H. Brooks, 1839. Source: (Brooks 1839, p.74)

5.1.2 The Victorian Olde English Style.

In his book, "The Victorian Country House" (Girouard, 1979 p.71) Girouard attributes the first true use of the term "Olde English Style" to Richard Norman Shaw and William Eden Nesfield. This occurs in their descriptions of their own contributions published in Eastlake's 1872 "History of the Gothic Revival in England" (Eastlake and Crook, 1970), including Shaw's design for his cousin James W. Temple, Leyswood in Sussex (Figure 46). Girouard notes that they were not the first to use the term, as we have previously seen with the work of Brook, nevertheless he argues that they were the first to us it to describe the architecture known by this name today. Previously the term had been applied to describe both Tudor-Gothic and Elizabethan styles, such as those found in Goodwin's "Domestic Architecture" (Loudon, 1834b p.133).

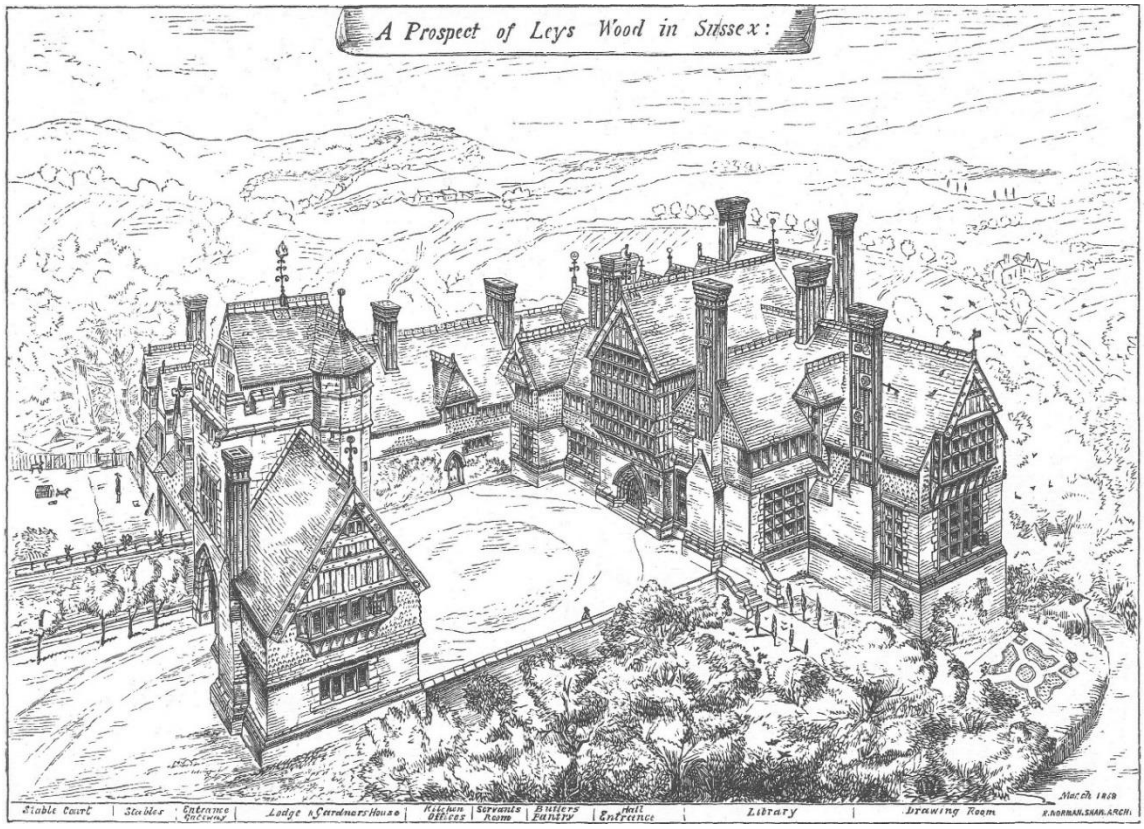

Figure 46 Leyswood, Sussex by R. Norman Shaw 1868-9 Source: (Eastlake and Crook, 1970)

One of the great influences on both Shaw and Nesfield was the architect George Devey, 1820-1886 (Allibone, 1991 p.29, 44 & 81). Son of a solicitor, Devey undertook a nine-year apprenticeship under the architect Thomas Little. Following this in 1846, he undertook his own grand tour, visiting Belgium, Germany, Italy and Greece. Upon his return, he worked part-time restoring churches and designing cottages. Amendments to the cottage of his father's client Revd Mr Boissier, then curate of Penhurst, Kent, led to his introduction and later patronage by Lord De L'Isle and Dudley of Penhurst Place and Lieut. General Sir Henry Hardinge of South Park (Allibone, 1991 p.23). The restoration and extension of the cottages, Leicester Square (Figure 47 and Figure 48), at the entrance to Penhurst Place, were the first example of his style based on the vernacular buildings of the Weald (Allibone, 1991 p.23).

Figure 47 Sketch for restoration and additions to a cottage on the east side of Leicester Square, Penhurst, Kent by George Devey late 1840s Source: (Devey, 1848-51)

Figure 48 Cottage on the east side of Leicester Square, Penhurst, Kent by George Devey 2011 source: (Google, 2016)

Devey went on to design other buildings for Lord De L'Isle in Penhurst, including a group of three cottages on Rogue Hill (Figure 49) which are designed as a *Wealden House*, complete with recessed central section and a flying bressummer.

Figure 49 Cottages on Rogue Hill, Penhurst, Kent by George Devey 1850s. Source: (Allibone, 1991 p.34)

The Old English style continued to be popular throughout the late Victorian period and on into the Edwardian, being used for both domestic, public and commercial buildings across England and beyond. It was perhaps however in its use by speculative builders for the suburban developments of Britain's cities that it would become best known.

5.1.3 Metroland and the Interwar Semi

Many of Britain's cities expanded substantially during the Victorian period, yet for most, and for London in particular, it was during the period following Queen Victoria's death in 1876 that they would see the most dramatic increase in their physical size (Jackson, 1973 p.21). Aided by the introduction of motorised transport and the growing railway network,

suburbia as we know it today began to emerge (Jackson, 1973 p.25). From the beginning of the 20th century until the outbreak of World War I, London's suburbs steadily expanded outwards (Jackson, 1973 p.35). Many of these new homes continued in the footsteps of the Victorian Old English Style, with applied half-timbering to their upper stories and gable ends (Figure 50, Figure 51 & Figure 52).

Figure 50. Newly completed houses c1909, Dalmeny Road, Carshalton. Source: (Jackson, 1973 p.96)

Figure 51. Dalmeny Road, Carshalton, South London 2015. Source:(Google, 2016)

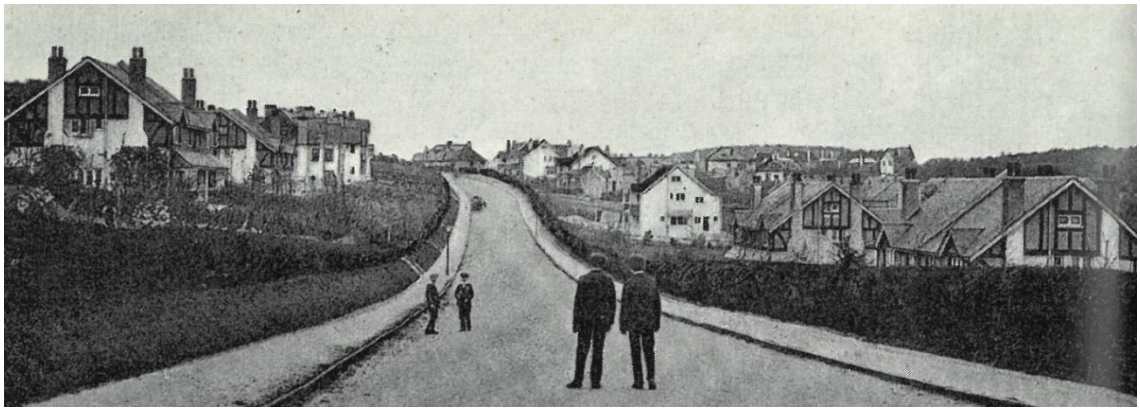

Figure 52. Furze Lane, Purley, South London. Source:(Jackson, 1973 p.97)

Directly following the war, the government drive for houses "Homes for Heroes" tended towards a plainer style with little applied timberwork, yet was still clearly inspired by vernacular architecture (Swenarton, 1981). Concurrently the private speculative housing went on reflecting the desire for "*'Tudor', 'Elizabethan' or simply 'Olde World*' (Jackson, 1973 p.138). This desire continued with force as the construction boom really kicked in, with 287,500 houses built between 1934 and 1935 alone (Jackson, 1973 p.100). The cover of the promotional guide produced by the Metropolitan Railway (Figure 53) and entrants to the Daily Mail's Ideal Home design competitions (Figure 54) show a promise of spaciousness and solitude rarely found in reality (Figure 55).

Figure 53 Guide to Metro-Land. Sources: (Wikipedia, 2012, Amersham Museum., 2016, Pinterest)

Figure 54. "The Maple House" from Daily Mail's Architectural Competition1927 Source: (Daily Mail, 1927)

Figure 55. Windsor Road, Harrow built c1935 and Tudor Drive, Sutton, London built c1938. Source: (Google, 2016)

Although deemed by the commercial builders to be what the public desired, the appreciation of this style of housing was not shared by all. John Gloag in his book "Design for Modern Life," begins with a chapter entitled "Who Knows What does the public wants" in which he questions

"*Why are you, or perhaps your neighbours, living in an imitation Tudor house with stained wooden slats shoved on to the front of it to make it look like what is called a half-timbered house? Those slats have nothing to do with the construction of the house …Why do we live in this sort of half-baked pageant, always hiding in the clothes of another age?*" (Gloag, 1934 p.19-20).

His views are echoed by Anthony Bertram in his book "Design in Daily Life when discussing the newly constructed Liberty's *"Farm-house style"* department store *shop* off Regent Street (Bertram, 1937 p.80), of which his objection is

"*that it is obviously not built in the manner it professes. Its structural character looms through the elaborately imposed stylization like a policeman disguised as a night-club prostitute*" (Bertram, 1937 p.80).

It would therefore appear that the basis of both Bertram and Gloag's criticism would be the lack of honesty, a disjunction between the construction technique employed and that expressed.

Some earlier designs did incorporate true timber framing, such as the The "Interloc" house published in the Daily Mail Bungalow book (Daily Mail, 1922) with the option for brick cavity walling or *"old English half-timber construction… …Skeleton framing""* (Daily Mail, 1922 p.64). However, the majority of houses were brick built, the framing purely applied decoration. Gloag and Bertram were not alone in their derision of the style, both at the time and since. In his book "Pillar to Post: English Architecture without Tears" (Lancaster, 1956) the English cartoonist Osbert Lancanster satirises the style's development with his "Wimbledon Transitional" (ibid, p.60), "Stockbroker's Tudor" (ibid, p.62) and "By-Pass Variegated" (ibid, p.68). Writing in 1946, J.M. Richards noted

"*We know the epithets used to revile the modern suburb – 'Jerrybethan', and the rest – and the scornful finger that gets pointed at spec-builder's Tudor with its half-inch boards nailed flat to the wall in imitation of oak timbering*" (Richards, 1973 p.16).

"*Very often even those people who live in a mock-Tudor home feel the need to apologise for it*" (Simpson, 1977 p.29).

Yet the style has also had its supporters. The last two quotes are actually both from works published to state the case in favour of timber-frame inspired architecture. Simpson's article in the Architectural Review is titled "Beautiful Tudor," whilst Richards in his book "The Castles on the Ground" (Richards, 1973) argues

"*perhaps we should not criticize so fiercely the architectural idiom the suburb has adopted… …The suburban style – that style which is, we are told, the very citadel of debased and vulgar taste – is, in fact, part of the background of the England we have all grown up in*" (ibid, p.16-17).

5.1.4 Contemporary developments

Whilst the debate on the tastefulness of "mock-Tudor" may appear today to have been won by those against it, it has remained an ever-present stalwart of mass-produced housing in the UK. Examples can be found throughout the 20th century and across the country, including areas where few original historic timber-framed buildings survive (Figure 40, Cardiff and Figure 56, Doncaster).

Figure 56 Mell Homes's Residential Development, Doncaster, Yorkshire, 2016. Source:(Mell homes., 2016)

It can be found as the merest hint, reduced to a few symbolic stripes (Figure 57) or in a minority of cases can even include the use of a true green-oak frame (Figure 58). Exposed timber framing may have ceased to be a common construction technique, yet its place in our collective consciousness remains. The question that poses itself is therefore, why? In the next section a number of arguments will be examined, that potentially together can begin to provide an answer.

Figure 57 Barratt's top-of-the-range Premier Collection house, 1995 Source(Barrett Homes., 2016)

Figure 58 New house for sale in Beaconsfield, Buckinghamshire, 2012. Source:(The Telegraph., 2012)

5.2 Age Old Roots, the Rural Idyll and the Handmade

5.2.1 Looking to the Past and Nationalism

5.2.1.1 The Tudoresque

In their book "Tudoresque: In Pursuit of the Ideal Home" (Ballantyne and Law, 2011a) and their chapter "Tudoresque: and the Self-Reliant Englishman" (Ballantyne and Law, 2011b), Ballantyne and Law set out a clear argument for our fascination with the timber-frame resulting from its links to the past, and more specifically a Tudor past. An argument also espoused by other supporters of the style such as Gavin Stamp (Stamp, 2006) and Duncan Simpson (Simpson, 1977). This "Tudor" period, from the crowning of Henry VII in 1485, until the death of Elizabeth I in 1603, is revered as a golden age of England (Ballantyne and Law, 2011a p.16). Its monarchs are seen as the most English of monarchs, rather than the French who preceded them or the Scots, then Germans, who followed, despite the fact that Henry VII's grandfather, Owain ap Maredud ap Tudur, was Welsh and his claim to throne was through his grandmother, Catherine of France (Ballantyne and Law, 2011a p.30). Nevertheless, this perception of their Englishness, coupled with Henry VIII's break from Rome and the Catholic Church, and the links with Shakespeare all add to the celebration of this age as truly "Old England" (Stamp, 2006 p.5).

"[Tudoresque] connects with a culture that relishes traditional aspects of Englishness, in a way that is not rigorously programmatic or codified, but which is evident in traditional pubs and tea shops, in copper kettles and dark oak furniture, in fine china and chintzes decorated with flowers."(Ballantyne and Law, 2011b p.125).

For as had been noted a century earlier by Stewart Dick and Helen Allingham in their "The Cottage Homes of England" (Dick and Allingham, 1938 p.4) for many the Old English cottage is "*the most typical thing in England*." A sentiment confirmed by the Ideal Home article "A Small Country House" in April 1920:

"*the desire has been to secure a suggestion of homeliness and comfort, something free from all pretension and ostentation; something, indeed, traditionally English*." (Ballantyne and Law, 2011b p.139)

It is argued that this upholding and reinforcing of the nation's identity coincided with times of threat from abroad. The French Revolution of the late 18th century saw the aristocracy and landed gentry keen to impress on their tenants and general public that they were not French[37] through a reassertion of "Englishness," just as the Napoleonic and World Wars required the same (Ballantyne and Law, 2011a). At the same time, Ballantyne and Law note that the Tudor period, or more specifically the Elizabethan, was a time of increased care for the cottager, citing the Land act of 1589 passed by Queen Elizabeth I requiring all new cottages to be provided with a minimum of 4 acres of land (Ballantyne and Law, 2011b p.131).

5.2.1.2 Simpler Times

The association between half-timbered architecture and the Tudors is undoubtable. Often referred to as Tudoresque, Mock-Tudor, Tudor Revival and Jacobethan. However, although strong, the arguments for timber framing's appeal being directly related to the desire to invoke the Tudor period, are debatable. If the intent was to create an association with that specific age, would it not be more precise to use architectural styles developed during Tudor rule, at the vanguard of the time, representing that time alone? If so then surely the emerging renaissance architecture of Elizabethan houses such as Hardwick Hall, "*more window than wall*" (Pevsner, 1976 p.324 note 80) (Figure 59) or the great brick palaces of Henry VIII such as Hampton Court or St James, would be better archetypes to follow.

[37] and therefore should not rise up in revolution

Figure 59. Hardwick Hall, Derbyshire by Robert Smythson 1527-1608 Source: (National Trust 2016)

In fact, strands of Victorian and Edwardian architecture existed that did draw on Renaissance examples (Franklin, 1989 p.9)., including Harlaxton Manor 1831-51, Lincolnshire by Anthony Salvin (Pevsner et al., 1989 p.362), Batsford Park 1887-93, Gloucestershire, by Sir Ernest George & Peto (Verey and Brooks, 2002 p.160) and Avon Tyrell 1891, Hampshire, by William Richard Lethaby (Pevsner and Lloyd, 1967 p.86, Muthesius, 1979 p.38). Yet, the half-timbered designs contemporary to these examples do not draw on the most emblematic of the Tudor timber-framed buildings, those in the ornamental style epitomised by houses such as Little Morton Hall (Figure 60). Instead, they look towards the vernacular architecture of the Kent and Sussex Weald, as so clearly illustrated by the work of Devey (Figure 48 & Figure 49). Could it not therefore be said that these buildings did not look back to a specific Tudor past, but rather to a more generic Old England? A simpler, pre-industrial time gone by (Simpson, 1977 p.36, Ballantyne and Law, 2011a p.38-39).

Figure 60. Little Morton Hall, Cheshire 1559. Source: (Gunns, 2004)

As Anthony Bertram states,

> "*Probably the popular love for Tudor, whether genuine or bogus, is based on fear and a wish to escape. When I was broadcasting I had many letters that said quite frankly, "The suggestion of those quiet old days gives us the restful atmosphere we seek in our homes." …These are insecure and frightening times and I believe that economic depression and the fear of war are the chief promoters of the Tudoresque*."(Bertram, 1938 p.58).

This desire for restfulness is echoed by Simpson

> "*The Englishman's mock-Tudor home is not his castle; it's his homely country cottage, his piece of Old England, conveniently brought up to Croydon for him*" (Simpson, 1977 p.31).

And although Bertram is no doubt correct that the idea of the quiet old days is a myth, the comfort of the cottage was identified a century earlier by William Howitt in his "The Rural Life of England (Howitt, 1844).

> "*…happiness is a fireside thing; and the simplicities of cottage life, the fewness of its objects, and the strong sympathies awakened by its trials and sufferings, tend to condense the affections, and to strike deep the roots of happiness in the sacred soil of consanguinity*" (Howitt, 1844 p128).

Yet here we see that it is not only to the past that we are turning but also to the countryside. As summed up by Girouard when writing of the Queen Anne style

> "*Dislike of the present led them to the past, dislike of the town, the country… As an antidote to the present they recreated the past as an ideal world of pre-industrial simplicity, at once homely and Arcadian*" (Girouard, 1977 p.5).

5.2.2 The rural idyll and the picturesque

Timber framing is essentially seen as a rural architecture, as such, just as it represents the past, it also is synonymous with the countryside. In his book "The Country and The City" Raymond Williams argues both the yearning for a simpler past life, now lost, and the dichotomy between country and city can both be traced back to biblical times, and are linked to the desire to return to the garden of Eden (Williams, 1973 p.12). Yet, the countryside has not always been seen as "better" than the city. In mediaeval times the city was seen in a more positive light, with rural life being dominated by hardship, feudal oppression and the dangers of the wilds (Short, 2006 p.135). Only the royal family and the richest of the lords sought out leisure in the countryside, within the hunting forests and chases, and the rural royal palaces (ibid). With the advent of the Renaissance there was a notable return in literature to a pastoral arcadia, seen previously in Roman writing such as Virgil's *Ecogues,* however these arcadias were based on mythology, occupied by nymphs and satyrs, rather than the common rural landscape (Short, 2006 p.136, Bunce, 1994 p.6). In fact, the hierarchical view of the Renaissance world placed nature below human civilization, and as such inferior and of little interest (Bunce, 1994 p.23). It was not until the Enlightenment of the 18th century that this view was fundamentally challenged by the philosophies of David Hume, Immanuel Kant (Bunce, 1994 p.24) and Rousseau. Hume expressed views extolling the "economy" of nature, whilst Kant's philosophy set human's causality within it (Bunce, 1994 p.24) and Rousseau's noble savage was superior to modern man due to his proximity to it (Younkins, 2005). A century later Darwin would go on to theorise that in fact man and nature were one. As such, the romantic movement of the 18th

and 19th century moralised the dichotomy between town and country, with health, honesty and virtue being characteristics of the country and corruption, greed and vainglory the town (Tuan, 1974 p.236). The popular 18th century English poet Cowper writes in 1785

> "*God made the country and, and man made the town*" (Cowper and Milford, 1934 p.145).

And as stated in 1909 by Raymond Unwin, advocate of the Arts and Craft movement, and designer of England's first Garden City, the results can be far from pleasant,

> "*we are apt to forget that this ugliness may be said to belong almost exclusively to the period covered by the industrial development of the last century… …Is it any wonder, then, that our towns and our suburbs express by their ugliness the passion for individual gain which so largely dominates their creation*" (Unwin, 1994 p.11-13).

The industrial revolution that had started in the North West mill towns of Lancashire in the second half of the 18th century (Toynbee and Jowett, 1890) had made Britain "*The Workshop of the World*" (MacLeod, 2014). This fact was celebrated by the Great Exhibition in 1851, at a time when Britain produced over half the world's coal, iron and cotton cloth (ibid). However by the 1870s Britain was losing its industrial supremacy to Germany and the United States (Howkins, 1986 p.63). As such, the metaphor of "*the workshop"* fell out of favour, with industrialization increasingly now being seen as something un-English (Daniels, 1991 p.15). Engels wrote in 1844[38] of the terrible conditions of the working class in the great Northern towns (Engels, 1958). These towns were a direct product of industry, with industry committing "social murder" (ibid p109). Ten years later Charles Dickens's Hard Times is set against the grim backdrop of the fictitious Coketown, a generic northern mill town, the unfortunate product of the Industrial Revolution (Dickens, 1869). This anti-industrial sentiment continued into the early 20th century. It has been argued that whilst Germany saw the First World War as a crusade for modernism, Britain fought to defend its

[38] Engels text was based on his stay in Manchester 1842-44 and was published in German 1845 but not published in English until 1887.

traditions, and that in the Second World War, Nazi Germany was portrayed as "an industrial society run amok" (Wiener, 1985 p.77), whereas England was "*humanely old fashioned and essentially rural*" (ibid). This difference between German and British attitudes is evident in the previously presented suburban architecture of the inter-war years. As pride in the industrial north faded and power moved south (Howkins, 1986 p.65), the "workshop of the world" became replaced with a "green and pleasant land" (Bunce, 1994 p.21) and not just any green and pleasant land but one specifically formed by an idealised "South Country" (Howkins, 1986 p.65). The boundaries of this "south country" could not be physically defined but rather it was a notional definition of rurality, embodied in the countryside of southern England as seen by those looking out from the urban world (Howkins, 1986 p.64) where even the southern cities were demonised

> *"…that great foul city of London there, — rattling, growling, smoking, stinking, — a ghastly heap of fermenting brickwork, pouring out poison at every pore…"* (Ruskin, 1902).

At the same time, traditional rural life was under threat. Steamships and railways had enabled the transportation of cheap food from abroad. Beef from Argentina, lamb from Australia and corn from the States, all flooded the British market and national cultivation declined (Lowe, 1989 p.115). In 1851, agriculture had employed a quarter of the males aged 20 and over, while by 1900 this had declined to 10 percent (ibid p1). Between 1861 and 1881 the number of male agricultural labourers dropped by over 20 percent and the number of female labourers saw an even sharper decline (ibid p12). Whereas once industry had attracted people to the city, the lack of rural employment now drove them to it (ibid). In 1851 the census had shown that just over half the population was living in urbanised areas (ibid p3). In order to stem this flow from country to city, Ebenezer Howard through his "Garden Cities of Tomorrow" intended to "*restore the people to the land*" (Howard et al., 1970), returning the people to the countryside, rather than bring the countryside into

the town. "*The country magnet declares herself to be the source of all beauty and wealth*" although dull for lack of society (Howard et al., 1970).

As the productivity of the countryside declined, its potential as an escape from the city increased. Writing in 1844, William Howitt speculates of how the new, emergent network railways will open up

"*terræ incognitæ, as it were, to the millions that in the dense and ever-growing mass of monstrous London pant after an outburst into the country*" (Howitt, 1844 p316-5).

Even for those who could not physically escape, the countryside provided mental escape, brought to them through poetry and painting. Landscape as described by Wordsworth has been described as

> "*a 'medicine' for the soul suffering from the effects of weariness, doubt and the pressures of an increasingly urbanised society*" (James, 1989 p.64).

Artists such as Constable and Turner did the same with their paintings. Both bringing the rural to the galleries of the city, and encouraging the population to go out to it, with Thomas Cook organising trips to "Constable country" as early as the 1890s (Daniels, 1991). Equally in the 1860s the effect was brought to the masses through Cadbury's use of rural scenes painted by artists such as Myles Birkett-Foster (Short, 2006 p.141).

Just as the works of Wordsworth, Constable, Turner, Birkett-Foster et al provided a link for the city dwellers to the rural idyll, so did the shorthand for the vernacular of the "South Country", timber framing. As James Malton states in the foreword to his cottage designs, "*the peculiar beauty of the British, picturesque, rustic habitations*" (Malton, 1798 p.1) represent a simpler, carefree life, removed from the "*boisterous clamour of cities*" (ibid). He notes

> "*Often has the aching brow of royalty resigned its crown, to be decked with the soothing chaplet of the shepherd swain*" (ibid p6).

Whether this is a direct reference to the recently beheaded French Queen, Marie-Antoinette, or a more general observation, it is true that just 15 years earlier, influenced by the philosophies of Rousseau, Marie-Antoinette had Richard Mique design the *Petit Hameau* in the gardens of the Petit Trianon at Versaille. The style of the hamlet, *le style normand,* a mix of stone and half-timbering, which although Ballantyne and Law dismiss as "*not being a reference to anything Tudor*" (Ballantyne and Law, 2011a), is most certainly a recreation of the rural idyll, a place for her to indulge in peasant role-playing. The buildings are picturesque and as Ruskin (writing under his pseudonym Kata Phusin) states of French cottages in general, have

> "*a general air of nonchalance…aided by a perfect want of everything like neatness*," (Ruskin, 1837 p.559).

Ruskin compares this to the English Lowland cottage where he claims the "*principal thing worthy of observation…is its finished neatness*" (ibid p556). Not all would agree with Ruskin on the neatness of all English cottages. Malton for a start delighted in the haphazard architecture that "*has come about by chance*" (Malton, 1798) and William Cobbett, writing of his travels to discover the true conditions of rural 19th century England, writes in 1830, of the village of Knighton near Leicester,

> "*…look at the miserable sheds in which the labourers reside! Look at these hovels, made of mud and straw; bits of glass, or old off-cast windows, without frames or hinges frequently, but merely stuck in the mud wall..."* (Cobbett, 1912 p.266).

Yet, whether neat or otherwise, the country cottage and more specifically the timber-framed country cottage represent an ideal based in a mythical rural past.

> "*The ordinary house-buying public, conservative in their tastes, did not welcome designs that advanced too far from their concept of what a house should look like. Many were still seeking the rural-romantic, to which the new styles made no concessions at all.*" (Jackson, 1973 p.140)

Therefore, we can see that the significance of timber-framed architecture can be traced to the past, be it a specific Tudor past or a more generic past. At the same time, it draws on a desire for an escape from the city, a return to the country. However, if these were the only issues at play here, could you not say the same about stone cottages or other rural typologies? Surely, there is something specific about the materiality of timber-framed buildings that sets it apart. Its materials, the oak for the frame, the hazel withies for the wattle and the earth for the daub, come directly from the soil of our land, thereby making it truly an architecture with roots.

5.2.3 An architecture with roots

On the frontispiece of Laugier's 1753 *Essai sur l'architecture* (Laugier, 1977) his "*rustic hut*" (Figure 61), influenced by the writings of Rousseau, Laugier defines as "*true perfection*" in architecture (ibid p12).

Figure 61 Laugier's Rustic Hut as shown in the frontispiece to Essai sur l'architecture Source:(Laugier, 1977)

Although in the text Laugier's savage raises four fallen branches upright, in the etching they are shown as tree trunks growing from the ground. This underlines the notion that the timber-framed cottage is rooted to the ground. A notion that the art historian Karen Sayer believes set them at the heart of Victorian psyche,

> "*…the cottage's walls, roof and (timber) frame connoted an age-old, fundamental link between soil and house, nation and village, as if the cottage had grown up out of the land on which it stood*" (Sayer, 2000 p.115)

and according to R.T. Mason make them at one with the landscape,

> *"…our vernacular buildings spring from the very soil upon which they stand, and therefore cannot fail to blend happily with their environment. All necessary materials, except a few iron nails, could be obtained in the surrounding fields and woods…*"(Mason, 1974 p.12).

These views were expounded by the interwar Conservative Prime Minister Stanley Baldwin, in his inaugural speech to the Royal Society of Arts, January 26th 1927. He noted that timber-framed architecture

> *"…has an appearance in the country of spontaneous and natural growth, wholly lacking in those abortions of red brick and slate which have risen with such alacrity over the face of the country since the industrial era began*" (Daily Mail, 1927 p.59).

The perception of timber-frames growing makes them part of the place, more so than stone which must be quarried or brick that must be fired. For although the trees must be felled, squared and converted into beams and posts, this process is still identified as being more direct, perhaps more human scale, than that of masonry. Equally, they are a renewable resource, unlike fossil materials such as stone and clay. The connection with the earth appears to continue even once the tree is cut, as if the timbers have been merely transplanted. This makes them at once established and accepted. Ballantyne and Law also make this connection, noting how the Old English style was embraced by the self-made industrialists of the 19th Century for their philanthropic work to suggest continuity and tradition, and disguise new money and social change (Ballantyne and Law, 2011a p.99).

5.2.4 The hand of the craftsman

As well as noting that timber-framed architecture appeared to grow, Stanley Baldwin in the aforementioned speech also made the connection to the craftsman. He stated that

> "*it was difficult to contemplate the beautiful old cottages of England without realising that this architecture was one of the tributaries of the main stream of mediaeval craftsmanship which had come down to our time, and, as such, was of inestimable value to us*" (Daily Mail, 1927 p.59).

The handbook that accompanied the Daily Mail Ideal Homes show of the same year took great pride in including Baldwin's comments, and highlighted the affinity with their three of the main exhibits, The Maple House, The Suntrap House and the Tollgate Bungalow, which all feature exposed timber framing. In an earlier Daily Mail publication, an advert for a builder expresses their pride in their handicraft. John I. Williams & Sons, of Oxted, Surrey, state that three generations of the family have "*sought to preserve the tradition of the past*" specialising in the Tudor period (Daily Mail, 1922 p.67). Through their work, the company

> "*has earned a reputation which more than entitles it to comparison with the builders of the past, who set time-defying cottages and manor houses on the countryside as evidence of their uncompromising selection of materials and sincere workmanship*" (ibid)

Though it may be questioned the craftsmanship in machine cut applied timbers of their designs, we find here another component of the significance of timber framing, that of the handmade. As previously noted, the process of building with timber can be perceived as more direct and human scale. Many will have received woodworking classes at school or done minor timber DIY. Timber, being a softer material than stone or brick, can easily be cut by hand, and as such, appears more approachable. There is the sense that almost anyone could, if not build from scratch, at least add to and amend a timber-framed, or apparently timber-framed home (Ballantyne and Law, 2011a p.125, Ballantyne and Law, 2011b p.140). Yet at the same time, there is the acknowledgement of the skill and care of

the artisan. Writing of a house by Mackay Hugh Baille Scott in Meadway, Hampstead Garden Suburb, Raymond Unwin writes,

> "*Lovers of oak and honest English timber will find pleasure in the beams and panelling of Mr Baillie Scott's interiors, which recall old traditions of English craftsmanship*" (Unwin and Scott, 1909 p.21).

This embodiment of the craftsman skill and ancestral knowledge are recognised by ICOMOS the key values of wooden architecture (ICOMOS, 2017).

The perceived hand of the craftsman inherent in timber framing has also been repeatedly used to soften the introduction of new technologies. At Gregynog Hall, Newton, Powys, the concrete panels that clad the entire building, a startling innovation in the 1840s, are painted black and white to mimic ornamental timber framing, thereby diminishing the impact of this unknown material.

Figure 62. Concrete panel clad Gregynog Hall, Newton, Powy. Source: (Croker, 2009)

Similarly, when in 1875, W.H. Lascelle's patented a new construction technique using reinforced concrete panels the supporting timber-frame was exposed, thereby emphasising this element of its design over the concrete (Builder, 1875 p.731) (Figure 63).

Figure 63. Examples of Lascelle's first construction technique with timber-framed concrete panels. 44-50 Gloucester Road, Croydon. (Cherry and Pevsner, 1983) Source: (Google, 2016)

By 1878 Lascelle's technique had evolved to include the use of pre-cast reinforced concrete posts in the place of the timber framing. These however were recommended by the Builder magazine for use only in "*very damp situations*" or for when the entire house must be fire proof (Builder, 1878 p.908-909), with timber being deemed more economical and convenient (ibid). To publicise the system a book was published, "Sketches for cottages and Other Buildings" (Shaw et al., 1878) with designs by R. Norman Shaw, drawn by Maurice B. Adams (Figure 64 and Figure 65). Here it can be seen that the outer face of the concrete panels had in some places been textured to resemble tile-hanging (Shaw et al., 1878). Whether timber or concrete, the frame was often exposed. Of the 27 designs contained within the book, 21 display some degree of exposed timber framing, many use the tile-hung textured panels, whilst only 3 are roughcast directly onto un-textured concrete panels (Shaw et al., 1878).

Figure 64. Richard Norman Shaw. Plate 6. Pair of cottages for a rural site Source:(Shaw et al., 1878)

Figure 65. Richard Norman Shaw. Plate 28. Shops for a village street Source:(Shaw et al., 1878)

In reviewing the book The Builder praised the practical advantages of the construction method but questioned Shaw's designs,

> "*We cannot but think, however, that even a better result might have been obtained had there been less archæology and more architecture in these little buildings. …we fail to see the reason for thus imitating old rustic buildings in a modern material,*

> *unless it be to catch the sympathies of the large class of people who still believe that there is a charm in whatever is old-fashioned in building and something wrong about whatever is new* (Builder, 1878 p.908-909).

It was clearly felt that the opportunity to find expression of a new style through this new construction technique "*has been deliberately and almost perversely thrown away..." with "…so much labour thrown away in making a sham*" (Builder, 1878 p.909). It is however quite possible that Shaw believed, as with Gregynog Hall, that the new construction technique would not be accepted by the public if it was too explicitly machine made. A similar sentiment would be seen again in the application of applied timberwork to the repetitive, mass-produced interwar semi-detached houses. Despite the lie, by imitation of the handmade timber-frame, the impact of these vast estates, previously not seen on such a scale, was hoped to be diminished. The founder of the British Journal of Aesthetics, Harold Osborne argued in 1977 that in a world in which production becomes increasingly mechanised there is a counter-reaction to perfection, an attribute previously aimed for by the skilled artisan, and the irregularities resulting from manual labour become more highly prized (Osborne, 1977).

> "*Machine products are standardised and so become impersonal. The small irregularities and imperfections which are the marks of what we call handwork, causing each product to differ slightly from every other, are eliminated… …In reaction from the mechanical regularity of the machine we nowadays tend in contrast to put higher value on the irregularities and imperfections which proclaim that a thing is hand made*" (ibid p141-142).

This sentiment is reiterated almost word for word by Richard Sennett in "The Craftsman" (Sennett, 2008 p.84), where he traces it back to the *Encyclopaedia*, or *Systematic Dictionary of the Sciences, Arts, and Crafts,* compiled by the French philosophers Diderot and le Rond d'Alembert between 1751-72 (ibid, p104). Sennett also draws on Ruskin's appreciation of rough-hewn beauty, and scorn of mechanised civilisation (ibid p108-109) and the American

sociologist Thorstein Veblen, notes in his book *The Theory of the Leisure Class* (Veblen, 1970)[39]

"*the visible imperfections of the hand-wrought goods, being honourific, are accounted marks of superiority in point of beauty, or serviceability, or both*" (ibid, p115).

He goes on however to accuse both Ruskin and Morris of the "*exaltation of the defective*" (ibid) through their call for a return to handicraft, which Veblen laments as "*propaganda of crudity and wasted effort*" (ibid). Yet the concept of the added value of handmade products, or at least those marketed as handmade still remains today. A recent article by Fuchs, Schreier and van Osselaer (Fuchs et al., 2015) states that one of the key factors is the perceived love and personal care that has been invested in the production of the product, by the craftsman, as opposed to the impersonal, emotionless work of the machine (ibid). Timber framing with its axe signatures (Figure 66), saw marks and carpenter's marks, clearly manifests the hand of the artisan in its production, and as a consequence, Fuchs et al would argue, their love.

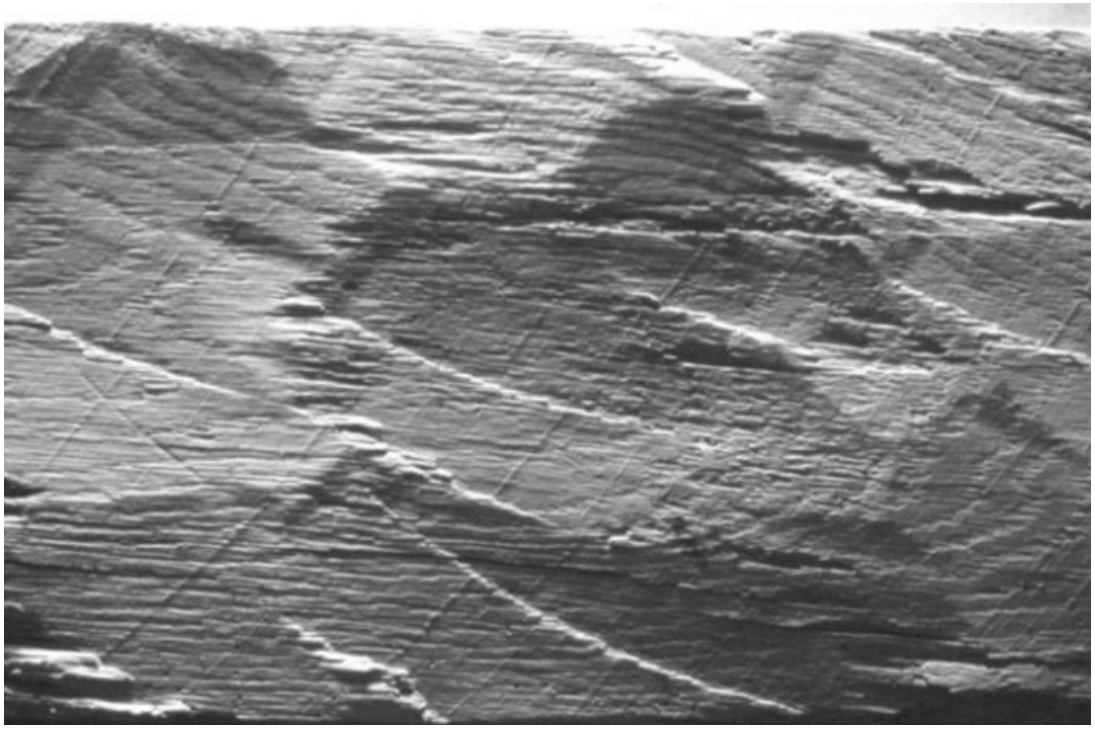

Figure 66. Axe signatures Source: (Harris, 2016)

[39] First published 1899

5.3 Conclusion

The enduring importance of timber-framed buildings in the British or more specifically English cultural identity would therefore appear to be a combined result of three key factors. A connection to the past, be this specifically a Tudor past or a more general times gone by; its evocation of the rural idyll, being not only present in the countryside but physically made of it; and the evidence of the hand of the craftsman, increasingly valued in an progressively more mechanised world. All three are symptoms of the industrialised world. They are the desire to return to a time before it, escape from the city created by it and the rejection of the perfection it has enabled. We have seen that even after timber framing ceased to be a common structural solution, its aesthetics continued to be replicated. Yet whilst this chapter has focused on these imitations, in doing so it also underlines the need to conserve the remaining examples of true timber-framed buildings that inspired them. If we were to be left with only reproductions, with their half-timbers only skin deep, then an integral part of our identity would be lost. It can be argued therefore that their continued use and conservation is of national importance.

6 SURVIVAL

6.0 Introduction

Having reviewed the value and significance of timber-framed building in the UK, it is important to understand the context and scale of the challenge of their continuing conservation. In order to do so a review was undertaken of the surviving examples of these buildings in the UK. This chapter presents the methodology followed and the analysis of the result regarding quantities, use, age, panel infill material and distribution. The distribution pattern of the surviving timber-framed buildings is then correlated against physical, climatic and economic patterns in order to try to understand the factors influencing the location and ongoing survival of these buildings.

6.1 Methodology

6.1.1 Literary sources

6.1.1.1 UK Timber-Frame Distribution

Prior to embarking on the scientific quantification of surviving timber-framed buildings, a review was undertaken of texts concerned with the typology and distribution of vernacular built heritage in each of the historic nations of the United Kingdom. This work was in addition to that undertaken to produce the previously presented chapters. By doing so, it was possible to ascertain the scope of the study and gain an overview of the rarity of this building type in England, Wales, Scotland and Northern Ireland.

In England, the work of Ronald William Brunskill provides an introduction to the vernacular styles of English architecture and their distribution across the country. In his book "Illustrated handbook of vernacular architecture" (Brunskill, 1978) there are detailed descriptions of the variations and details of English timber-framed buildings (ibid, p52-71) and maps of their distribution (ibid, p191-193). Another useful resource, focused specifically on timber framing is the work of John T. Smith (Smith, 1965, Smith, 1981) which

provides more detailed information on the distribution of the different timber-frame techniques. However, neither Brunskill nor Smith quantify the number of buildings. It is only with the aid of Geographic Information Systems (GIS) and the ability to co-ordinate registers that it has been feasible to bring this work forward.

In Wales, Peter Smith's "Houses of the Welsh countryside: a study in historical geography" (Smith, 1988) is an invaluable resource. The book contains not only detailed descriptions of the vernacular typologies and distribution maps but also includes a full list of all known examples of that typology complete with national grid references. For timber-framed buildings, Smith lists 1,389 timber-framed buildings, although some are listed as "demolished" (ibid). Smith's work has been continued and expanded upon by other members of the Royal Commission on the Ancient and Historical Monuments of Wales (RCAHMW), principally Richard Suggett (Suggett, 2005, Suggett and Dunn, 2014).

For Scotland, an overview of vernacular architecture was gained from Robert Naismith's "Buildings of the Scottish countryside" (Naismith, 1985). This confirmed that surviving timber-framed buildings were almost non-existent in Scotland (ibid pg87) even though as we have seen there is a history of their construction there. A similar story was encountered in Northern Ireland in Alan Gailey's "Rural Houses of Northern Ireland" (Gailey, 1984) which states that no example of this construction technique survives to this day (ibid, p44). Box-framed houses were reportedly built by the British settlers in Ulster in the early 17th century, however many of these were burnt down in the 1641 rebellion and the remaining few disappeared in the 19th century (ibid).

6.1.1.2 European Timber-Frame Distribution

Although not the focus of this thesis, it is useful to set the UK timber-framed buildings within the context of timber-frame construction across the rest of Europe and beyond. In order to focus this study, only examples with similarities to UK timber-frame construction were included. That is to say half-timbered construction with solid infill panels. The principal source for this review was the Paul Oliver's extensive compilation on international vernacular architecture, the "Encyclopaedia of vernacular architecture of the world" (Oliver, 1997). This identified a principal concentration of this building technique in Northern Europe.

In Denmark, timber-frame construction can be found in the provinces of Zealand, Jutland and Funen (Oliver, 1997). These longhouses, are half-timbered with infill of wattle and daub, dried earth brick or fired brick, with evidence of the tradition dating back to 2800 BC (ibid). Examples can be seen at the Lyngby open-air museum (ibid). A similar construction technique can be found in the far south of Sweden in the province of Skåne (ibid). It is noted that this part of Sweden is historically influenced by both Denmark and Germany (ibid). In Germany there is a widespread tradition of infilled timber framing known as *fachwerk,* examples can be found in Westerfalia, Swabia, Schleswig-Holstein, Saxony (principally in the lowlands and northwest), Niedersachsen, Franconia, Hessen and Alsace (ibid). Regional differences do exist with brick nogging prevalent in Westafalia and wattle-and-daub in Swabia (ibid). Timber framing is also common across France (Figure 67), with Normandy being particularly noteworthy in the quantity of surviving examples (Calame et al., n.d.). Half-timbered buildings with wattle-and-daub are also recorded in Belgium, with the towns of Haspengouw and Hesbaye being specifically cited (Oliver, 1997).

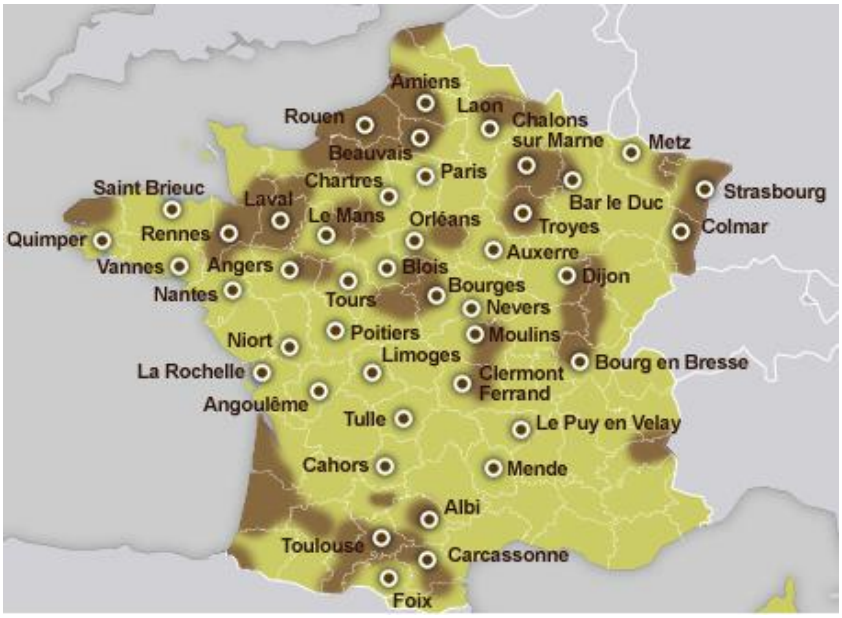

Figure 67. Map showing rural areas with vernacular timber-frame edifices (shaded areas) and prefecture-level towns with at least twenty timber-frame houses. Source: (Calame et al., n.d.)

In southern Europe, there are also examples of surviving timber-frame construction, although this appears to become less common. For example in the Pelion region of Greece the traditional construction is of upper timber-framed stories set on lower ones of stone (Alexandrou, no date). This technique appears to be of Ottoman origin and similar examples can also be found in Bursa in North West Turkey (Oliver, 1997) and in Safranbolu and Yörük in Anatolia (Sanz et al., 2002).

Moving further beyond the borders Europe we find other examples of indigenous vernacular timber-frame architecture such as in China and Japan (Yokobayashi and Sato, 2015), in addition to locations where the technique has been exported through the process of colonisation. Examples of this include French colonial West Indies, particularly Martinique, Guadeloupe and St Martin but also Cayenne (Oliver, 1997); Southern Brazil where areas were settled by German immigrants from Westafalia and Pomerania (ibid); the east coast of North America; the Texas Hill Country another area of German immigration; and the west coast of Chile where the technique is combined with adobe in the cities and towns of the British owned nitrate industry.

Further research is required to establish the existence of indigenous timber-frame architecture outside Europe. Equally, it would be of great interest to extend the mapping and correlation covered in the rest of the chapter to surviving timber-framed buildings both within Europe and across the world. This work however falls beyond the scope of this thesis but could indicate potential areas for future research.

6.1.2 Quantification of surviving UK timber-framed buildings

In order to quantify the number of surviving timber-framed buildings in the UK it was assumed that all historic (pre-1850) timber-framed buildings are designated as listed buildings. This may be seen to be a large assumption, however, based on the findings of the previous chapter it is evident that the significance of this building typology, since the listing process began, has led to the listing of most of its surviving examples. As such, information from Historic England (Historic England, 2014), Peter Smith's "Houses of the Welsh Countryside" (Smith, 1988), the National Monuments Record of Wales (RCAHMW, 2014), Historic environment Scotland (Historic Environment Scotland, 2016a) and the Department for the environment for Northern Ireland's (Department of the Environment, 2017) formed the raw data set for this analysis. This raw data was then cleaned to remove buildings that had been demolished, buildings listed as "formerly timber-frame" or those subsequently entirely encased with a continuous solid masonry envelope. In addition, entries covering multiple buildings were duplicated to create one entry per building. A full detailed methodology of the pre-processing of this raw data set can be found in appendix B.

After refinement, the search in England returned a total of 66,975 surviving timber-framed buildings, that for Wales 1020, none in Northern Ireland and just 3 in Scotland. Those in Scotland are all in Edinburgh, and are predominantly stone buildings with timber-framed upper storeys or projecting galleries. Overall, the resulting data set contained the details of 67,998 surviving timber-framed buildings in the UK. This was subsequently plotted using

ArchGIS® geographic information system, allowing the cross-referencing and comparison of the surviving buildings' distribution with geological, topographical, climatic and economic data. The results are presented in section 6.4.

6.1.3 Limitations of the dataset

6.1.3.1 Limitations of the listing designation descriptions

One of the key limitations of the dataset and the results that arise from it is the principal assumption that all pre-1850 timber-frame buildings are listed. As discussed it is possible that there are buildings that should be included in this study that are not listed. A second limitation, and perhaps more important, is that both the initial search and the subsequent classification are based on the text of the designation description which is written at the time of designation by the listings officer and varies greatly in both quality and detail. As such, the contents of the description is based on the information and knowledge available to the officer at that time. Assumptions may be made, and biases or misconceptions of the officer may be included. Only very rarely are the designation descriptions updated. Therefore, information such as further dating work through dendrochronology or information gained through maintenance and repair and opening up would not be included. Nor would any subsequent changes of use or building work. The work presented is therefore is an approximation and should be read as such. It does still however present a clear picture of the surviving timber-framed buildings in the UK today.

6.1.3.2 Fragility and Portability

It should be also noted prior to reviewing the results that they represent only those buildings that have survived until today. Therefore, both the quantities and distribution patterns must be read remembering that they do not represent the number of buildings that were built for that use, in that place or at that time, but only those that continue to stand. Although it will be shown that many buildings have survived for centuries, timber-

framed buildings, especially those built for the poorest of society, have often been far less substantial than their masonry counterparts. Unlike the timber-framed houses built for merchants and noblemen, peasants' houses would typically have used smaller section timbers or 'scantlings' for their framing and some would have been little more than daubed wattlework panels or 'flakes' (Innocent, 1971 p128). As previously discussed, the flimsy nature of 12th century houses is shown by the Assize of Clarendon 1161, article 21, which states that as a punishment *"… the house in which they have been shall be carried without the town and burned…"* (Henderson, 1892). Their insubstantial nature is also apparent by the fact that aldermen of the city of London in 1212 were provided with no more than a crook and cord to pull down burning houses (Innocent, 1971 p.128) and a historical report of a village in South Yorkshire that blew away (ibid). It is therefore most probable that the majority of the most humble timber-framed dwellings survived no more than a generation.

We must also consider that the surviving may not be in their original location. There are numerous accounts, both historical and modern, of timber-framed buildings being relocated. In 1250 it was recorded that a timber-framed house in Newport, on the Isle of Wight, was moved on rollers to a new site (Cave, 1981 p.65). In 1316 the Hall of Llwelyn was dismantled in Conwy and transported by sea to Caernarvon where it was re-erected (ibid) and in 1432 a four-bay house was bought in Sherwood for relocation to Nottingham Castle, where it was rebuilt in three days (ibid). More recent examples include a 14th century house in Exeter that was moved 70m on rails in 1961 (British Pathé, 1961) and a similar example of a 17th century house in Hereford (British Pathé, 1965), not to mention all those buildings that have been relocated to museums such as St Fagan's, Avoncroft or the Weald and Downland open-air museum. Even one of the case study buildings featured in this thesis was moved 30m across a field. As such, it must be considered that whilst most of the buildings included in the results of this study have remained where they were built some may have moved and most of the more ephemeral ones will have disappeared.

6.2 Statistics

There follows the results of the classification of the 67,998 identified surviving timber-framed buildings by use, age, location and panel infill or cladding material.

6.2.1 By Use

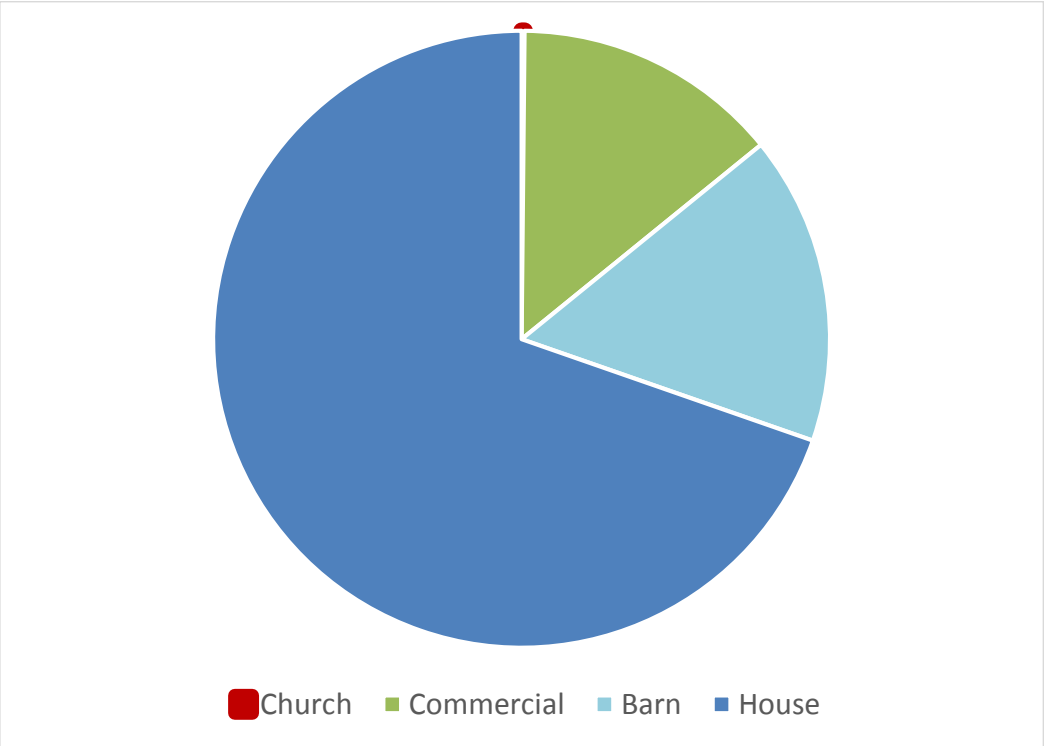

Figure 68 Percentage of surviving pre-1850 timber-framed buildings in England and Wales by use. Source: (Author's own based on (Historic England, 2014, RCAHMW, 2014)

Table 7 Quantity of surviving pre-1850 timber-framed buildings in England and Wales by use. Source: (Author's own based on (Historic England, 2014, RCAHMW, 2014)

Use	Number of buildings	Percentage (%)
Church	104	0.15
Commercial/Public	9,515	14
Barn	11,007	16
House	47,372	70
Total	**67,998**	

The most common current use for timber-framed buildings is as dwellings (Figure 68), representing over two thirds of all surviving examples, a figure that is no doubt increasing as timber-framed barns in rural locations are converted for residential use. It is difficult to say whether more timber-framed houses were built than agricultural and commercial premises or if more examples have survived because they are houses. Potentially it could be argued that less changes may have taken place with regard to habitational needs compared to those of commerce and agriculture, or that the changes that have taken place are easier to accommodate. For example as agriculture became industrialised many barns would have been replaced with larger structures required by the new mechanised processes and similar changes would have taken place for commercial premises. In addition, many commercial premises would have under greater pressure for continual modernisation and development due to their often central locations within urban areas. Conversely, it is possible that agricultural buildings in remote locations may be overlooked and are yet to be listed. At the same time, it is possible that for commercial buildings and more particularly for churches, that masonry would have been the preferred building material, representing solidity, safety and prestige. That said, the fact that a higher percentage of timber-frame buildings are dwellings is perhaps to be expected, as in 2014 it was estimated that there were around 24.5 million dwellings in England and Wales (Beckett, 2014 p.4, Caunt, 2014 p.3) and only around 1.5 million commercial premises (VOA, 2016).

Given that such a large percentage of the surviving buildings are residential, this underlines the key issue facing the energy retrofit of these properties. These buildings are people's homes, spaces in which they expect to feel comfortable and want to spend time. If the ongoing survival of these buildings is to be ensured, people must want to continue living in them.

6.2.2 By Age

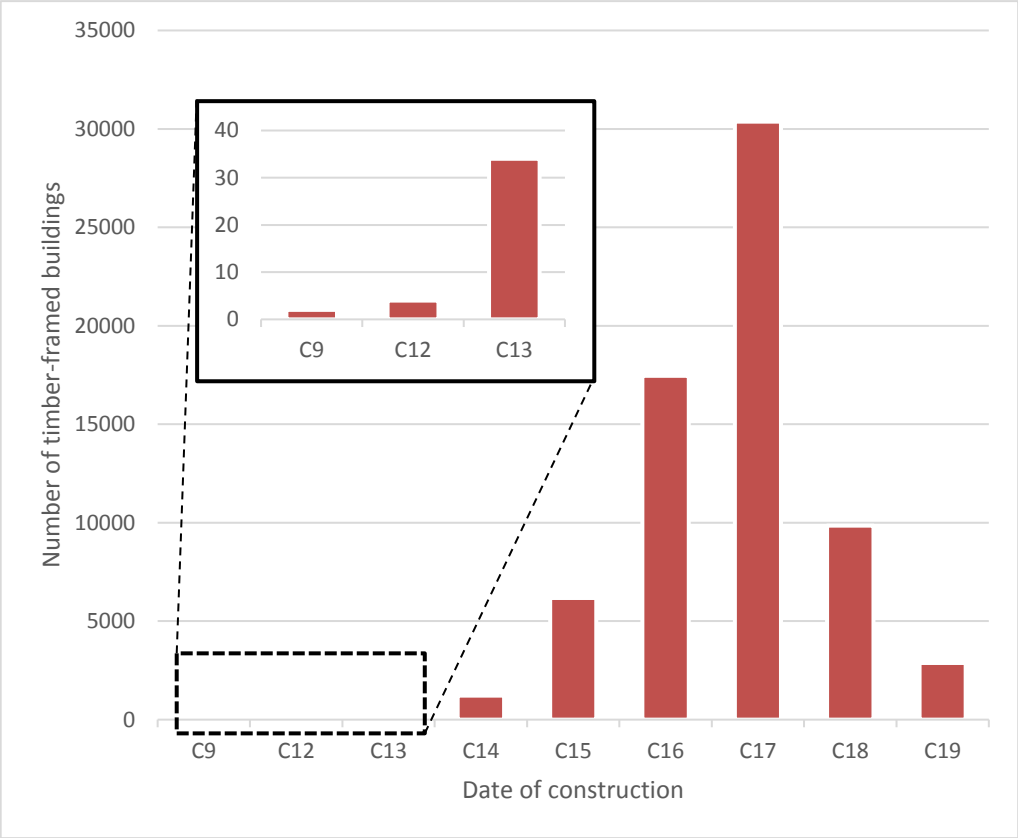

Figure 69 Percentage of surviving pre-1850 timber-framed buildings in England and Wales by age. Source: (Author's own based on (Historic England, 2014, RCAHMW, 2014)

Table 8 Quantity of surviving pre-1850 timber-framed buildings in England and Wales by age. Source: (Author's own based on (Historic England, 2014, RCAHMW, 2014)

Century	Number of Buildings	Percentage (%)
C9	2	0.003
C12	4	0.006
C13	34	0.05
C14	1,227	2
C15	6,172	9
C16	17,463	26
C17	30,377	45
C18	9,847	14
C19	2,872	4
Total	67,998	

Perhaps not surprisingly the most abundant group of surviving timber-framed buildings date from the 17th century. As discussed in chapter 4, we know that due to regulations introduced following the Great Fire of London that by the 18th century timber framing was in decline as a common construction technique (Harris, 2010 p.3, Martin, 1995 p.27) and as such the 17th century is the most recent century in which timber framing was a common construction technique. Figure 69 could be viewed to suggest a gradual increase in timber-framed construction, reaching its peak in the 17th century. Whilst this may be the case, as previously noted, this only represents the surviving buildings and so quite possibly, timber framing may have been as prevalent in earlier centuries, yet less of these examples have survived. What is perhaps more notable is the dramatic drop-off that occurs in the 18th and 19th centuries, illustrating the decline of the construction technique discussed in previous chapters. The outcome of this is that over 80% of the buildings covered by this thesis are over 300 years old. This influences their individual significance and highlights the care that must be taken with any interventions that are undertaken.

6.2.3 By panel infill or cladding material

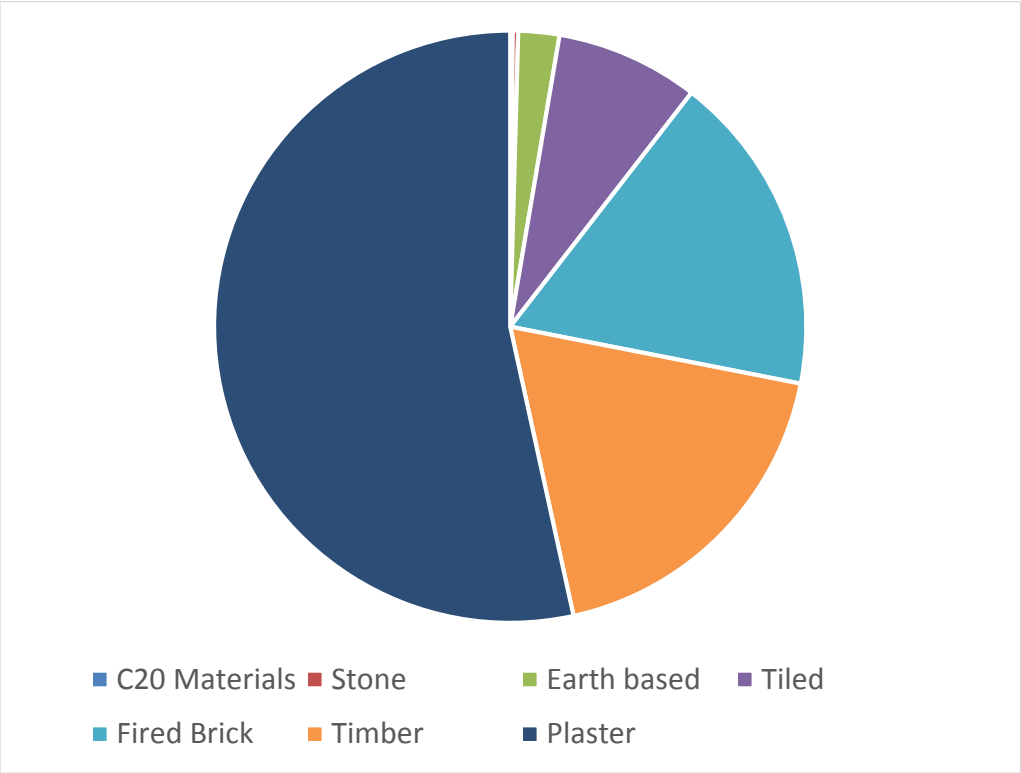

Figure 70 Percentage of surviving pre-1850 timber-framed buildings in England and Wales by panel infill or cladding material. Source: (Author's own based on (Historic England, 2014, RCAHMW, 2014)

Table 9 Quantity of surviving pre-1850 timber-framed buildings in England and Wales by panel infill or cladding material. Source: (Author's own based on (Historic England, 2014, RCAHMW, 2014)

Material	Number of buildings	Percentage (%)
C20 Materials	93	0.14
Stone	201	0.30
Earth based	1,523	2
Tiled	5,318	8
Fired Brick	11,959	18
Timber clad	12,569	18
Plaster	36,329	53
Total	**67,998**	

Figure 70 and Table 9 would suggest that the most common infill or cladding material for timber-framed building is plaster, representing over half of the surviving. It should however be noted that the term plaster includes those cases where the panel infill or entire building has been rendered. As such, there may be many cases where the designation description is based on only the external appearance of the wall or panel, with no exploratory investigation to determine the core material. There may therefore be cases of wattle and daub or brick nogging that are not recorded here. The 2% recorded here as “Earth Based” are predominantly wattle and daub but also include mud and stud and cob infill. These represent only those cases where earthen materials are specifically detailed in the designation description. It is therefore possible that others are hidden behind other materials, as just noted, or that the designation officer did not think it necessary to record the detail. The same would also apply in the case of the 20th century infill materials where there exists the strong possibility that more infill panels have been replaced with modern materials since the date the designation description was written.

Given the rarity of traditional earth based infill panels, this increases their collective and individual significance and where possible their retention should be prioritised.

The distribution of these materials is presented geographically in Figure 81.

6.2.4 By location

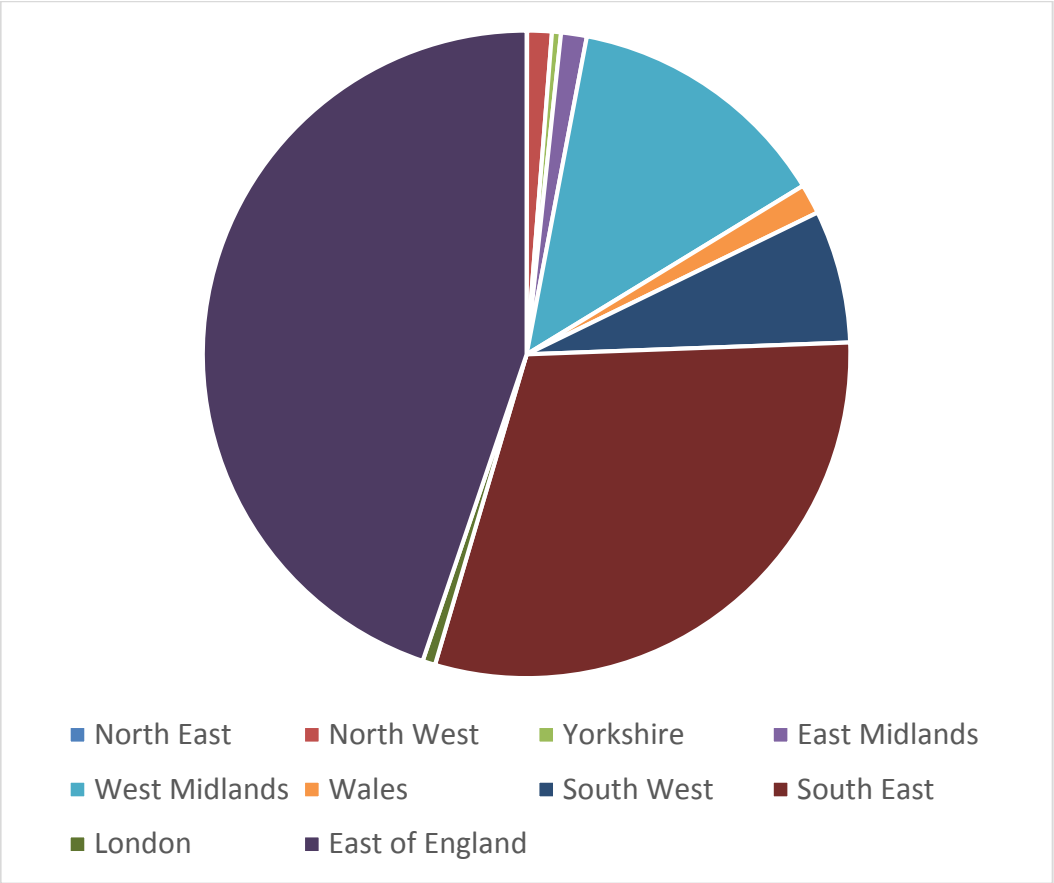

Figure 71 Percentage of surviving pre-1850 timber-framed buildings in England and Wales by region. Source: (Author's own based on (Historic England, 2014, RCAHMW, 2014)

Table 10 Quantity of surviving pre-1850 timber-framed buildings in England and Wales by region. Source: (Author's own based on (Historic England, 2014, RCAHMW, 2014)

Location	Number of buildings	Percentage (%)
North East	16	0.023
Yorkshire	306	0.4
North West	835	1.2
West Midlands	9,042	13
East Midlands	872	1.3
East of England	30,459	44
South East	20,503	30
South West	4,510	6.5
London	432	0.6
Wales	1,020	1.5
Scotland	3	0.004
Total	**67,998**	

The location of the surviving timber-framed buildings is best illustrated with the following distribution maps. However, Figure 71 and Table 10 demonstrate that 75% of the surviving timber-framed buildings are located in the East and South East of England, with the West Midlands being the next largest concentration. The factors behind the predominance of this construction technique will be discussed in the following chapter.

6.3 Distribution maps

There follows a series of maps that present the results of the GIS mapping of the results and correlation of this data against geology, topography, historic woodlands, climate and socio economic factors.

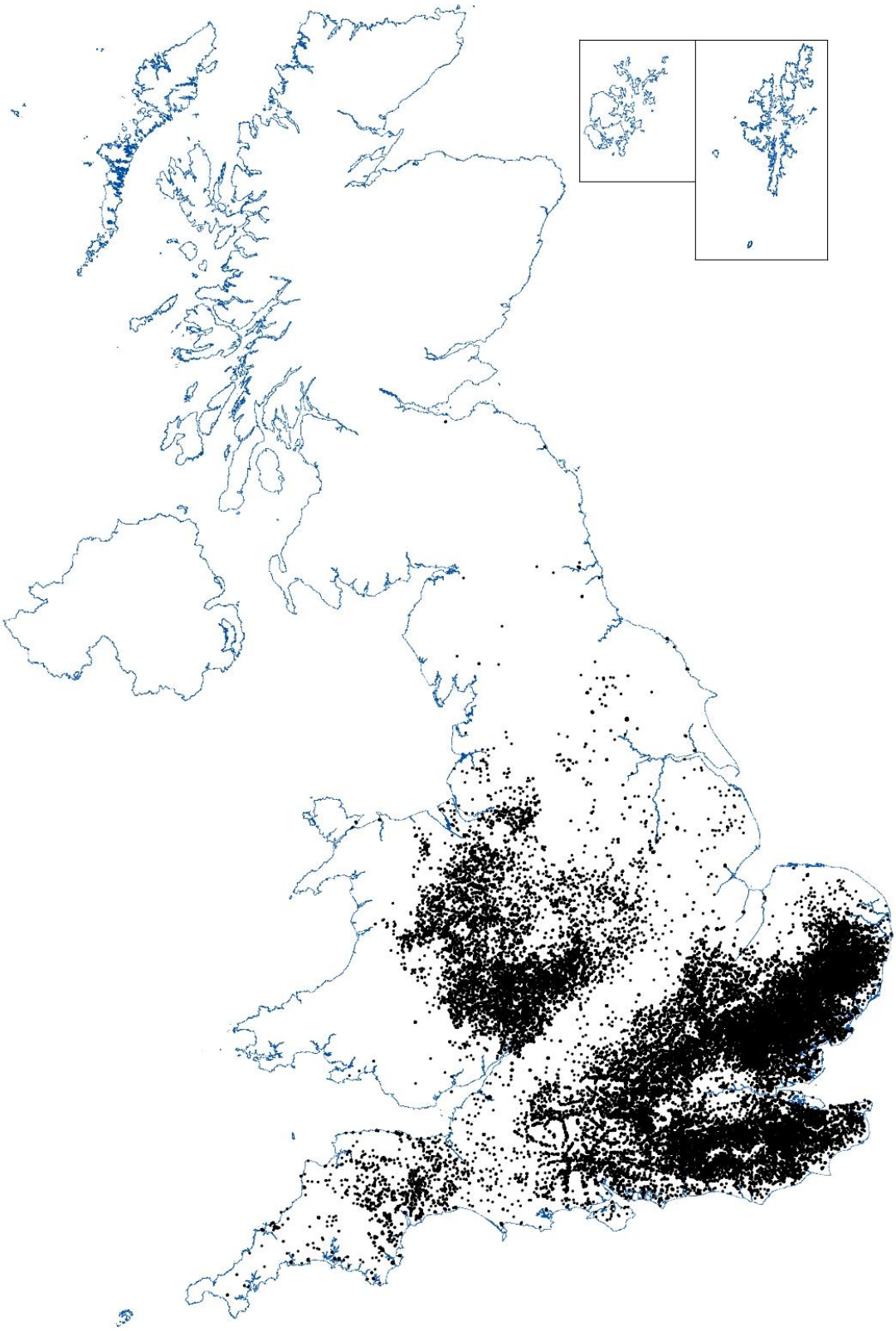

Figure 72 Distribution of timber-framed buildings in the UK. Source: (author's own based on (Historic England, 2014, RCAHMW, 2014))

6.3.1 Overall Distribution

The overall distribution shown in Figure 72 demonstrates the two main concentrations of surviving timber framed buildings, these being the East and South East of England, and the West Midlands and Welsh Marches spreading across the border into Wales and up into the lower portion of North West England. Within both of these concentrations, the metropolitan areas of London and the West Midlands Conurbation can be identified as clear areas, with only 433 buildings within the metropolitan boundary of London and 82 within the West Midlands Conurbation. The areas covered by the cities are identified in red in Figure 73 for clarity. In the case of London this will in part be due to the destruction of the Great Fire of London of 1666 and the subsequent laws prohibiting the construction of timber-framed buildings (Knowles and Pitt, 1972 p.29). However, the economic pressures for redevelopment in both these cities will also have played a role in the replacement of ancient buildings.

A third minor concentration can be identified in the South West of England around the border of Somerset and Devon. Further reasons for these distributions patterns will be discussed in detail later in the chapter.

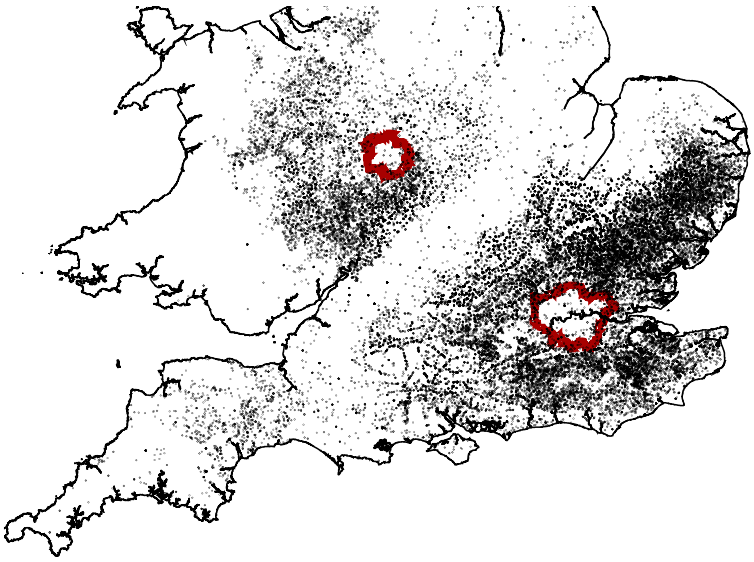

Figure 73 Distribution of timber-framed buildings in Southern Britain with London and Birmingham highlighted. Source: (author's own based on (Historic England, 2014, RCAHMW, 2014))

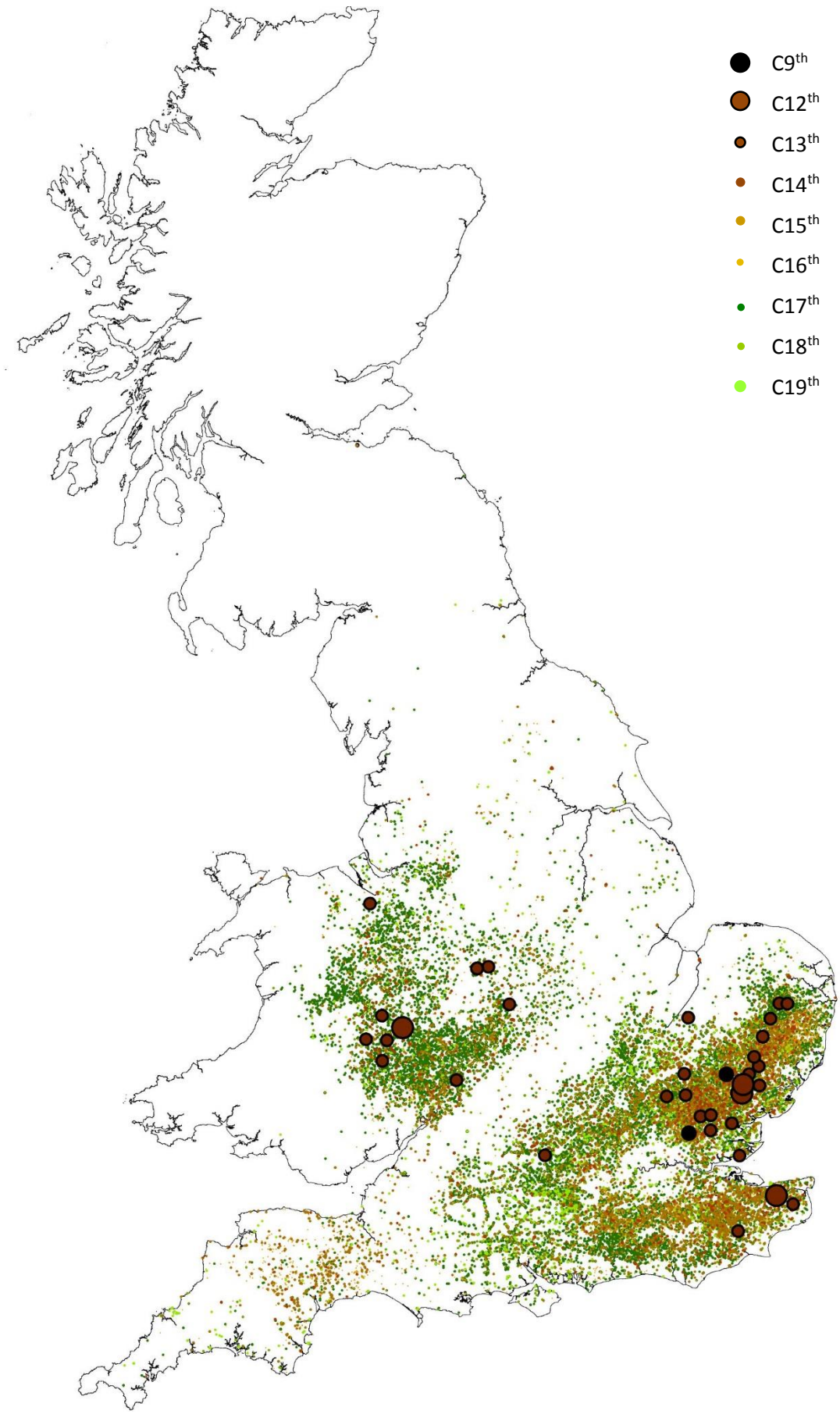

Figure 74 Distribution of surviving timber-framed buildings in Great Britain, classified by age. Source: (author's own based on (Historic England, 2014, RCAHMW, 2014))

6.3.2 Distribution by age

When looking at the distribution of age (Figure 74), a number of patterns appear. These are most clearly illustrated when those buildings built in each century are separated out (Figure 75-to Figure 80). The very earliest timber-framed buildings are to be found in the East of England. Given the resemblance, previously noted, of these early examples to Scandinavian architecture, this suggests the influence of the Viking raids, starting in AD789 (Richards, 1992 p.16), and the subsequent settlement of the East of England by the Danes.

The concentration of 15th and 16th century buildings again is at its densest to the north and south of the Thames estuary an area heavily involved with profitable trade with both London and the wool trade with the Low Countries (Heard, 1997 p.46). The production of traditional broadcloth woollen textile in Essex and Suffolk reached its peak in the last decades of the 15th century (Pilgrim, 1972 p.253) creating great wealth for families such as the Paycocks of Coggeshall, the Springs of Lavenham and the Webbs of Dedham (ibid), all places already noted for their plethora of historic timber framing.

The West Midlands and Welsh Marches have a few buildings dating from the 14th century; however, it is not until the 16th century and more markedly the 17th century that we find significant concentrations of surviving buildings in this area. Like East Anglia, the principal generator of wealth in the Welsh Marches was wool, however initially this was dominated by the Lords of the Marches and the great monastic estates (Sylvester, 1969 p.135). These large landowners would have probably favoured stone constructions to assert their power and protect their wealth from border raids and local wars. This was to change with the Welsh Acts of 1536 and 1542 which brought an end to the power of the marcher lords and led to greater stability in the area (ibid, p129). At the same time, the dissolution of the monasteries removed the other main monopoly holder on wool production. As such both these fundamental changes brought about by Henry VIII would see the rise in the

prosperity of the squires and smaller landowners over the next century (ibid, p131). Many of the timber-framed buildings in this area have been attributed to this rise in prosperity, especially with regard to the wool trade (Rowley, 1986 p.178).

The West Country was another producer and exporter of woollen cloth to Antwerp (Heard, 1997 p.46), which might also explain the previously noted third minor cluster in the South West which appears to date principally from the 15th and 16th century (Figure 76 & Figure 77)

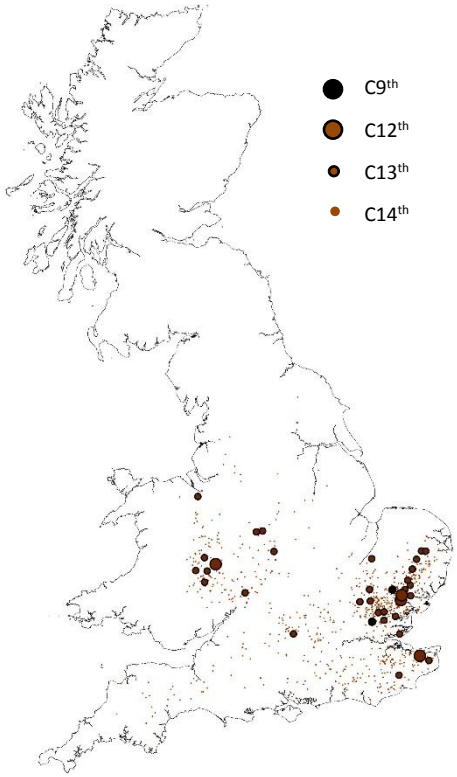

Figure 75 Surviving C9th-C14th timber-framed buildings

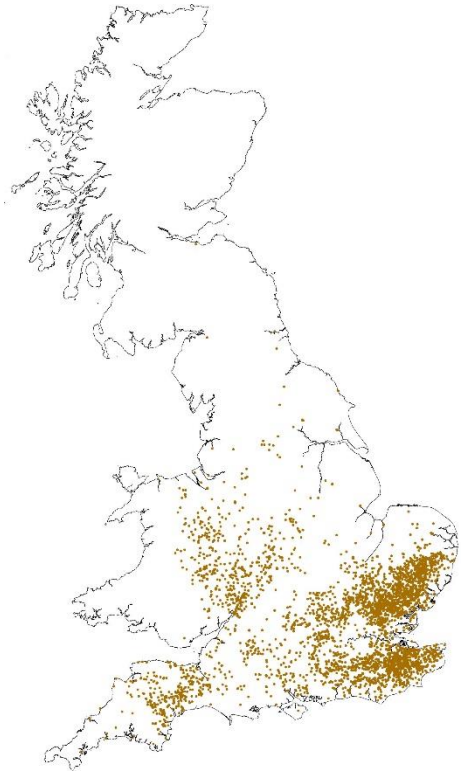

Figure 76 Surviving C15th timber-framed building

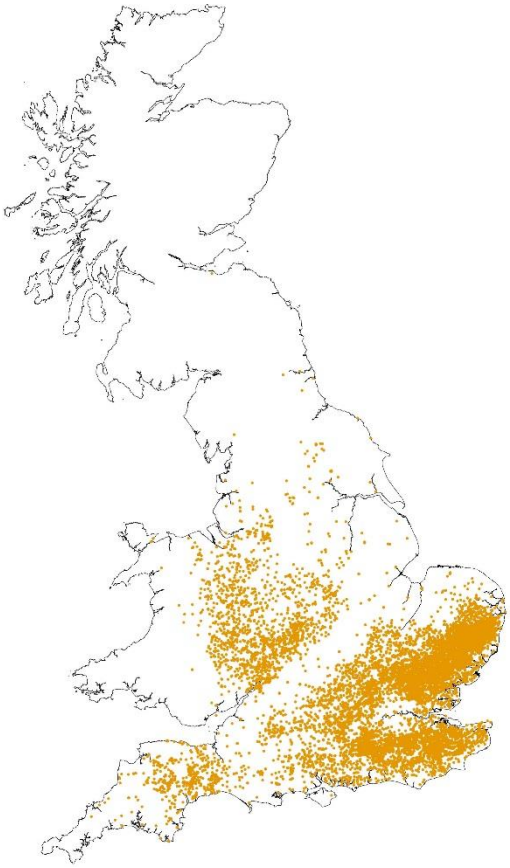

Figure 77 Surviving C16th timber-framed buildings

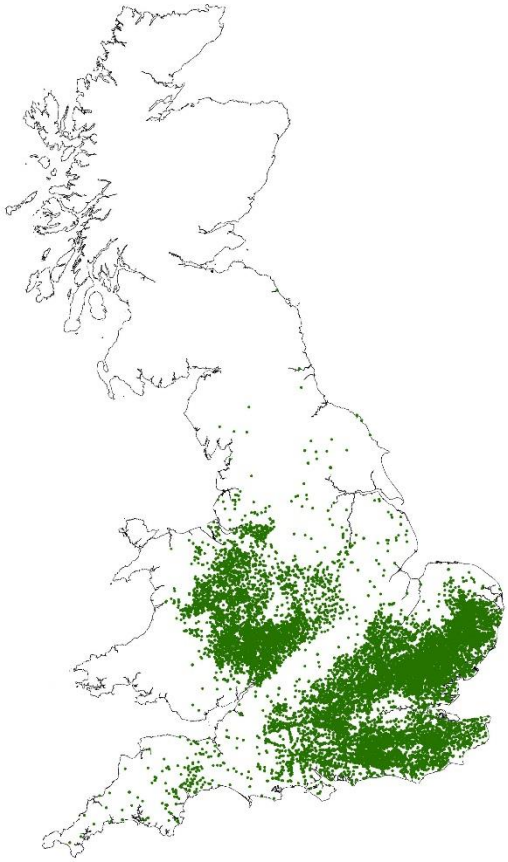

Figure 78 Surviving C17th timber-framed building

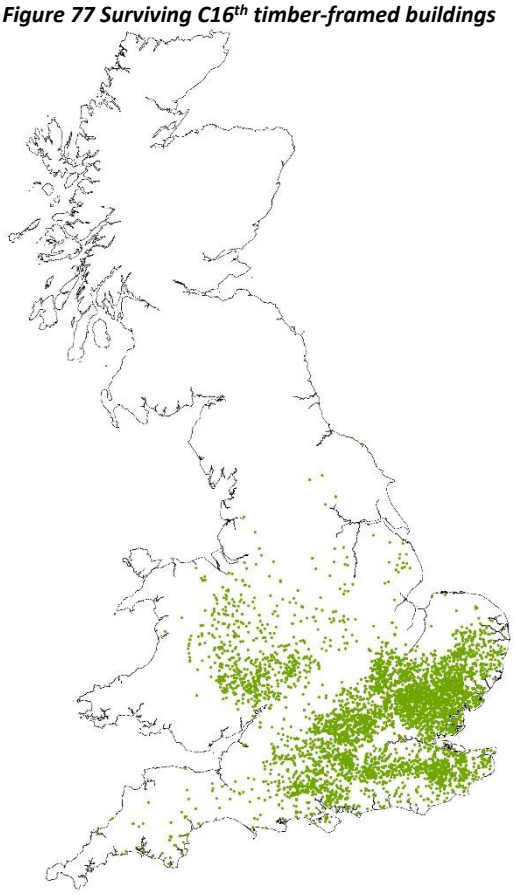

Figure 79 Surviving C18th timber-framed buildings

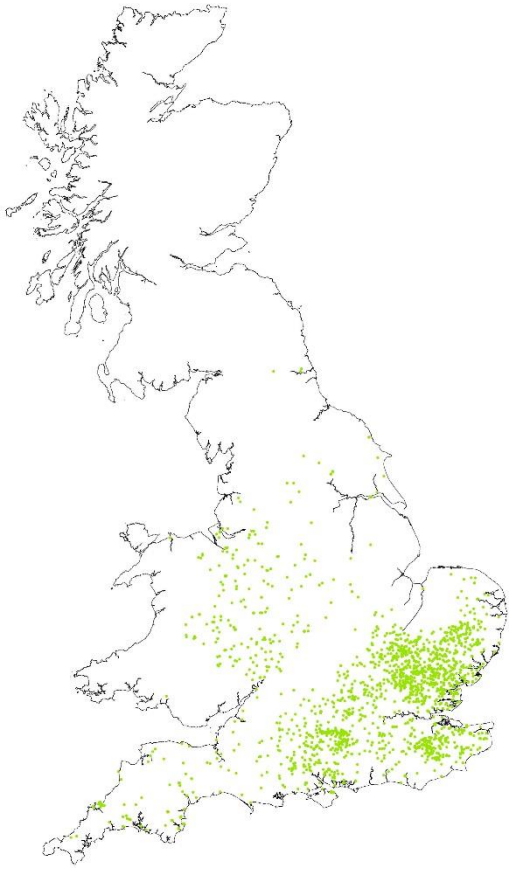

Figure 80 Surviving C19th timber-framed building

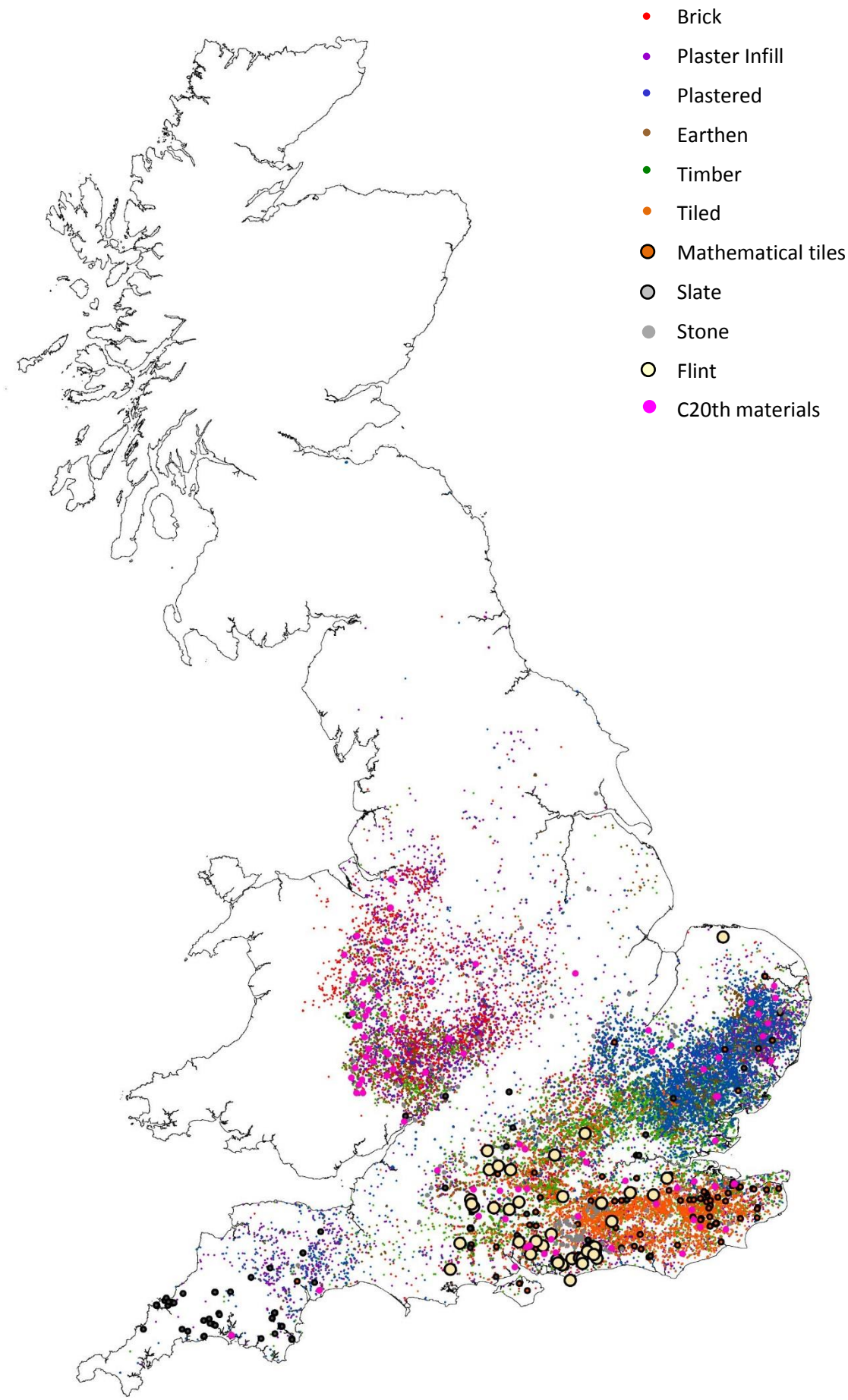

Figure 81 Distribution of timber-framed buildings in Great Britain, classified by panel infill and cladding type. Source: (author's own based on (Historic England, 2014, RCAHMW, 2014))

6.3.3 Distribution by infill material and cladding

Again, with the distribution by panel infill material or over cladding material (Figure 81), the patterns are easier to identify when each of the materials is plotted separately (Figure 82 - Figure 87). These show that whilst some infill materials such as earthen (principally wattle and daub) (Figure 82) and plaster (Figure 83) are fairly evenly spread across the country. When it comes to over cladding, this is far more prevalent in the East of the country. East Anglia shows a higher concentration of surviving buildings that are completely plastered over (Figure 84) and also buildings with timber weatherboarding (Figure 85).

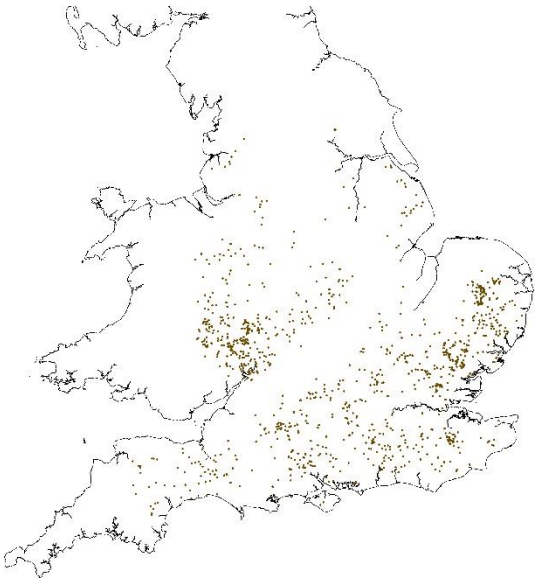

Figure 82 Distribution of earthen infill panels

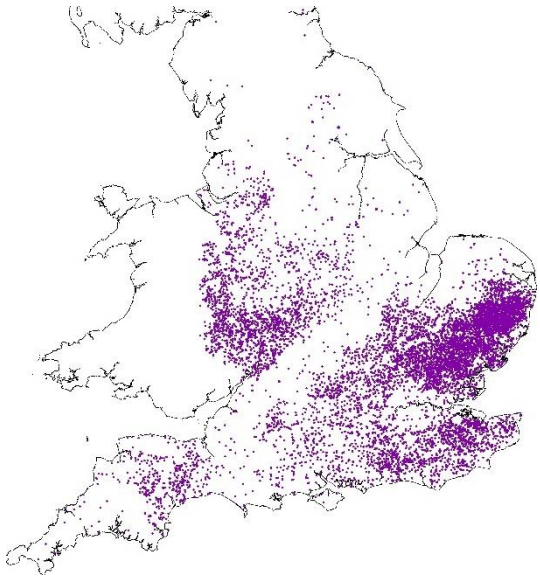

Figure 83 Distribution of plaster infill panels

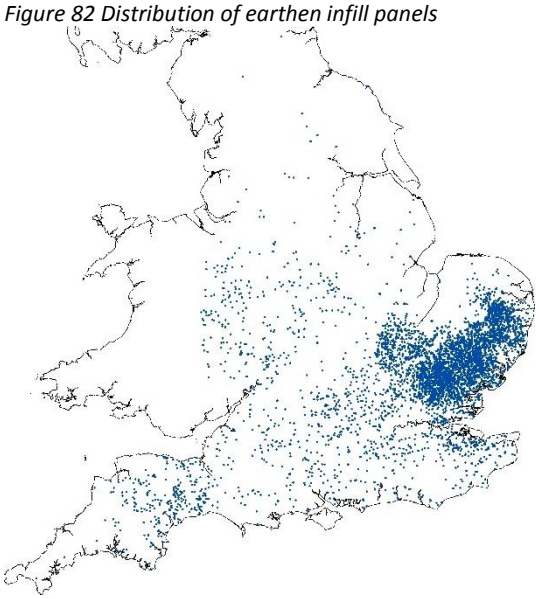

Figure 84 Distribution of plastered over frames

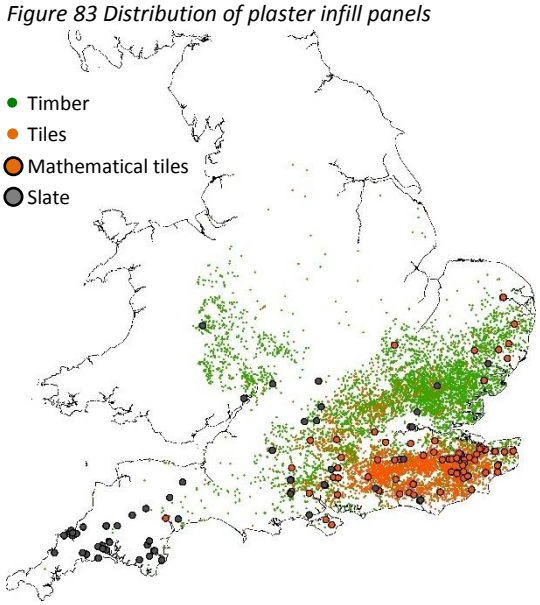

Figure 85 Distribution of plastered over-cladding

Kent and Sussex have the highest concentration of tile-hanging (Figure 85), although mathematical tiles can be found across the Southeast and slate-hanging is concentrated principally in the Southwest. Some of the reasons for these distribution patterns will be explored in more detail when correlations are made between distribution and climatic factors in section 6.4.2.

With masonry panel infill materials, these appear to be concentrated in the centre of the country, both in the West Midland/Welsh Marches and to the West and Southwest of London (Figure 86), with a notable reduction in their use in the East. This may however be coupled with the increased use of continual plastering and over cladding in these areas, thereby hiding brick nogging from the observer. The use of stone as an infill material is uncommon and is spread across the country, although a particular concentration of surviving examples of its use, along with that of flint, can be found just to the north of the South Downs, around the borders of Hampshire, West Sussex and Surrey (Figure 86). The reason for this is unknown and could be an interesting area for further research.

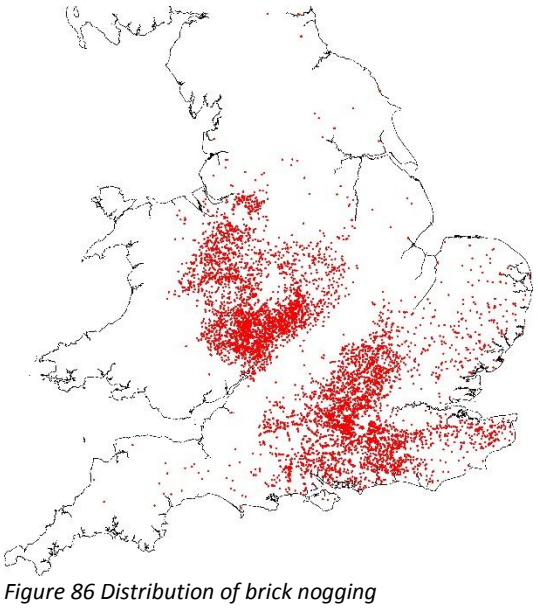

Figure 86 Distribution of brick nogging

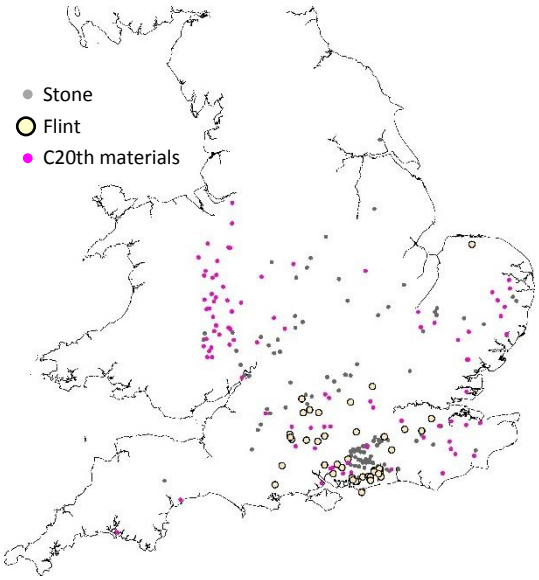

Figure 87 Distribution of stone, flint and C20th infill

6.4 Correlations

To gain greater insight into the previously presented distribution patterns of surviving timber-framed buildings, there follows a series of maps correlating their occurrence with other geographical factors. These begin with physical factors such as geology, topography and historic woodland distribution, before moving on to climatic factors, and conclude with some socio-economic factors both historical and modern. For each of these maps GIS software (ArcGIS) has been used to not only create the maps but also analyse the correlations that occur with them.

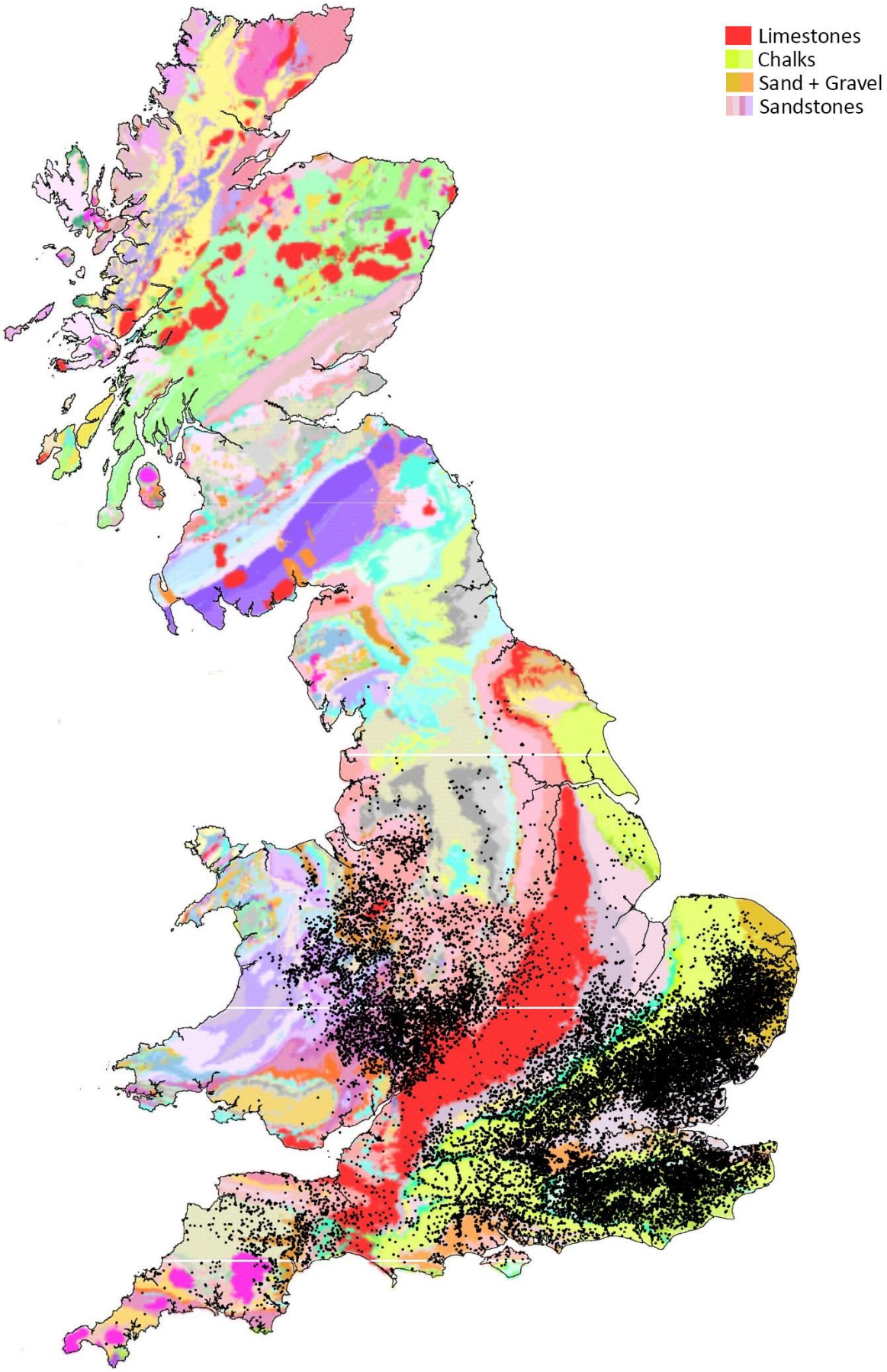

Figure 88 Distribution of timber-framed buildings in Great Britain overlaid on geological bedrock data. Source: (Author's own based on (Historic England, 2014, RCAHMW, 2014, British Geological Survey, 2010))

6.4.1 Physical factors

6.4.1.1 Geology

Figure 88 overlays the distribution of surviving timber-framed buildings on a map of the bedrock of the UK (British Geological Survey, 2010). By doing so, one of the principal reasons for the clear band stretching from the Bristol Channel to The Wash becomes clear. This band, known as the “Limestone Belt”, overlies a strip of lias and oolitic limestone. Detailed GIS analysis shows that only 3.5% of the surviving timber-frame buildings are built over this geological feature. Instead, 39% are built over sedimentary rocks, 29% over clays, sands and gravels, 27% over chalk, with the remaining 1.5% built over igneous rocks other than limestone. This would therefore perhaps suggest that the availability of good quality building stone made the need for timber-framed construction unnecessary. Inversely, as will be seen, the thin soils overlaying the Limestone Belt are not conducive to the growth of great forests, thereby reducing the availability of building timber. It has been acknowledged that the survival of vernacular architecture in Britain is largely confined to those areas where abundant building materials were available (Mason, 1974 p.24) or within a reasonable haulage distance of them. For small dwellings, Mason sets this haulage distance at 5 miles (ibid), although for more prestigious buildings such as Westminster Hall materials could travel far greater distances (Harris, 2010 p.15). With the case of timber-framed buildings, this would suggest that their survival should correspond with the locations of historic woodland.

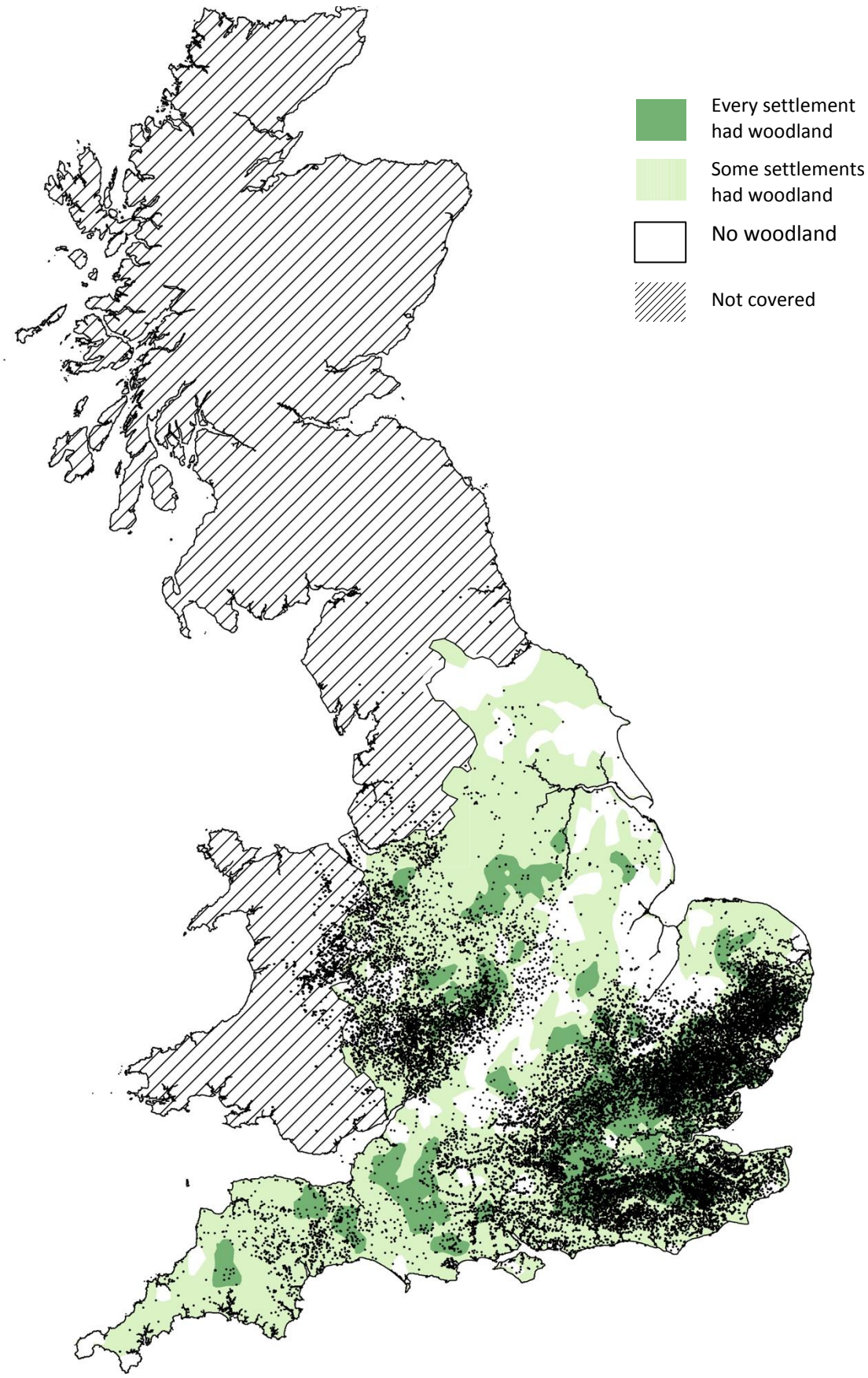

Figure 89 Distribution of timber-framed buildings in Great Britain overlaid on the presence of woodland in the Doomesday Book England in 1086. Source: (Author's own based on (Rackham, 1995 p.76, Historic England, 2014, RCAHMW, 2014)

6.4.1.2 Historic Woodlands

This theory that timber-framed buildings should survive in areas of historic woodland is upheld when the distribution of surviving timber-frame buildings is overlaid with Oliver Rackham's map of the presence of woodland as recorded in the Domesday Book England of 1086 (Rackham, 1995 p.76) (Figure 89 & Figure 90). Figure 90 shows that the highest concentration of areas where all settlements were recorded with woodland is located in the South East. The limestone belt is again a noticeable feature in Figure 90 coinciding with the main area with no woodland recorded. Cross-referencing the data using GIS, we see that 37% of the surviving English timber-framed buildings are located in areas where every settlement was recorded to have woodland, with this figure increasing to 66% when Mason's 5 mile haulage rule (Mason, 1974 p.24) is applied. Conversely, only 9% are located in areas where no woodland was recorded and this figure drops further to 0.5% when the 5-mile haulage rule is applied inversely. It is therefore evident that the presence of abundant good quality timber was a key factor in the location and survival of these buildings. Elsewhere, other building materials would have been favoured and those using timber-frame would have had to pay higher prices for transportation or used the scarce resources available, which may not have survived.

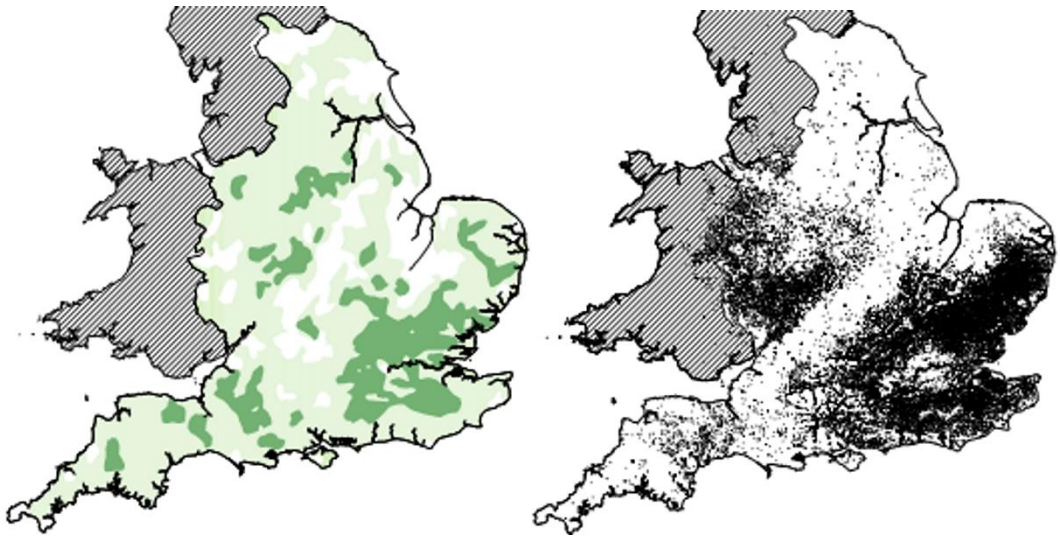

Figure 90 Presence of woodland in the Doomesday Book England in 1086 (left) set alongside the distribution of timber-framed buildings in Great Britain (right). Source: (Author's own based on (Rackham, 1995 p.76, Historic England, 2014, RCAHMW, 2014)

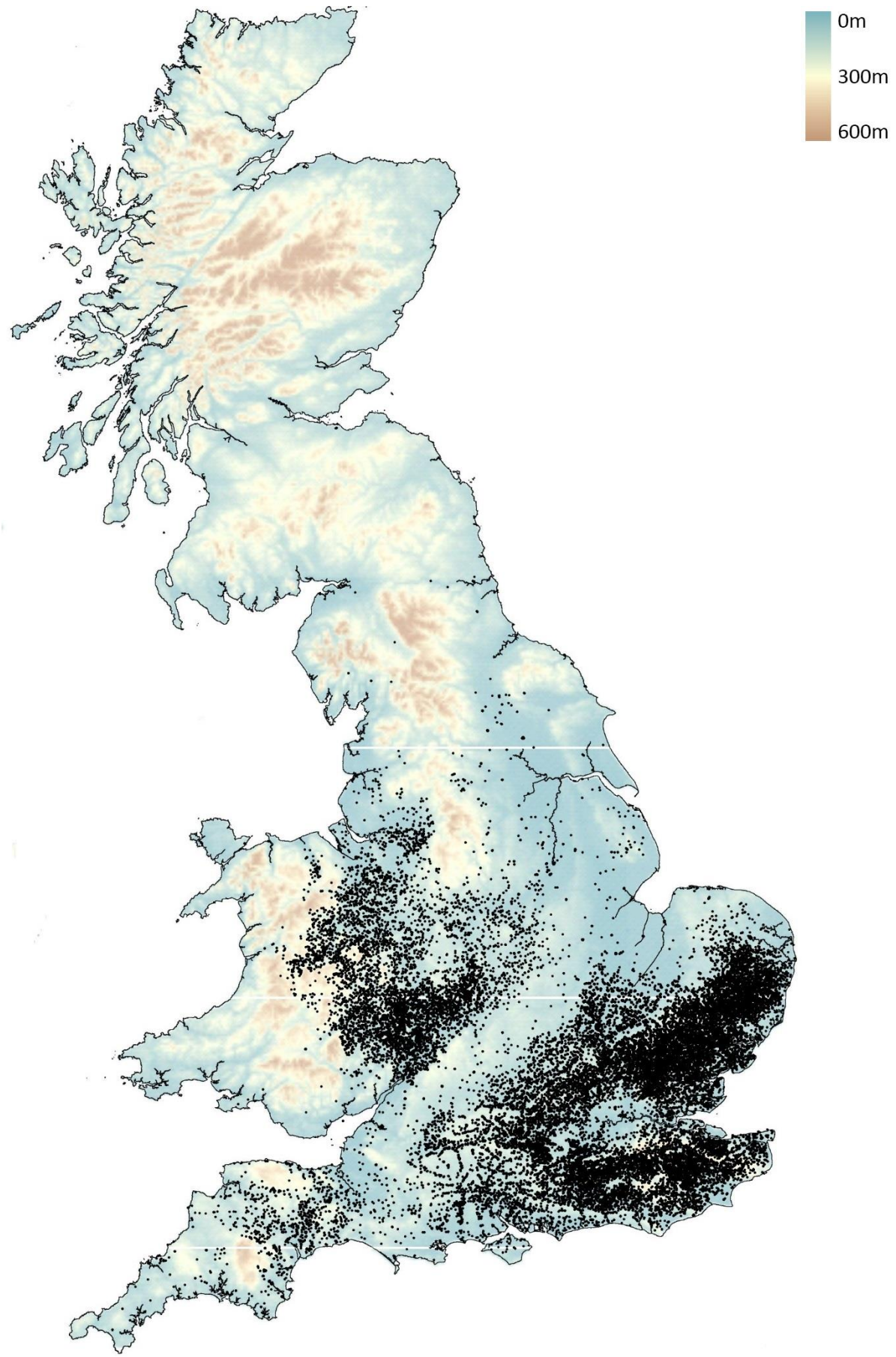

Figure 91 Distribution of timber-framed buildings in Great Britain overlaid on topographic data. Source: (Author's own based on (Jarvis et al., 2008, Historic England, 2014, RCAHMW, 2014)

6.4.1.3 Topography

By overlaying the distribution of the surviving timber-framed buildings on the topography of the UK (Jarvis et al., 2008), it is possible to see that the timber-framed buildings are located primarily in the low-lying areas of the country (Figure 91). The principle areas of high land in the Southeast of England such as the Chiltern Hills and the North and South Downs (Figure 92) are evident in the distribution pattern as clear patches, whilst other landmasses such as the Pennines, Cambrian Mountains and Cotswold Hills form boundaries to the West Midland/Welsh Marches concentration of timber-framed buildings. Dartmoor and Exmoor are also evident in the distribution pattern of the South West.

Figure 92 Principal areas of high land in Southern Britain. Source: (Author's own based on (Jarvis et al., 2008)

When the heights above sea level of each property are plotted, it becomes clearer the range of altitudes where they survive (Figure 93). The mean height above sea level is 68m, with a mode height of 43m. Overall 80% of the surviving buildings are less than 100m above sea level, with 19% between 100m and 200m and only the remaining 1% over 200m.

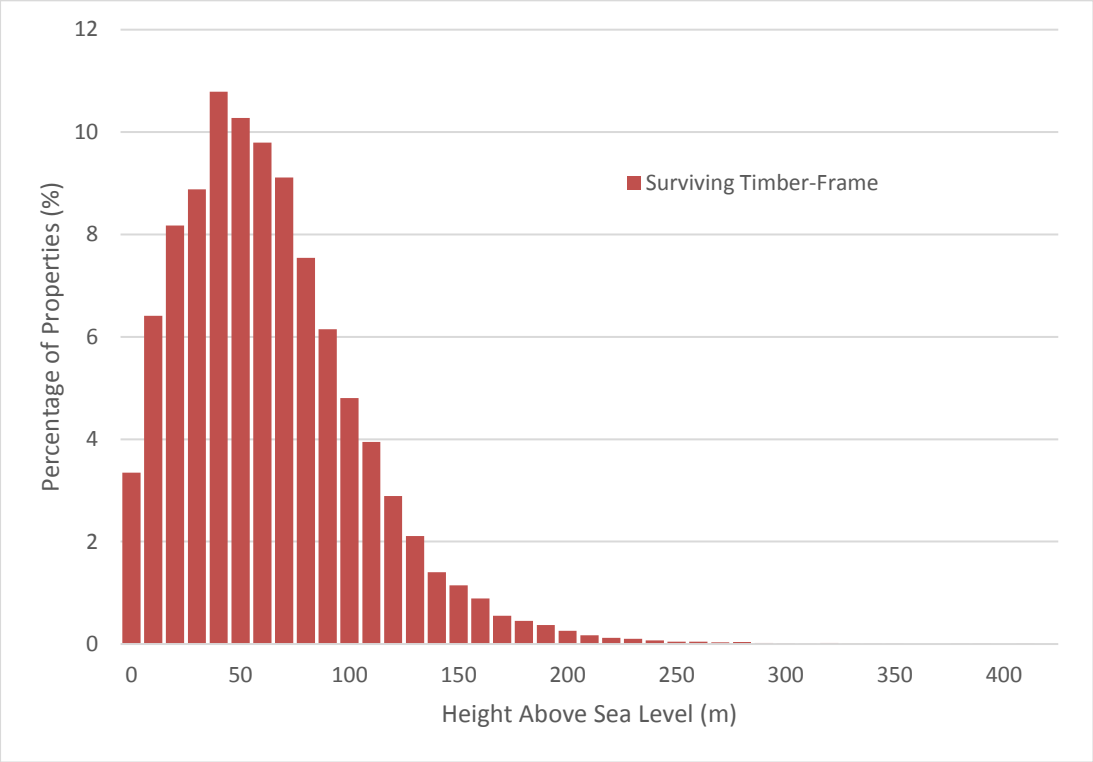

Figure 93 Height of surviving timber-framed properties above sea level. Source: (Author's own based on (Jarvis et al., 2008, Historic England, 2014, RCAHMW, 2014)

This might appear to suggest that timber-framed buildings survive at sites with a lower altitude than average. However, this preference for low altitude building sites may well be common for many settlements in the UK, with the higher more exposed sites not being favoured due to their greater exposure and thinner soils. This is confirmed when the height of the surviving timber-framed buildings is compared to a wider data set such as that for all houses sold in 2016 (Land Registry, 2016) (Figure 94).

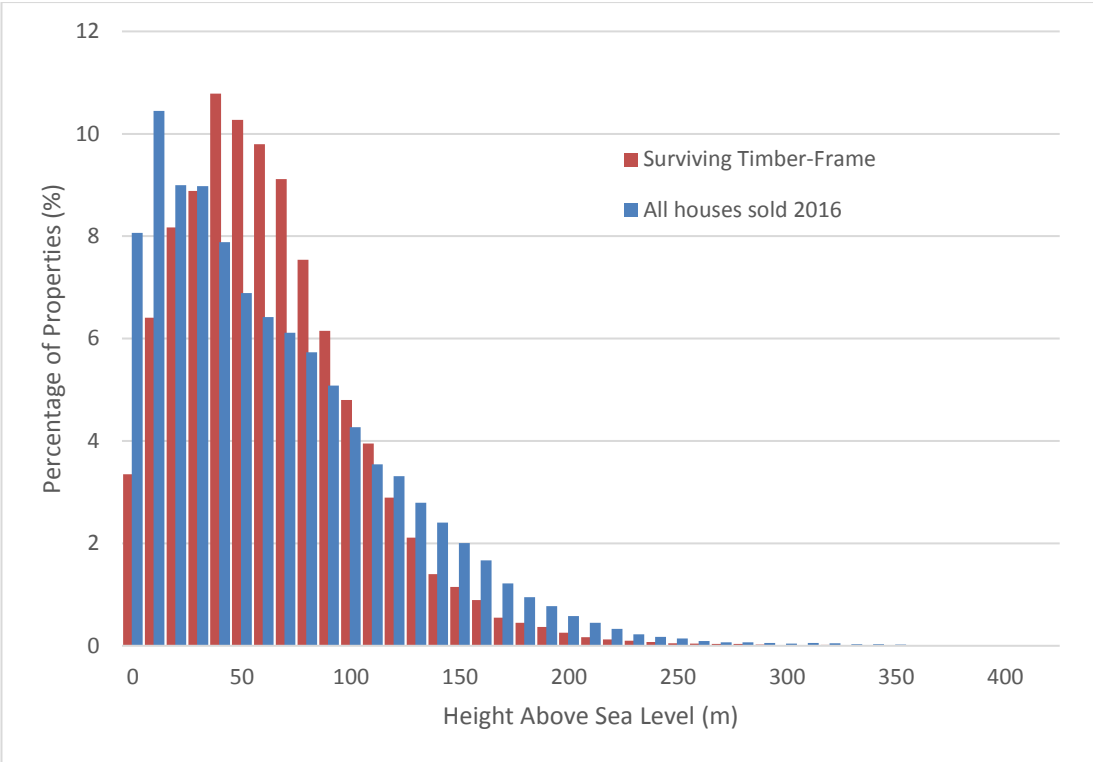

Figure 94 Height of surviving timber-framed properties above sea level, compared to all houses sold in 2016. Source: Source: (Author's own based on (Jarvis et al., 2008, Historic England, 2014, RCAHMW, 2014, Land Registry, 2016)

Figure 94 shows that the average height above sea level for surviving timber-framed buildings is in fact higher than the national average (based on homes sold in 2016), where the mean height is 70m but the mode height is just 7m. This would therefore perhaps suggest that timber-framed buildings have not survived, or were not built, on the very lowest altitudes that have higher ground humidity levels and may have been prone to flooding. The preferred sites may have been those of a slightly raised elevation, providing improved drainage and security. Above 100m the added height appears to cease to be an advantage, with decidedly less timber-framed buildings than the national average (20% versus 25%). This tendency for timber-framed buildings to be at mid altitudes suggests that this construction technique is not well suited to more exposed locations. This will be explored further with the study of the correlation between their distribution and climatic factors, many of which are also a direct result of the topography.

6.4.2 Climatic Factors

The following comparative distribution maps overlay the previously presented distribution of historic timber-framed buildings with gridded climatic data from the UK Met Office. The gridded data set covers the UK at a resolution of 5 x 5km (25 x 25km for humidity) and presents long-term annual averages of the period 1961-1990 (Met. Office, 2009)[40]. The climatic factors that have been studied here are those specifically related to hygrothermal conditions, that is to say those related to moisture and temperature. For moisture, four variables were studied, these were; Annual Average Relative humidity[41] (%) (Figure 95); Greatest 5-day precipitation total (mm) (Figure 97), that being the greatest total precipitation that occurred over five consecutive days during the year (ibid); Precipitation Intensity (mm/day) (Figure 99) this being calculated by dividing the total precipitation on days with ≥1 mm by the total number of days with ≥1 mm during the year (ibid); and Maximum number of consecutive dry days (days) (Figure 102) calculated as the average longest spell of consecutive days with precipitation ≤0.2 mm during the year (ibid). In addition, the risk of driving rain was plotted according to BS 8104:1992, Code of practice for assessing exposure of walls to wind-driven rain (British Standards Institution, 1992), as published in in the English Building Regulations Part C (HM Government, 2013 p.34).

For temperature, the metric used was the average annual number of Heating Degree Days (Figure 105) calculated as the day-by-day sum (over the period of one year) of the mean number of degrees by which the air temperature is less than a threshold value of 15.5 °C (ibid).

[40] Access to this data is restricted and permission for academic use was granted to the author on 18th January 2016

[41] The amount of water vapour present in air expressed as a percentage of the amount needed for saturation at the same temperature (Soanes and Stevenson, 2005).

An area for future research not covered by this thesis would be to complete the same exercise using climate change projection data. This would begin to identify the number and location of timber-framed buildings potentially at risk from this phenomenon.

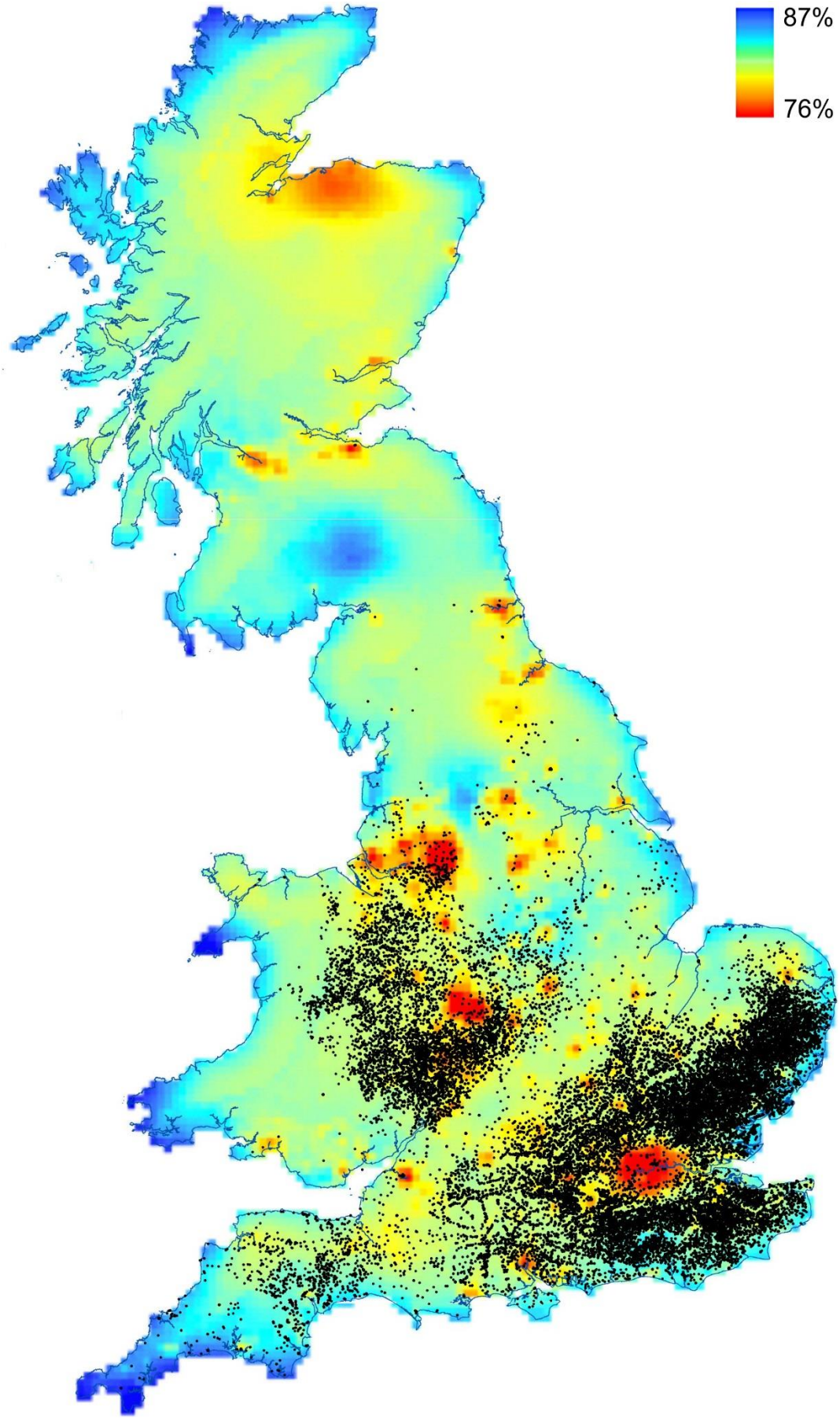

Figure 95 Distribution of surviving timber-framed buildings in Great Britain, overlaid on average annual relative Humidity. Source: (Author's own based on (Met. Office, 2009, Historic England, 2014, RCAHMW, 2014))

6.4.2.1 Average Annual Relative Humidity

Figure 95 shows that although not located in the very driest areas, which relate to cities, the surviving timber-frame buildings tend to occupy site with a relative humidity around or just below the mid-range of those seen across the UK. Detailed analysis shows this to be the case with the mean relative humidity for locations with surviving timber-frame buildings being 81%, 1% below the UK mean average, with very few of these buildings occurring in higher relative humilities (Figure 96).

The coastal areas with their high relative humidity show a distinct lack of surviving timber-framed buildings, as do the extreme west and north of the country. Given the role of high humidity in the degradation of timber through insect infestation and fungal decay, the scarcity of timber-framed buildings in areas of high relative humidity indicates either that they have not survived or that this construction technique was uncommon due to the high risk of biological attack.

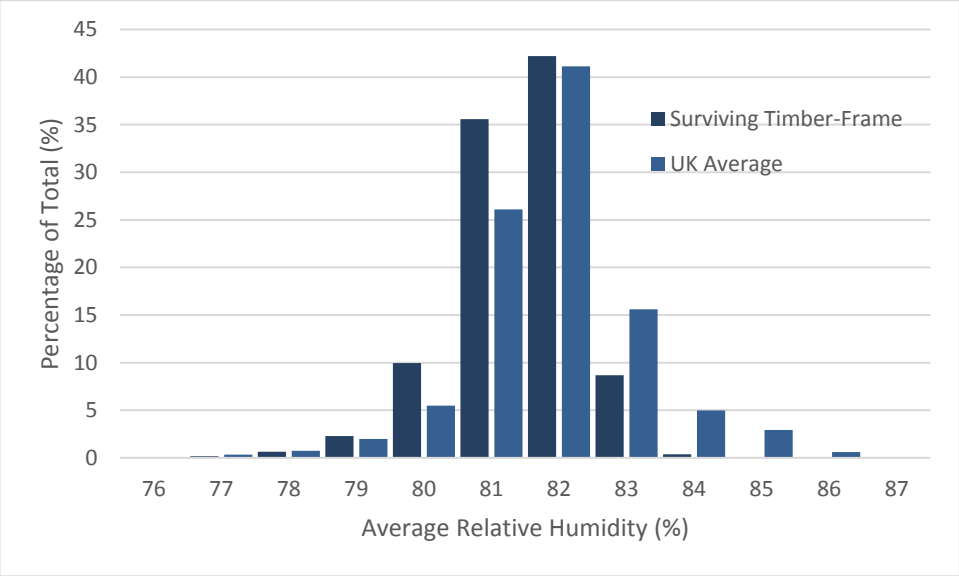

Figure 96 Percentage of surviving timber-framed buildings according to average annual relative humidity, compared to UK average. Source: (Author's own based on (Met. Office, 2009, Historic England, 2014, RCAHMW, 2014))

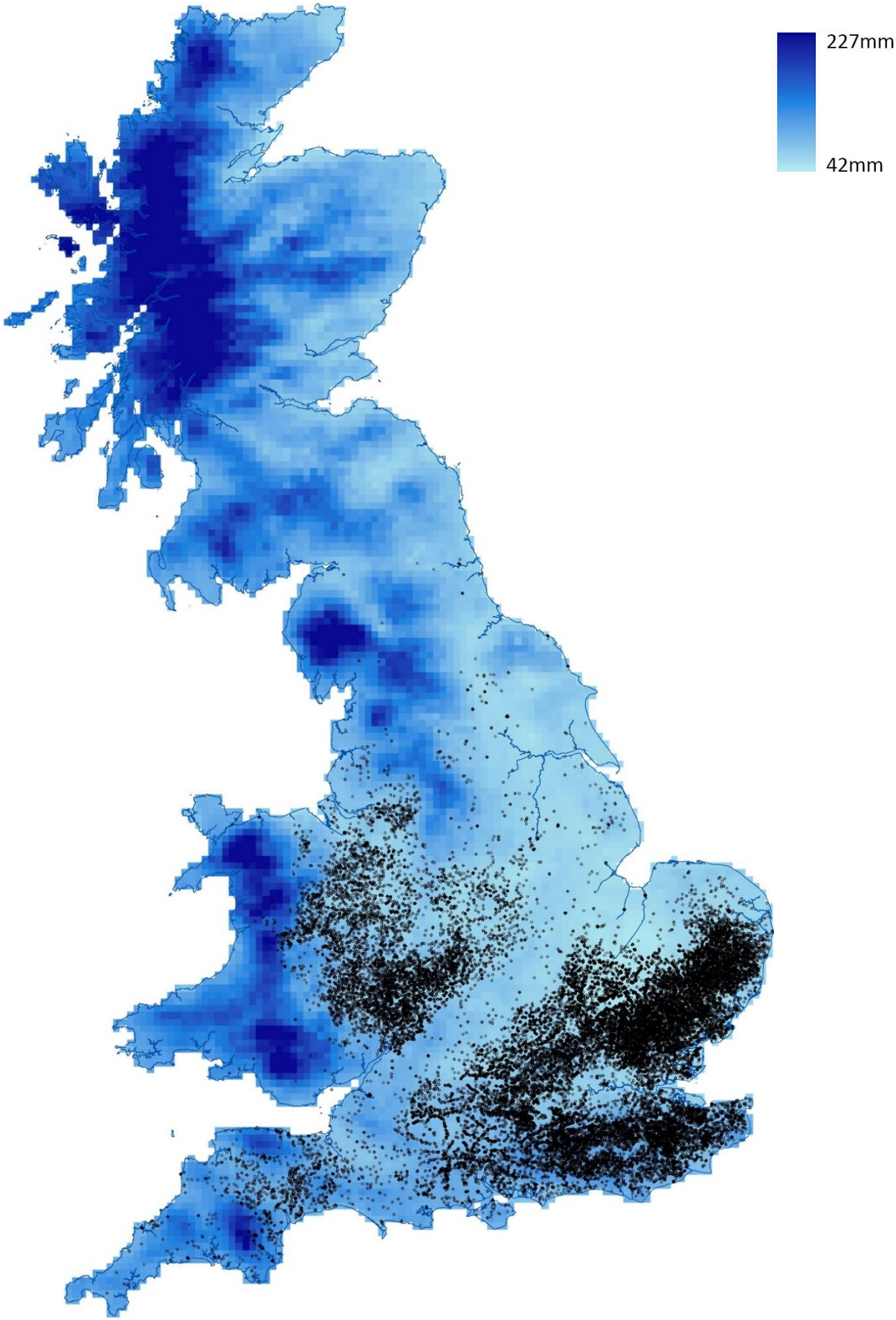

Figure 97 Distribution of surviving timber-framed buildings in Great Britain, overlaid on greatest precipitation in five consecutive days. Source: (Author's own based on (Met. Office, 2009, Historic England, 2014, RCAHMW, 2014))

6.4.2.2 Rainfall

6.4.2.2.1 Greatest 5-day precipitation total

Just as with high relative humidity, areas with high levels of precipitation will lead to increased moisture levels within exposed building timbers, thereby increasing the risk from biological agents. The absence of surviving timber-framed buildings in the west and north of the UK is made all the more evident when the distribution pattern is overlaid on the data for the greatest 5-day precipitation total (Figure 97) and that for precipitation intensity (Figure 99). Here the areas of increased rainfall created by the high lands of the Cambrian Mountains and the Pennines, and the masses of Dartmoor and Exmoor, clearly bracket and constrain the concentrations of surviving timber-framed buildings in the West Midlands/Welsh Marches, and the Southwest. The buildings come up to the eastern foothills in Wales but do not cross to the west coast. It is known that there are cruck buildings of principally timber-frame construction present in West Wales (Alcock, 2002); however, these are all encased in an external envelope of stone walling, thereby protecting the timber from the rain.

Detailed analysis (Figure 98) shows that the vast majority of surviving timber-framed buildings are located in sites with a greatest 5-day precipitation total of no more than 60mm.

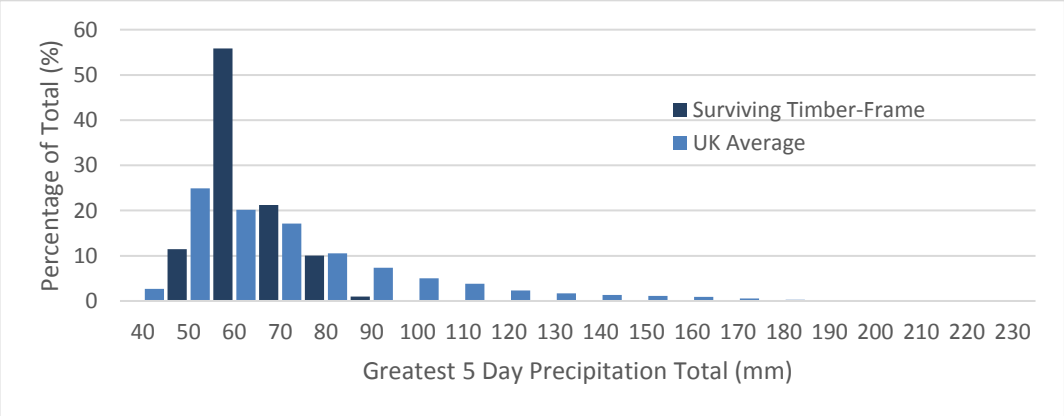

Figure 98. Percentage of surviving timber-framed buildings according to greatest 5-day precipitation total compared to UK average. Source: (Author's own based on (Met. Office, 2009, Historic England, 2014, RCAHMW, 2014))

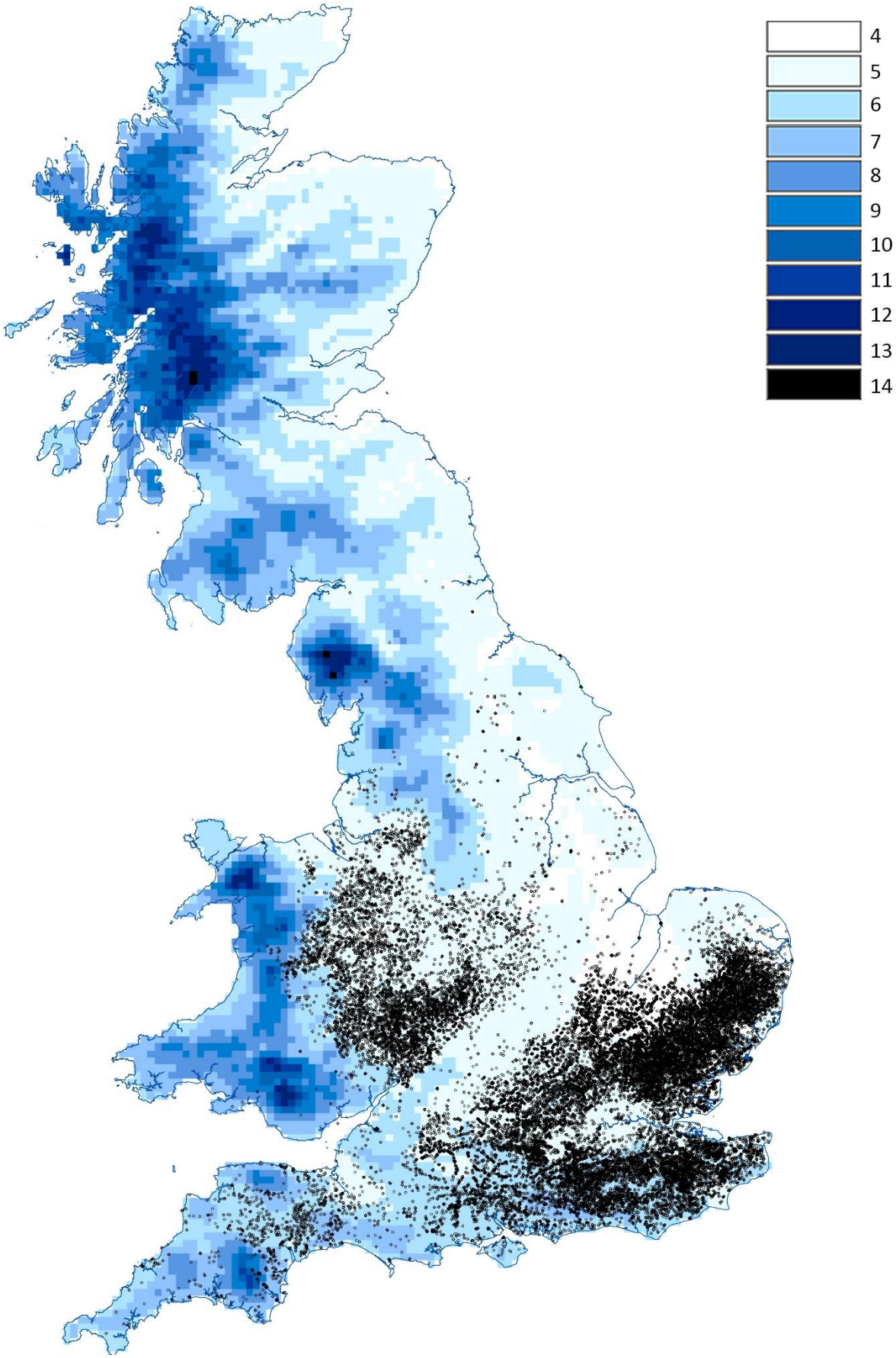

Figure 99 Distribution of surviving timber-framed buildings in Great Britain, overlaid on precipitation intensity data. Source: (Author's own based on (Met. Office, 2009, Historic England, 2014, RCAHMW, 2014))

6.4.2.2.2 Precipitation intensity

The observations made regarding the greatest 5-day precipitation data are reinforced by that for precipitation intensity (Figure 99 and Figure 100).

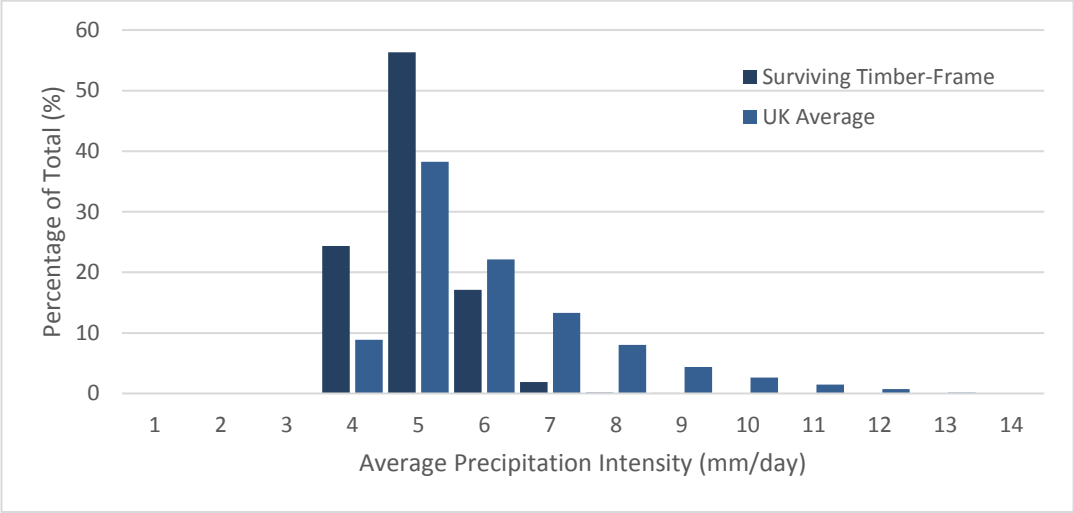

Figure 100 Percentage of surviving timber-framed buildings according to average precipitation intensity compared to UK average. Source: (Author's own based on (Met. Office, 2009, Historic England, 2014, RCAHMW, 2014))

In addition, the distribution map (Figure 99) highlights some areas of higher precipitation where surviving timber-frame buildings do exist, these being the Southwest and more notably the Southeast counties of Kent and Sussex (Figure 101). It is therefore interesting to note that this is the precise area previously identified, where tile-hanging (Kent and Sussex) and slate-hanging (Southwest) are the most popular (Figure 85). Both of these overcladding techniques are ways of providing additional protection to the timbers and were most probably developed due to the increased rainfall in these locations.

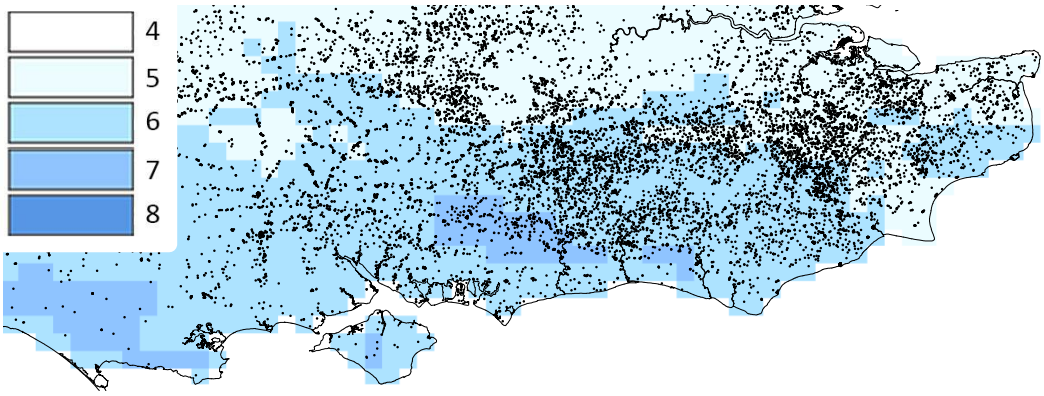

Figure 101 Distribution of surviving timber-framed buildings in Kent and Sussex, overlaid on precipitation intensity data. Source: (Author's own based on (Met. Office, 2009, Historic England, 2014, RCAHMW, 2014))

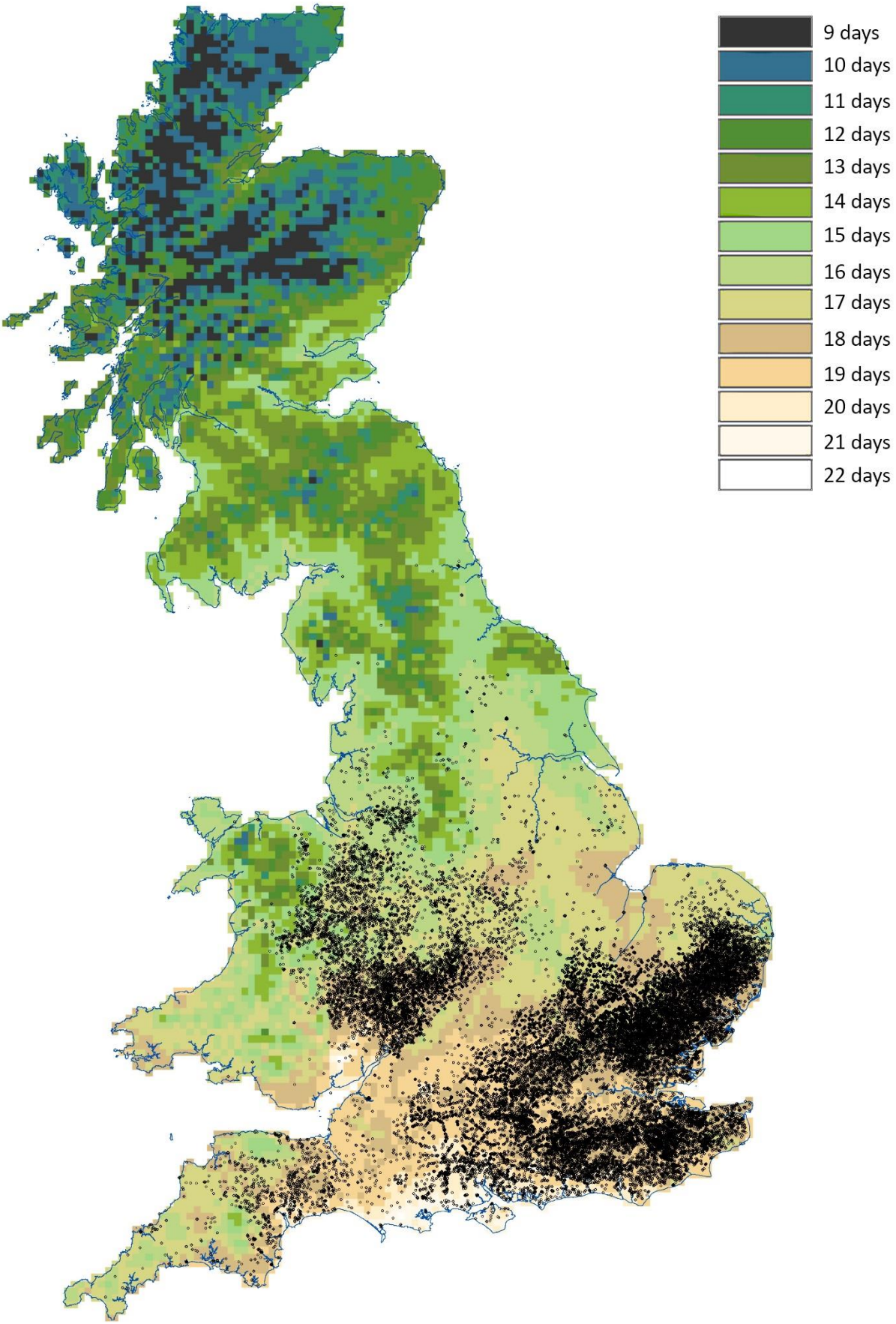

Figure 102 Distribution of surviving timber-framed buildings in Great Britain overlaid on data presenting average number of consecutive dry days. Source: (Author's own based on (Met. Office, 2009, Historic England, 2014, RCAHMW, 2014))

6.4.2.2.3 Maximum number of consecutive dry days

The map of the average number of consecutive dry days (Figure 102) again corroborates that already discussed with regard to precipitation, however it does also show that the areas of higher precipitation just discussed, in particular the Southeast, do have some of the longest spells of dry days in the country with up to 22 consecutive days without rain. Therefore, even those buildings in these areas without tile-hanging would have long periods, between 19-20 days for the timbers to dry out, unlike areas in the mountains of Wales, the Northwest of England and Scotland where there is less than half this period.

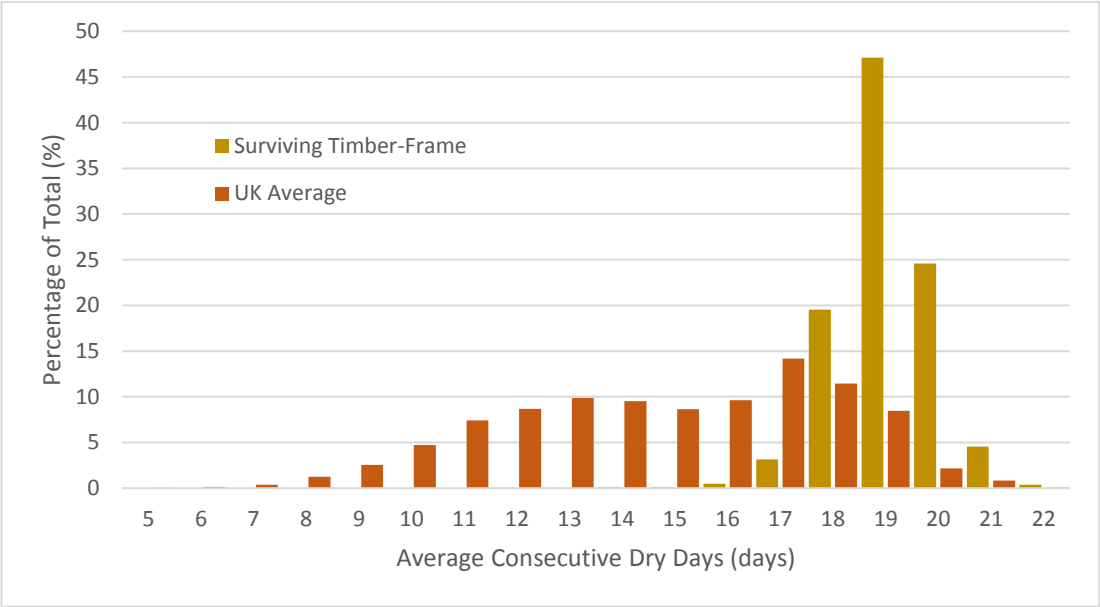

Figure 103 Percentage of surviving timber-framed buildings according to average number of consecutive dry days compared to UK average. Source: (Author's own based on (Met. Office, 2009, Historic England, 2014, RCAHMW, 2014))

Detailed analysis (Figure 103) confirms that the surviving timber-framed buildings only exist in those areas with the most number of consecutive dry days in the UK, with an average (mean) of 18 days and mode of 19 days compared to a national mean of 15 and mode of 17 days.

Overall the climatic data for moisture, both relative humidity and precipitation, shows a clear finding that timber-frame buildings have survived principally in the driest areas of the UK.

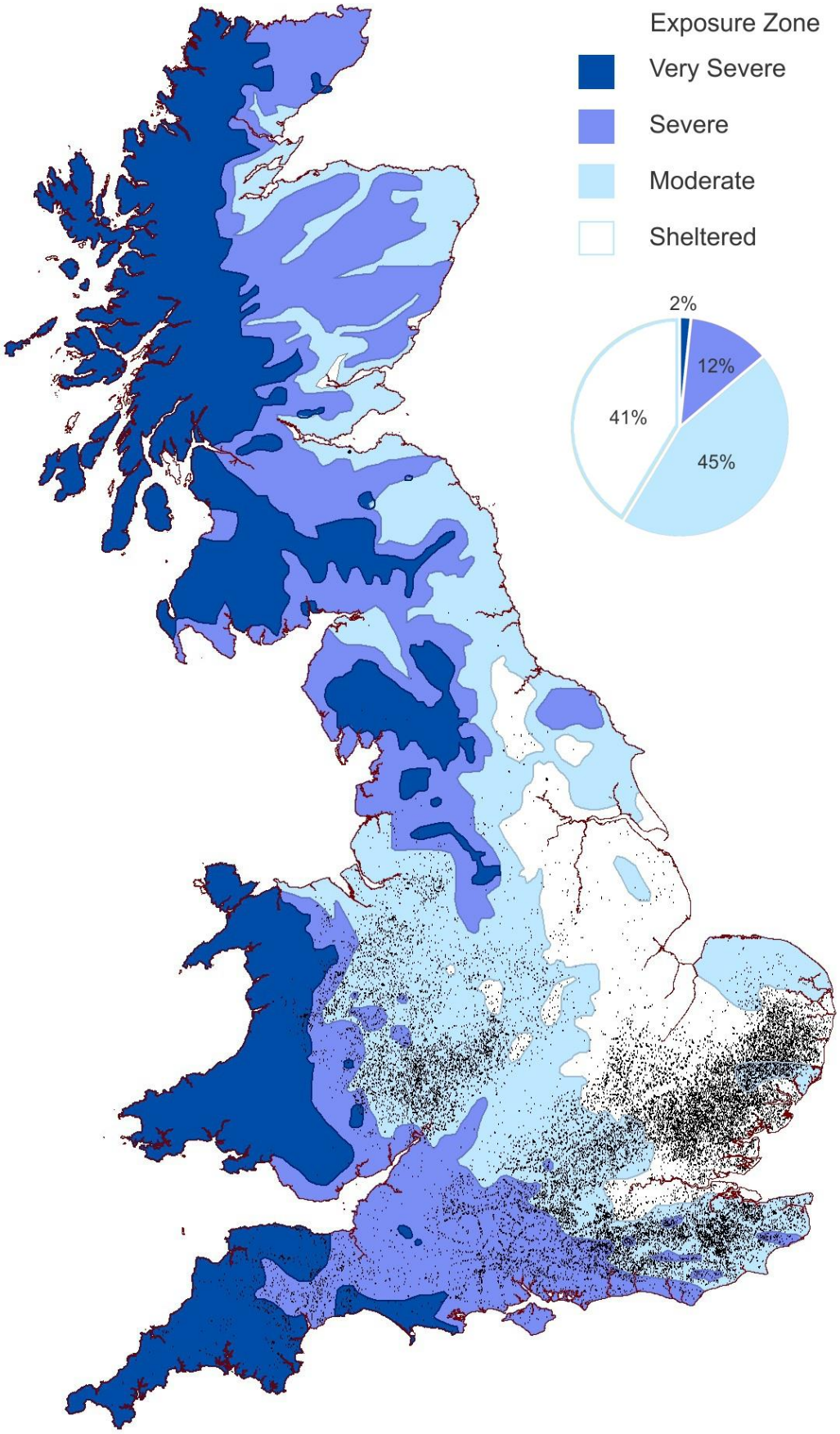

Figure 104. Distribution of surviving timber-framed buildings in Great Britain overlaid on data presenting risk of wind driven rain according to BS 8104:1992. Inset, percentage of surviving timber-framed buildings in each exposure zone. Source: (Author's own based on (HM Government, 2013 p.34)

6.4.2.2.4 Risk of Wind Driven Rain

The risk of wind driven rain (Figure 104) presents a similar picture to that which has been seen previously for precipitation (Figure 97 to Figure 101), with 86% of all surviving timber-framed buildings being located in sheltered areas and areas of moderate risk of wind driven rain. Only 2% of surviving timber-framed buildings are located in areas of very severe risk and 12% in areas of severe risk. Again, the northern and westerly borders of the distribution pattern are clearly defined by the areas of very severe and severe exposure zones; however, those surviving buildings in the Southwest of England and across central Southern England, including Salisbury Plain, are located within the area of severe risk. As with precipitation intensity (Figure 101), this area of severe risk extends in patches across Sussex and Kent, adding further validation to the previously mentioned theory that tile hanging developed specifically to counteract this increased exposure to precipitation. Within those areas of severe risk from wind driven rain in Sussex and Kent, just over one third (34%) of the buildings are tile hung with a further 12% achieving similar protection through the use of weatherboarding.

In the north of East Anglia, the area of moderate risk from wind driven rain correlates closely with the area of reduced density of surviving timber-framed buildings, however, a finger of moderate risk extending from the coast, well into mid Suffolk, appears to have notable effect on neither the distribution pattern nor the infill material or use of over cladding. A total of 2,233 surviving timber-framed buildings are located within this particular area, with an equal density as seen across the rest of East Anglia. It can only be assumed that this is due to the risk being only moderate and it being outweighed by other climatic factors.

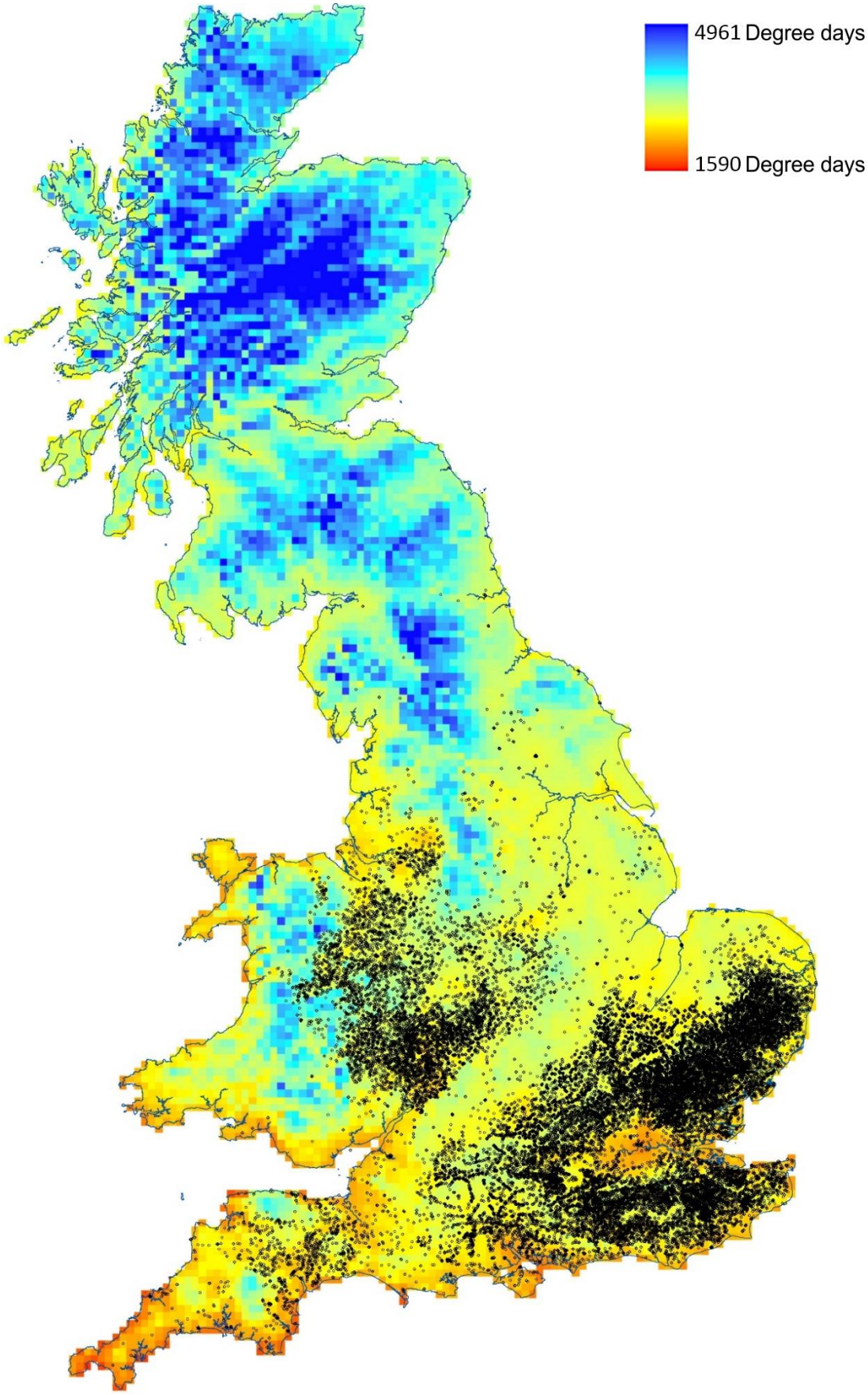

Figure 105. Distribution of surviving timber-framed buildings in Great Britain overlaid on data presenting average annual heating degree-days. Source: (Author's own based on (Met. Office, 2009, Historic England, 2014, RCAHMW, 2014))

6.4.2.3 Temperature

6.4.2.3.1 Heating degree days

A very similar story is seen with regard to the distribution of surviving timber-framed buildings and their correlation to temperature (Figure 105 and Figure 106). The vast majority of surviving timber-framed buildings are located in areas with relatively low number of heating degree days, that is to say warmer temperatures, with an average (mean and mode) of 2400 heating degree days, compared to the national average (mean) of 2700. However, the very warmest areas, those areas with the least number of degree days, appear not to be particularly conducive to timber-frame buildings' survival. These areas occur around the coast and in urban centres, where the high humidity and rapid redevelopment, respectively appear to take precedent over the warmer climate as drivers for change or replacement.

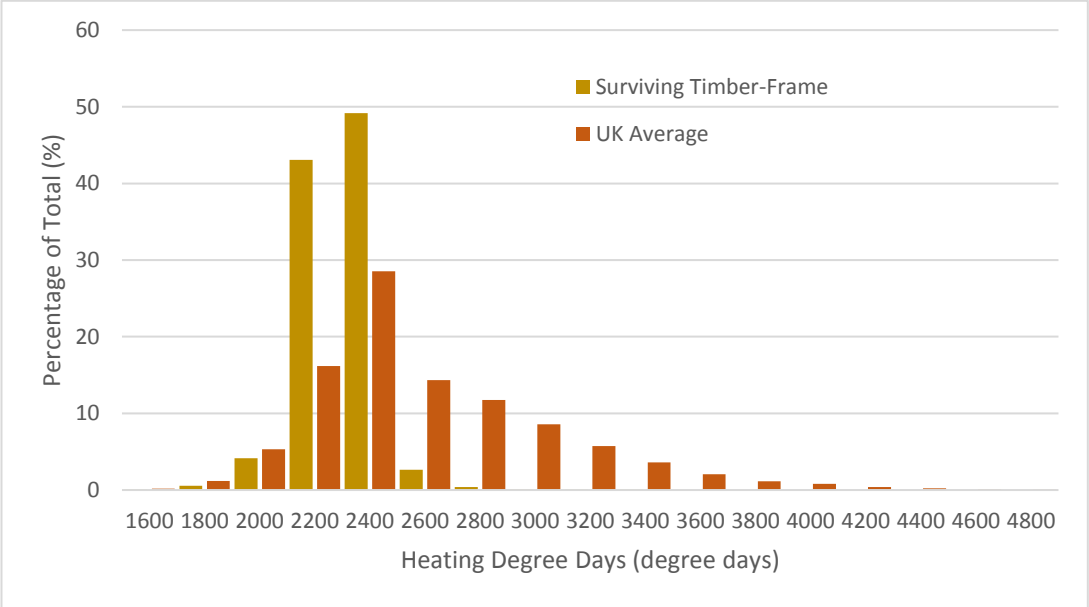

Figure 106. Percentage of surviving timber-framed buildings according to average heating degree days compared to UK average. Source: (Author's own based on (Met. Office, 2009, Historic England, 2014, RCAHMW, 2014))

The location of the surviving timber-frame buildings in the warmer parts of the country perhaps suggests a historic recognition of their poor thermal performance. At the same time, whilst retrofit is still required to attempt to improve hygrothermal comfort, the challenge is not as great as had they been located in colder climates.

6.4.2.4 Summary

It would therefore appear that the largest set of climatic factors affecting the siting and survival of timber-framed buildings are those related to moisture, namely relative humidity and precipitation. It can be assumed that in more humid locations, with higher levels of precipitation, the timbers of the framing would be at a greater risk from fungal decay. As climate change begins to affect the patterns of precipitation, temperature and humidity, the hygrothermal conditions that have existed and allowed the survival of these buildings may be irreversibly altered, thereby putting their future in question. It would therefore be an interesting area of future research to undertake the same study presented here but with climate change projection data such as the UKCP09 gridded data sets produced by the Met Office for the Environment Agency (Met. Office, 2009). This would allow the study of those areas where the predicted future climate could be detrimental to the survival of timber-framed buildings.

6.4.3 Economic Factors

There follows a review of some economic factors, both historic and current, and their relationship to the distribution of surviving timber-framed buildings.

6.4.3.1 Historic Economic Factors

The influence of wealth from the wool trade has already been presented as a factor in the patterns seen in the ages of the surviving timber-framed buildings. Figure 107 shows the other principal industries at the beginning of the 17th century (Heard, 1997 p.49), although it should be noted that agriculture is not included, for which the Welsh Marches were renowned (Rowley, 1986 p.178). Although the degree of accuracy of the map prohibits any detailed comparison analysis, a general correlation between those areas noted with principal industry and the distribution pattern of surviving timber-framed buildings can be seen.

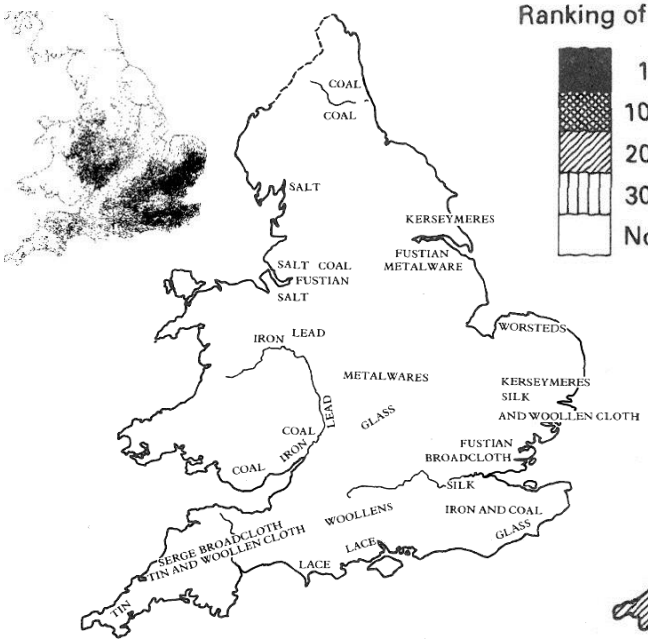

Figure 107 Principal industries circa 1600. Source: (Heard, 1997 p.49). Inset surviving timber-frame

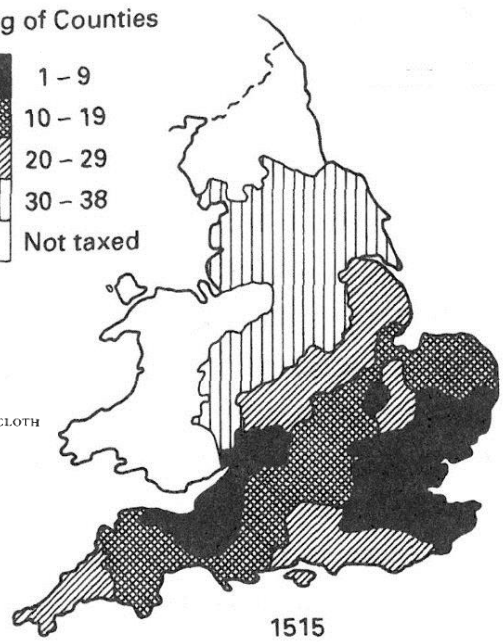

Figure 108. Distribution of wealth according to tax collected 1515. Source: (Dyer, 2009 p.359)

This hypothesis is further supported, at least for the Southeast of England, by Figure 108 which shows the distribution of wealth, based on the taxes collected, in 1515 (Dyer, 2009

p.359). Here the concentration of wealth around the Thames Estuary is clear, as is a second concentration at the head of the Bristol Channel, spreading down along its southern shore. The northern sector of this second concentration of wealth corresponds well to the surviving timber-frame distribution pattern, whilst the lack of surviving timber-framed to the south of the Bristol Channel is easily explained by the presence of the Limestone Belt as previously discussed. It should be noted that this map represents the situation prior to the Welsh Acts and the dissolution of the monasteries and as such does not show any concentration of wealth in the northern Welsh Marches.

The Limestone Belt was again influential in the economic development of the country as we move forward in time and come to the Parliamentary Enclosure Acts.

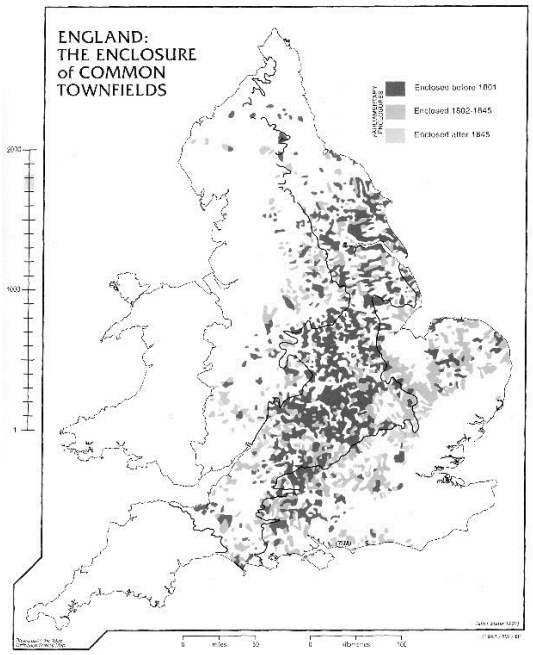

Figure 109. Map showing lands enclosed by parliamentary enclosure acts. Source: (Roberts and Wrathmell, 2002 p.61)

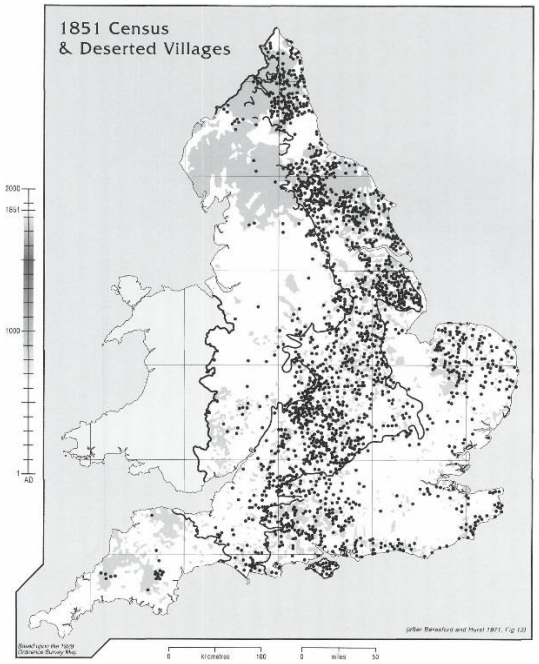

Figure 110. Map showing location of deserted village. Source: (Roberts and Wrathmell, 2002 p.50)

The thinner soils across the limestone belt led to the absence of historic woodlands, as we have seen. The lands were therefore developed as open fields, communally cultivated and common lands for grazing in what William Harrison described in 1587 as “champaign

grounde" (Harrison, 1968 p.196), as opposed to "woodland" where fields were smaller, surrounded by hedgerow trees and interspersed with woodland, as the name suggests. This difference in structure affected not only the agriculture but also the manner of inhabiting the land. As Rackham notes, the former is a landscape of big villages and few busy roads, whilst the latter is that of hamlets and scattered farms (Rackham, 1995 p.4-5). This differentiation would have been further increased by first the enclosure acts of the 17th and 18th century and later the industrial revolution as people moved off the land, first into villages, and later into towns and cities. Figure 110 shows the distribution of deserted villages recorded in 1963 by Beresford and Hurst (Roberts and Wrathmell, 2002 p.49-50). Many of these villages may have contained timber-framed buildings, yet as has been explored previously in this chapter, the lack of substantial quality construction timber in this central area would have greatly affected the quality of construction and as such the survival of any abandoned building. Equally, as populations moved to the nucleated settlements of larger villages, towns and cities, the pressures for redevelopment, not present in hamlets and isolated dwellings, would have lead over time to the replacement of historic timber-framed buildings. The survival of timber-framed buildings is therefore more prevalent in areas of dispersed occupation in those areas Rackham refers to as "ancient" as opposed to "planned" countryside (Rackham, 1995 p.3-5)

6.4.3.2 Modern Economic Factors

The following maps correlate the distribution of surviving timber-framed buildings with modern economic factors such as house prices and indices of multiple deprivation. The data for Scotland is not included due to the economic data being produced separately from that for England and Wales and there only being three surviving timber-framed buildings in the country.

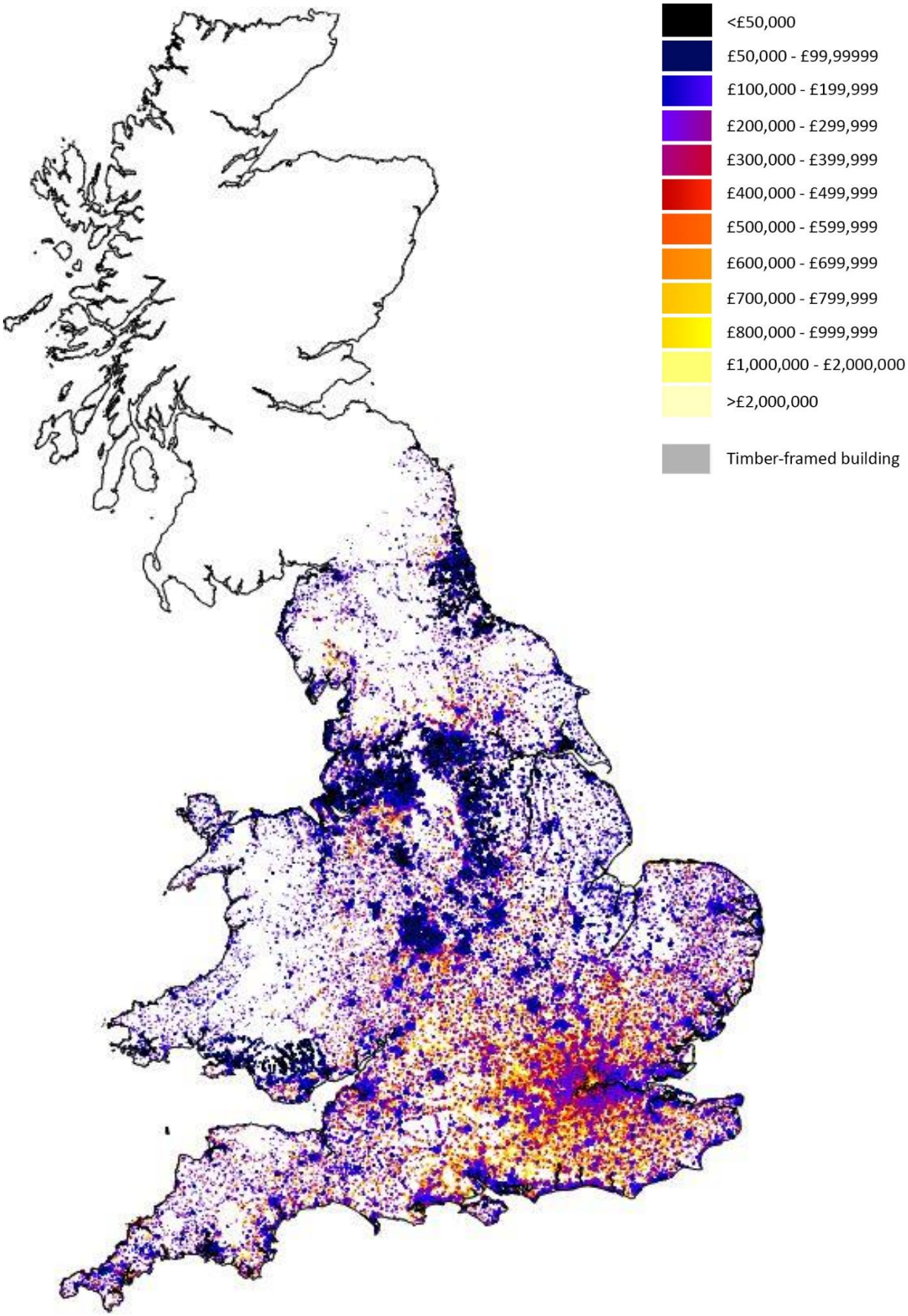

Figure 111. Map showing the sale price of existing houses in England and Wales sold 30th April 2015 – 29 April 2016, overlaid on the distribution of surviving timber-framed buildings.(House prices layered with cheapest on top) Source: (Author's own based on ((Land Registry, 2016, Historic England, 2014, RCAHMW, 2014))

6.4.3.2.1 House Prices

The house prices are taken from the information published by the Land Registry for houses sold in England and Wales over a specific year, in this case 2016 (Land Registry, 2016). Due to the density of information, the data is presented twice in two separate maps. The first (Figure 111 and Figure 112), layers up the data starting with the most expensive properties first ending with, and thereby emphasising the cheapest properties, whilst the second (Figure 113 and Figure 114) orders the layers in reverse finishing with the most expensive. Both maps show that the most expensive houses are concentrated in the Southeast, suggesting that little has changed with regard to the geographic distribution of wealth since the 16th century (Figure 108)

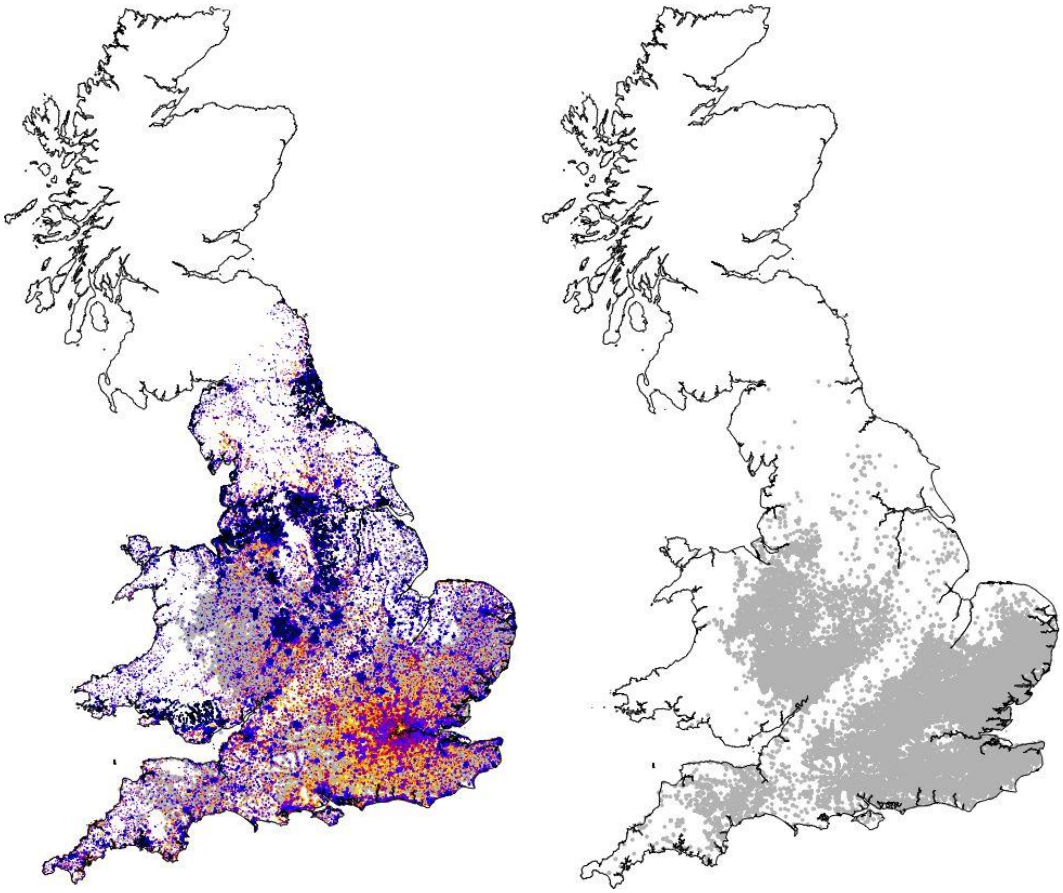

Figure 112. Map showing the sale price of existing houses in England and Wales sold 30th April 2015 – 29 April 2016 (left), set alongside the distribution of surviving timber-framed buildings (right).(House prices layered with cheapest on top) Source: (Author's own based on ((Land Registry, 2016, Historic England, 2014, RCAHMW, 2014))

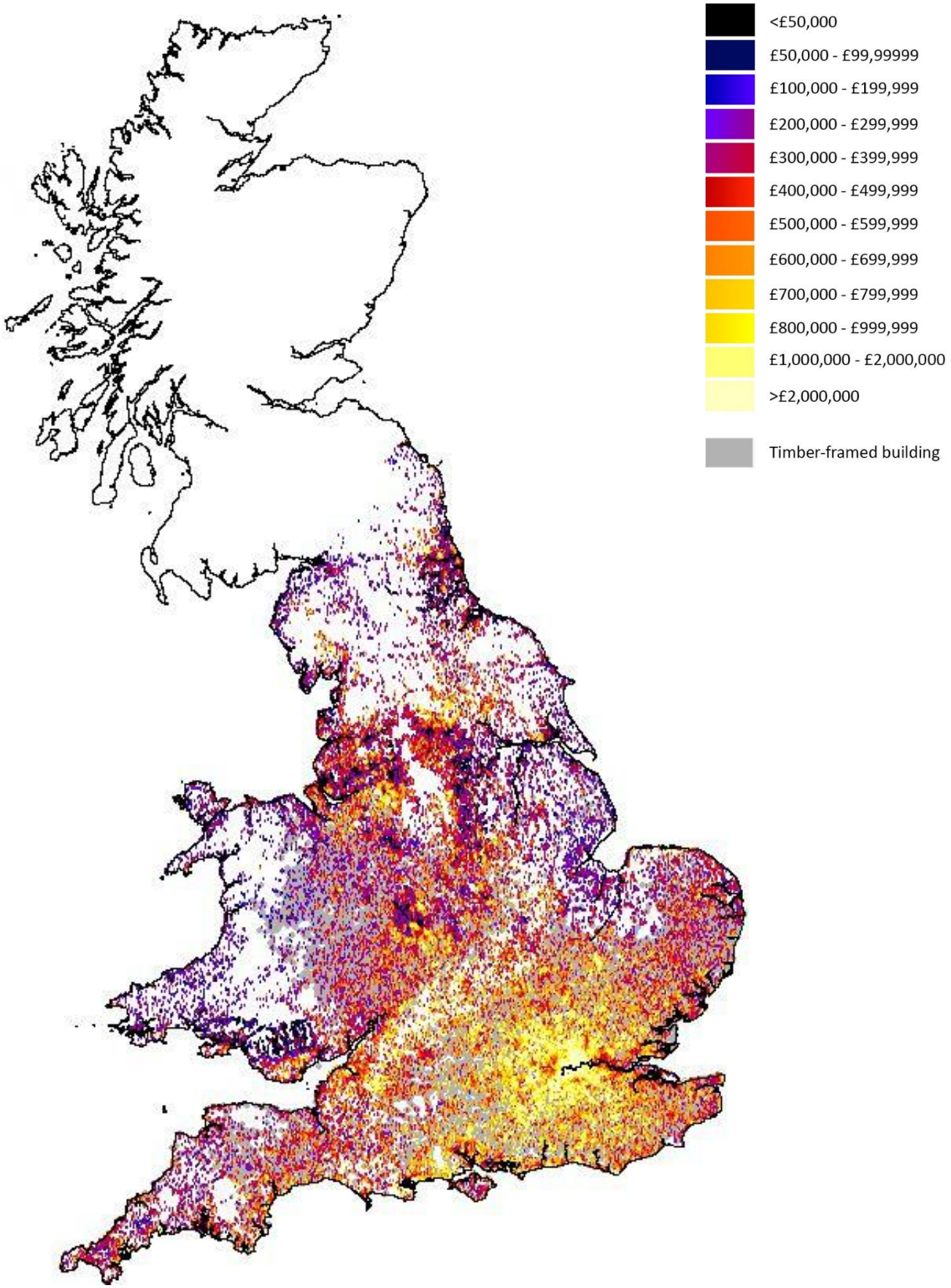

Figure 113 Map showing the sale price of existing houses sold in England and Wales 30th April 2015 – 29 April 2016, overlaid on the distribution of surviving timber-framed buildings.(House prices layered with most expensive on top) Source: (Author's own based on ((Land Registry, 2016, Historic England, 2014, RCAHMW, 2014))

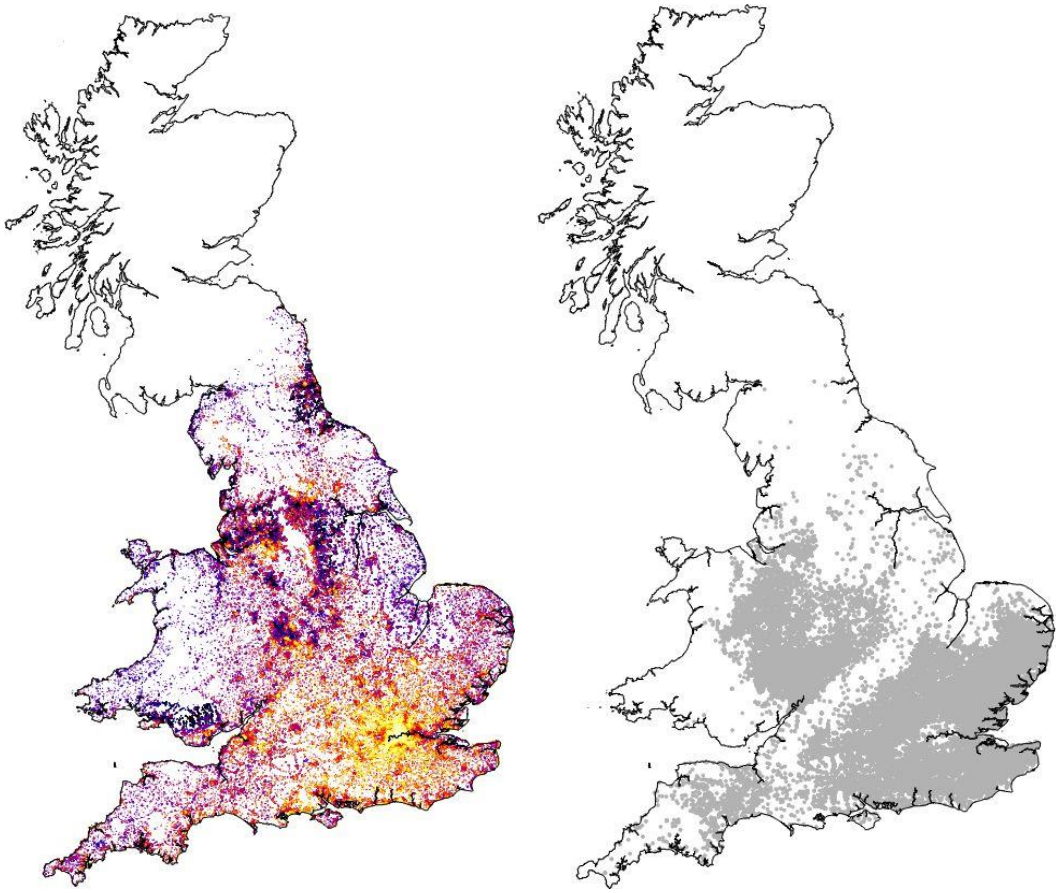

Figure 114 Map showing the sale price of existing houses sold in England and Wales 30th April 2015 – 29 April 2016 (left), set alongside the distribution of surviving timber-framed buildings (right).(House prices layered with most expensive on top) Source: (Author's own based on ((Land Registry, 2016, Historic England, 2014, RCAHMW, 2014))

ArcGIS software was used to compare the prices of houses sold in 2016 within a 1km radius of a surviving timber-frame building and the prices of all houses sold in 2016. In order to do this, first a 1km buffer zone was applied to the plotted locations of surviving timber-framed buildings using the geoprocessing tool "buffer". The geoprocessing tool "intersect" was then applied to select only those house prices from the Land Registry data that intersected this 1km buffer zone. The results from this analysis are shown in (Figure 115).

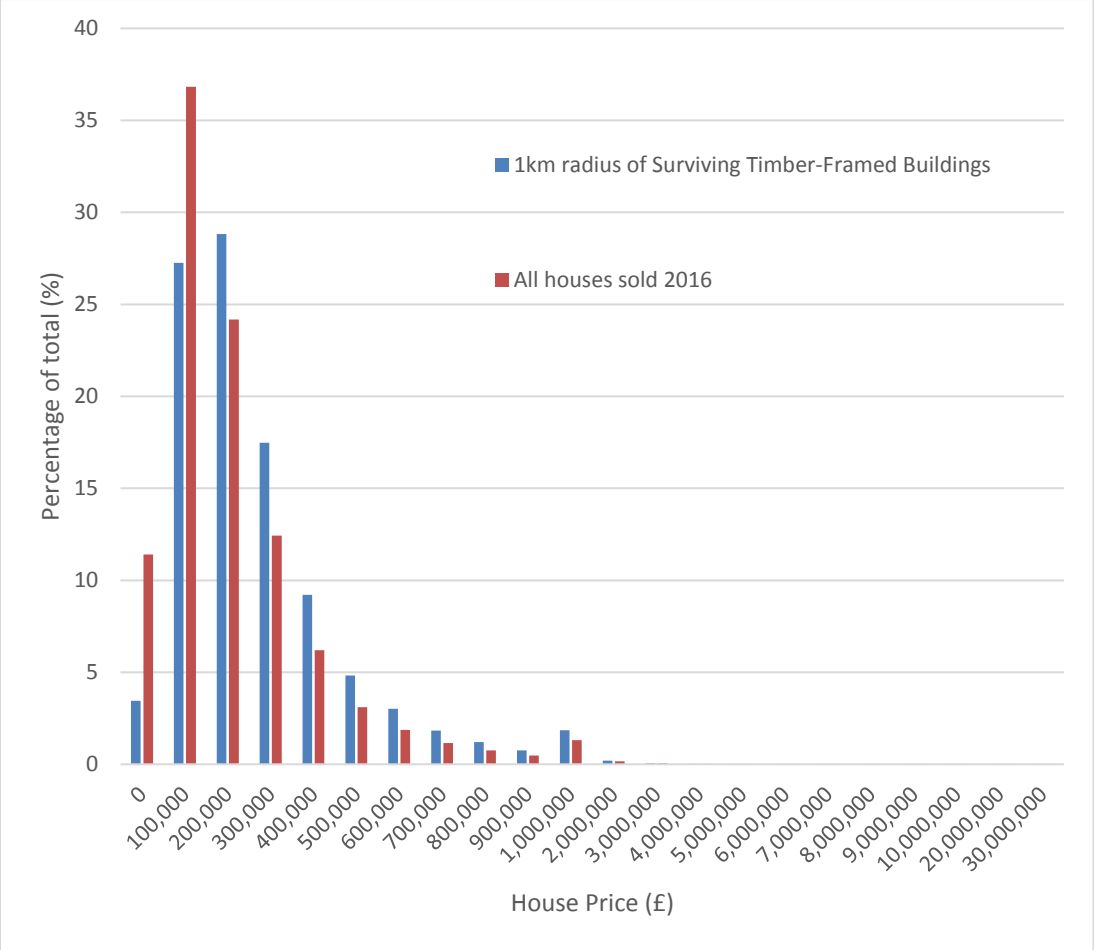

Figure 115. Prices of houses sold within a 1km radius of surviving timber-framed buildings in 2016 as compared to all houses sold in 2016. Source: (Author's own based on (Historic England, 2014, RCAHMW, 2014, Land Registry, 2016)

The results show that a slight increase in prices within the 1km radius, with an average price of £332,371 as opposed to the national average of £273,205. Overall, the distribution of prices moves upwards with a higher percentage of properties selling in the higher price brackets. Obviously, this data does not reflect the actual price of timber-framed buildings but rather those in their vicinity. It does however suggest that the areas where they are located are perceived to be some of the more desirable locations to live in the country.

6.4.3.2.2 Indices of Multiple Deprivation

The theory that timber-framed buildings survive in sought after locations is explored further by correlating the distribution pattern with the indices of multiple deprivation.

In England, the Indices of Multiple Deprivation is a comparative scale based on 37 indicators across seven domains. These domains are Income; Employment; Health and Disability; Education; Skills and Training; Crime; Barriers to Housing and Services; and Living Environment. These factors are reviewed for a total of 32,844 small areas known as Lower layer Super Output Areas (LSOA). These are then ranked against each other from most to least deprived, shown in Figure 116.

The Welsh Index of Multiple Deprivation (WIMD) follows the same logic, however in Wales the overall multiple deprivation shown in Figure 116 is based on eight indicators, these being, Income, Employment, Health, Education, Access to Services, Community Safety, Physical Environment and Housing. In Wales there is a total of 1909 LSOAs each containing an approximate population of 1600 people. (Welsh Government, 2015).

Due to the difference in calculation method, the two rankings have been plotted separately on the same map, rather than being combined as one ranking (Figure 116).

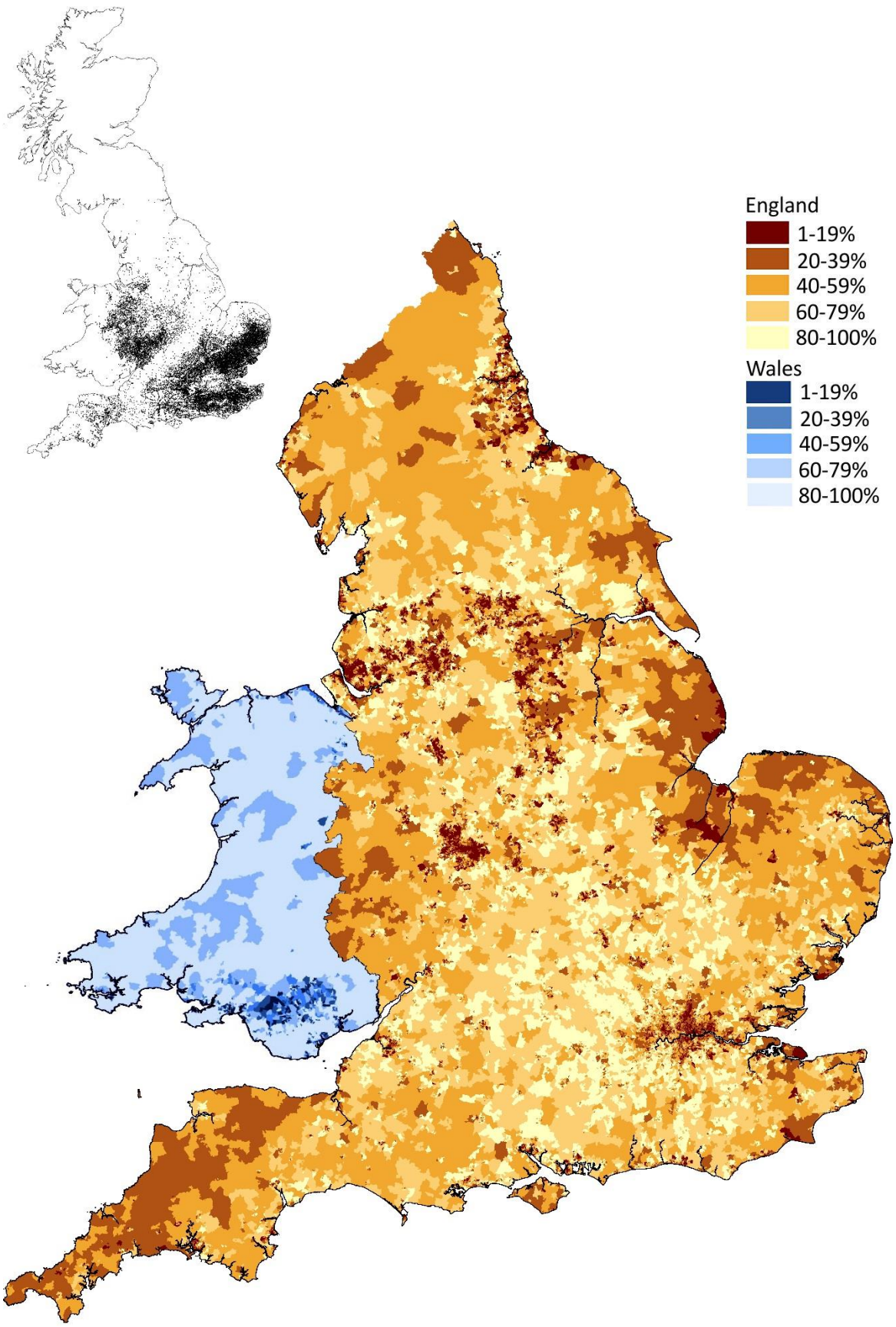

Figure 116 Index of multiple deprivation in England 2015 and Wales2014. Percentiles from most to least deprived. Inset, distribution of surviving timber-framed buildings. Source: (author's own based on (Rae, 2015, Welsh Government, 2015)

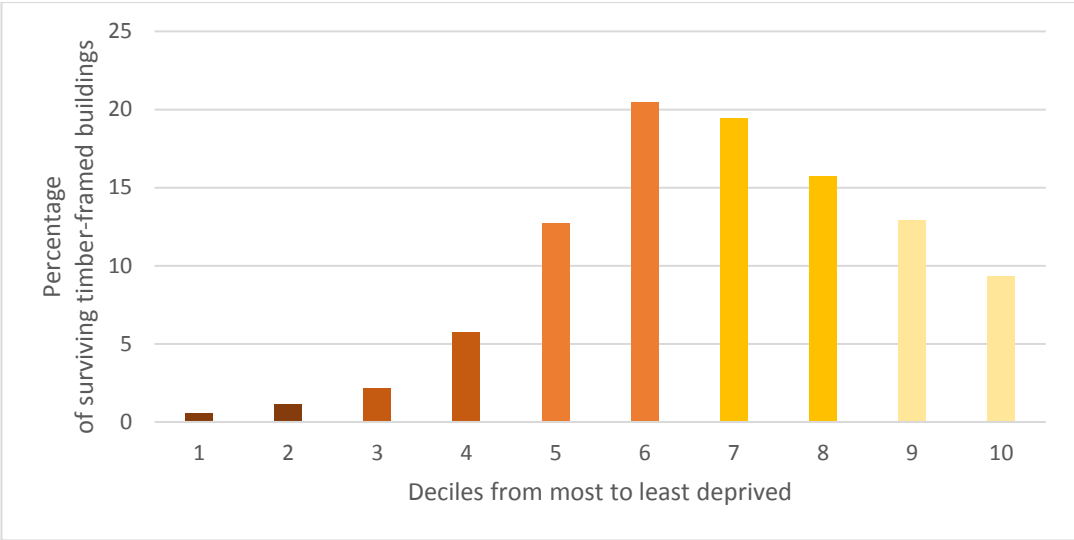

Figure 117 Percentage of surviving timber-framed buildings in areas according to index of multiple deprivation in England. Deciles are from most deprived (1) to least deprived (10). Source: (author's own based on(Rae, 2015)

Although perhaps difficult to see from the map (Figure 116), the results of detailed analysis with GIS (Figure 117) show that only 2% of the surviving timber-framed buildings are located in the most deprived quintile of the country with 68% of the buildings being located in the third and fourth quintiles and 22% in the fifth. Overall 78% of the buildings are located in the half of the country classed as being the least deprived. There may be a number of factors influencing this. Firstly, it is possible that the most deprived areas have historically been so, and as such, money was not available to build quality constructions that would have survived. Secondly, many of the most deprived areas are in inner city areas where as we have seen timber-framed building have not survived. Finally, it is possible that the least deprived areas have sufficient funds to maintain these buildings and as such ensure their continuing existence.

The affluence of those areas in which surviving timber-framed buildings are located, as identified by both the correlations with house prices and the indices of multiple deprivation are influential on the challenge facing the retrofit of these buildings. Whereas in poorer areas only the most essential changes to buildings are undertaken, in richer areas the ease and frequency of interventions, especially to people's homes is most probably higher.

6.5 Conclusions

The review of the surviving timber-framed buildings of the UK and their geographical distribution has confirmed the principal conclusions of the initial literature review. These buildings are located principally in England, with some across the border in Wales, and although once a common construction technique in Scotland, only three examples have survived there, with none identified in Northern Ireland. This highlights the potential fragility of this building typology and suggests that their continuing survival is not a certainty, especially within the context of anticipated climate change.

Overall, there are estimated to be 67,998 surviving timber-frame buildings in the UK, of which 70% are currently in use as dwellings. This is important when considering the retrofit of these buildings, as they are peoples' homes, spaces in which they expect to be comfortable. People must continue to want to live in them if their survival is to be ensured.

With regard to age, the largest percentage of the surviving buildings are 17th century, representing 45%, followed by 16th century, which make up 26% of the surviving examples. This is perhaps to be expected given that these centuries are the two most recent when timber framing was still a common, widespread construction technique.

The material used for the infill panels is difficult to ascertain precisely due to many of the panels being plastered, rendered or painted as external finish. As such, the designation listing descriptions are often limited to the knowledge of the designations officer and the access to the building allowed to them. From the available data, plaster would appear to be the most common infill (53%) followed jointly by timber cladding and brick nogging (18% each). The traditional earthen infills such as wattle-and-daub and mud-and-stud appear to be very rare with only 2% recorded. The protection and retention of any surviving examples of earthen infill is therefore of great importance.

The location of the surviving timber-framed buildings is predominantly in the East of England and the Southeast, totalling 74%, with the West Midlands and Welsh Marches being the only other area with significant numbers (13%). These two principal concentrations are evident when the individual property locations are plotted using GIS (ArcGIS) software, as is a third minor concentration in the Southwest around the border of Somerset and Devon. Within the two principal concentrations, the urban centres of London and the West Midlands Conurbation are notable by the reduced occurrence of timber-framed buildings within these areas. This will in part reflect the destruction of buildings by the Great Fire of London of 1666 and the subsequent historic laws prohibiting the rebuilding in timber but also will be due to the increased economic pressures for continual redevelopment. As such, the retrofit of timber-framed buildings is predominately a rural issue.

The other areas with a notable absence of surviving timber-framed buildings are Scotland and the North of England, the West of Wales, to a lesser extent the far Southwest of England, and a band stretching diagonally across the country from the mouth of the Severn to The Wash. This last feature can be explained principally by the presence of the geological feature of the Limestone Belt.

These strata of limestone rocks running across the country influence the survival of timber-frame buildings in this area in many ways. Firstly, they provided easy access to building material in the form of stone as an alternative to timber. Secondly, the thinner overlying soils influenced the distribution of historic woodlands. Analysis shows that only 0.5% of surviving timber-framed buildings are built outside a 5m radius of areas where woodland was recorded in the Domesday Book of 1086. And thirdly, the same lack of woodland led to the development of a settlement pattern centred on urban centres, rather than dispersed

dwellings, a pattern that was reinforced by the Parliamentary Enclosure Acts, and one that appears to have led to the survival of far less rural and in turn timber-framed buildings.

The absence of surviving timber-framed buildings in the other areas previously mentioned is best explained by climatic factors principally those created by topography and prevailing weather patterns. The high lands of the Cambrian Mountains, Pennines, and to a lesser extent Dartmoor, Exmoor, The Cotswolds, the Chiltern Hills and The North and South Downs create areas of increased precipitation, higher relative humidity and cooler temperatures. The same is the case for the west coast of England and Wales and all coastal areas suffer from increased relative humidity, if not higher precipitation. Exposed timber-frames in all of these locations are unlikely to have lasted long and vernacular tradition would have turned to other techniques, either to encase the timber-frame or to replace it with another material such as stone. An interesting example of this is in Sussex and Kent where an area of higher precipitation intensity exists and tile-hanging has been developed to provide additional protection to the timber-frame.

In general, the timber-framed buildings have survived in warmer areas with lower levels of precipitation and relative humidity, at an altitude above sea level between 20-100m. A review of historic economic factors shows that a correlation exists between the concentration of surviving timber-framed buildings and areas of historic wealth, especially with regard to wealth created through the wool trade and other industries of the middle class. These areas continue to be the wealthiest areas of the country. As such, it should be hoped that there is money to ensure the continual survival of these buildings. It may also however suggest that there is money available to undertake more extensive retrofit measures than may be possible in poorer areas, with fewer resources. This further underlines the need for the informed guidance that this thesis aims to inform and stimulate.

7 REPRESENTATIVE SAMPLE

7.0 Introduction

The previous chapter has presented analysis of the overall distribution, age and materiality of the surviving timber-framed buildings in the UK. The analysis looked at patterns within the whole dataset, however, with over 68,000 entries this dataset is too large to use for a more detailed study of the construction of these buildings, principally their orientation and panel size. In order to look at these aspects, a smaller representative sample was required. This chapter presents the production of this sample and the analysis of it.

7.1 Methodology

7.1.1 Defining the Representative Sample

Following the process of quantifying and locating the surviving timber-framed buildings in the UK, a representative sample of 100 buildings was selected to allow further detailed study of the typology. In order to allow the measurement of frame dimensions from only external photographs, a sub-dataset was created including only those buildings where the timber-frame was externally exposed and therefore visible for measurement. Externally plastered, weather-boarded, tile-hung and slate-hung buildings were therefore excluded. This sample selected from this sub-dataset was proportionally representational with regards to age, use, panel infill material and location. That is to say, two buildings were chosen to represent the 2% of 15th century houses with plaster infill in the East of England, one building to represent the 1% of 17th century barns with brick infill in the West Midlands, and so on. The sample buildings were also chosen to give a good geographic spread across each of the regions (Figure 118).

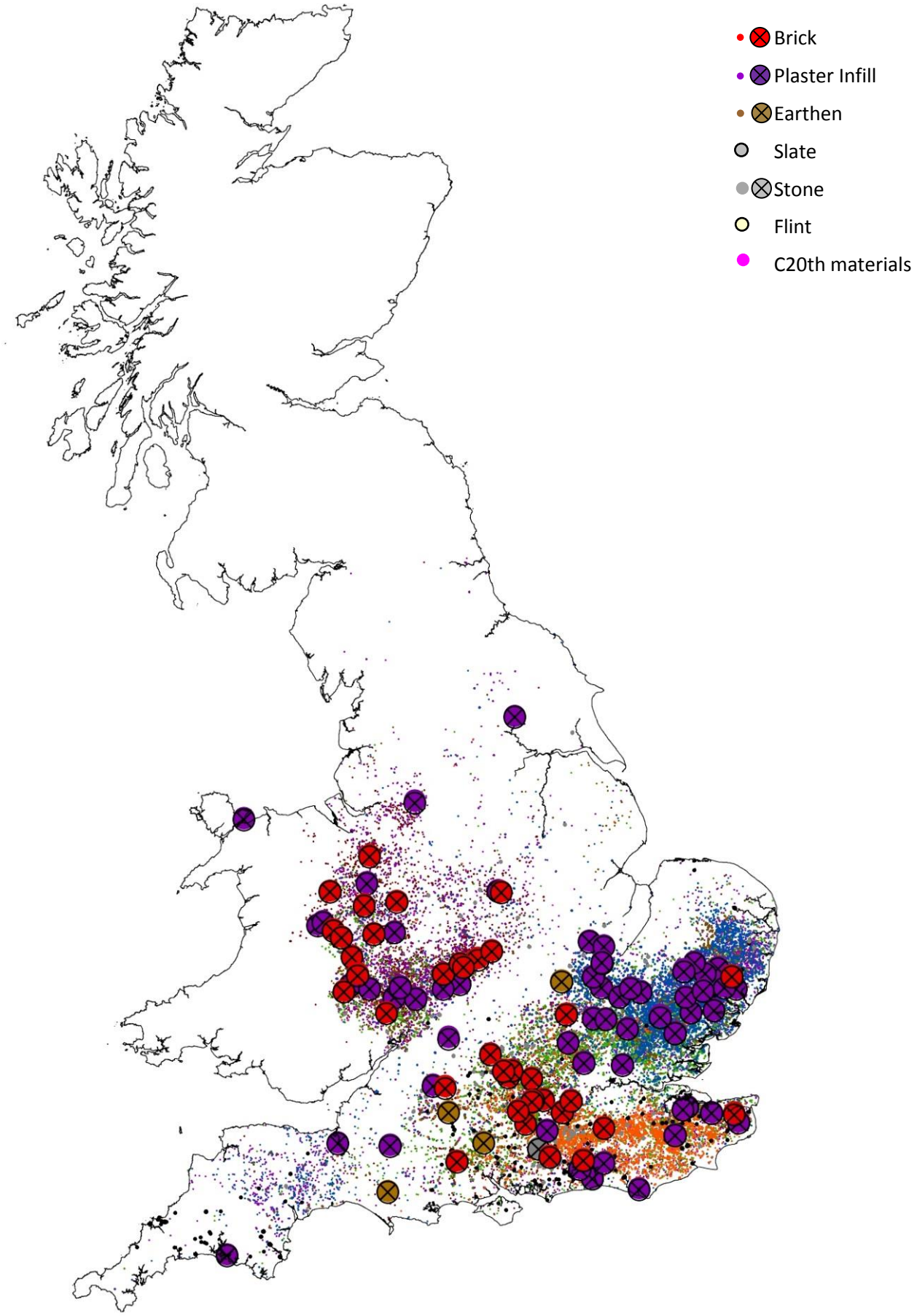

Figure 118 Distribution of 100 representative sample (large red, purple, brown and grey dots) overlaid on total distribution. Source: (Author's own based on (Historic England, 2014, RCAHMW, 2014)

7.1.2 Assessing orientation

It has been argued that vernacular architecture has developed adhering to bioclimatic [42]principals (Olgyay and Olgyay, 1963 p.4, Turan, 1990 p.8), maximising the beneficial aspects of the climate where it is located, whilst minimising those which are negative. If this is true for timber-framed architecture in a cool temperate climate, such as that found in the UK, then it would be expected that the building should favour a southern orientation to exploit direct solar gain (Hawkes, 2012 p.36, Olgyay and Olgyay, 1963 p.55), whilst seeking protection from wind-driven rain coming principally from the Southwest (British Standards Institution, 1992). In order to test this theory, Google Maps® was used to obtain aerial photos of the 100 buildings from the representative sample previously described. These photographs were then used to analyse the orientation of each building, both with regards to the cardinal points and with regards to surrounding features such as roads or street patterns. It should be noted that this work has been undertaken only with the information available through Google Maps® and Google Streetview® and as such only accounts for the current configuration of the buildings. It is obviously possible that both buildings and surrounding roads have been modified over time and future research should be undertaken to consult historic documentation to refine this analysis. This limitation should be taken into consideration when reviewing the following results.

7.1.3 Calculating average panel size

Again using Google Streetview® elevational photographs were taken of each building. These photos were then scaled and traced over in AutoCAD to allow measurements to be taken. Two different methodologies were used to calculate the average panel size. In the first methodology, the heights and widths of all panels visible in each image were measured and the mean average for each measurement calculated. In the second

[42] Designed to work with the local climate to provide hygrothermal comfort with limited external input of energy (Olgyay and Olgyay, 1963).

methodology the most typical or representative[43] panel from each image was selected and measured, thereby defining the mode. The results of these two methodologies were then plotted and analysed. They are presented in section 7.2.2.

7.2 Results and Analysis

7.2.1 Orientation

Key

Figure 119 aerial views of 100 representative sample showing main building axis and building orientation. Source: (Author's own based on Google Streetview (Google, 2016)

[43] The panel that represented the approximate size and style of panel that occurred most frequently in the image.

Figure 119 shows the aerial views of the 100 representative sample. The main axis of each building has been highlighted in addition to a perpendicular line indicating the direction in which the principal façade is facing. The angles of these two lines were measured in AutoCAD and are presented in Figure 120 and Figure 121.

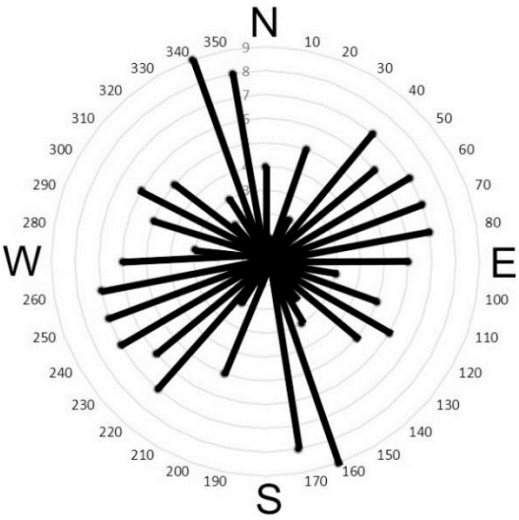

Figure 120. Orientation of main axis of 100 representative sample. Source: (Author's own)

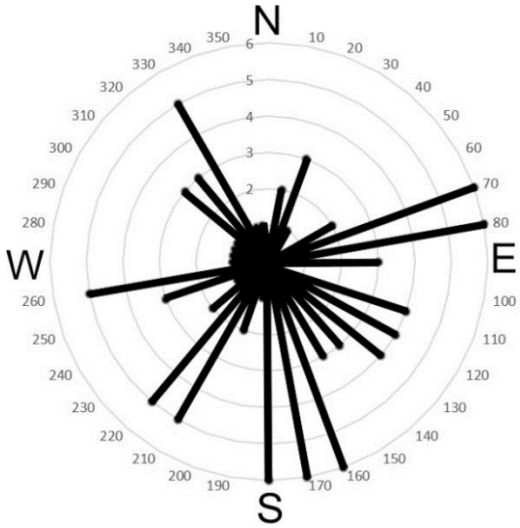

Figure 121. Direction faced by main façade of 100 representative sample. Source: (Author's own)

When looking at the principle axis of the buildings (Figure 120) it can be seen that 55% have a principal axis that runs approximately somewhere between East-West and Northeast-Southwest. The second most common orientation is North-South with 29% following this axis, followed by 16% with axes running Northwest-Southeast.

With regard to the direction that the principal façades (Figure 121) it can be seen that 81% of the buildings have an aspect ranging from 60° through to 300° and so would receive some direct sunlight onto the principal façade at some point in the year (Figure 122). More specifically 48% have an aspect facing between 120° and 240° and so would receive direct solar gain even in the depths of winter. It is interesting to see that there is also a tendency towards the South, Southeast and East, as opposed to the Southwest and West. This

reflects current bioclimatic advice to favour the morning sun following the cooler nights, rather than the afternoon sun, which can lead to overheating. In addition, in the UK the prevailing winds are from the Southwest further reducing the desirability of this aspect. From this research, it would appear that some degree of climatic response has been considered in the construction of the buildings. It should be noted that 97% of the buildings are aligned with the adjacent road or street, with the remaining 3% all oriented south. Without further research into the history of the buildings and the roads it is not possible to know which came first, however it is plausible that both building and street may have been influenced by bioclimatic considerations.

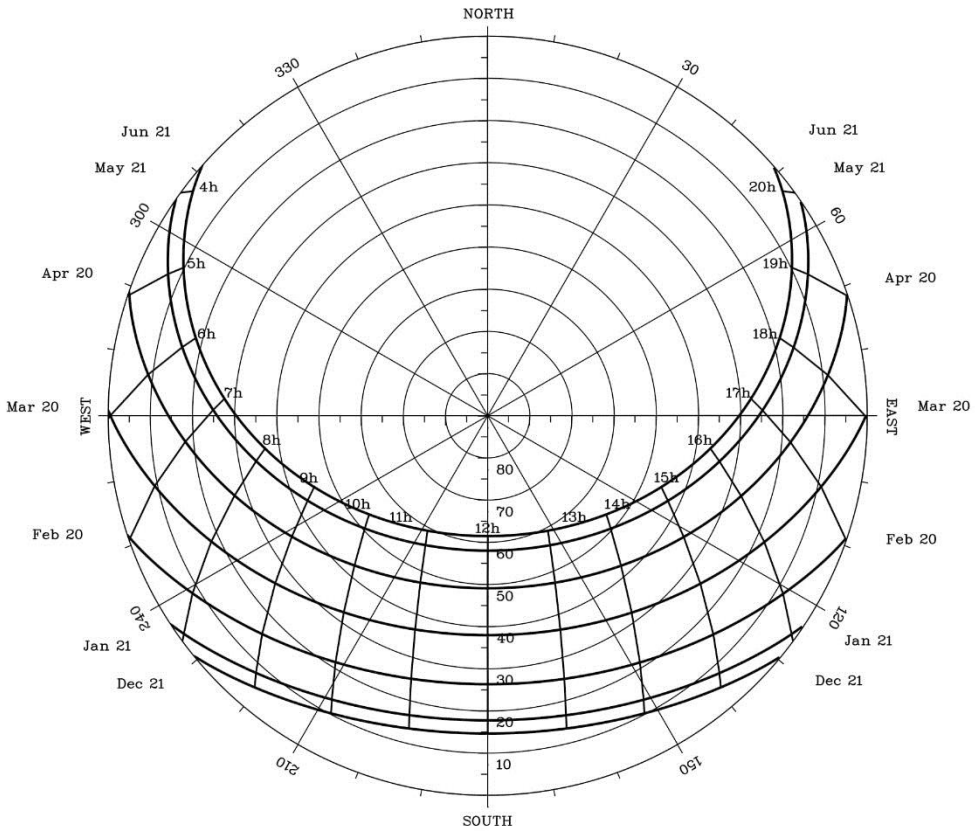

Figure 122. Sun path diagram for latitude 52° north (an average for the south of England). Source: based on (University of Oregon Solar Monitoring Laboratory, 2005)

7.2.2 Panel size

Figure 123 shows details from photographs taken of this sample using Google Streetview (Google, 2016). This illustrates the variety of frame types, sizes and infill materials. The sample demonstrated that close studding and square framing were the dominant frame typologies with 53% and 46% respectively; only 1% of the sample was ornamental.

Figure 123 elevational details of 100 representative sample of surviving timber-framed buildings. Source: (compiled using (Google, 2016))

Looking at the distribution of the square framing and close studding Figure 124, it can be seen that close studding is mostly found in East Anglia, with square framing more common in the West Midlands and Welsh Marches, and also in the centre of the South. The only example of ornamental panelling within the sample is to be found in Beaumaris on Anglesey in North Wales.

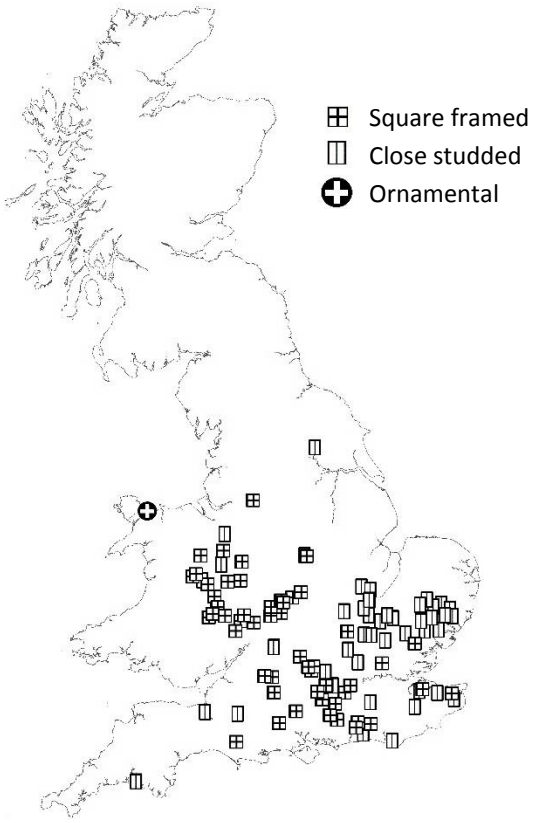

Figure 124. Distribution of the 100 representative sample, showing panel type. Source: (Author's own, 2017)

As detailed in the methodology, the photographs were scaled and traced in AutoCAD to enable the measurement of panel sizes. The results are presented in Figure 125.

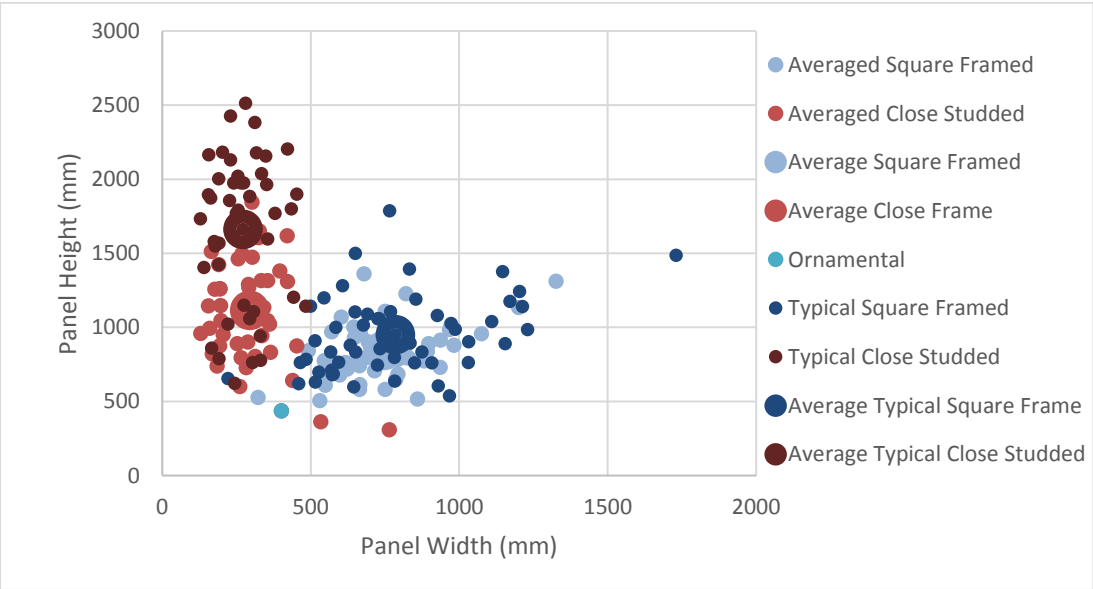

Figure 125 Measured sizes of 100 representative sample infill panels. "Averaged" refers to methodology 1 or mean and "Typical" to methodology 2 or mode. Source: (Author's own, 2016)

Figure 125 illustrates that the first methodology (measuring all panels in each image and calculating the mean average) produced smaller panel sizes due to the averaging of small and large panels within the same image. It must also be considered that these panels are however only theoretical and do not actually represent any real panel. The second methodology, measuring only the most typical panel in each image, is perhaps more representational of real panel sizes, as these panels plotted on the graph really do exist. This second methodology showed an overall average panel size to be 785mm wide by 950mm high for square framing, and 272mm wide by 1661mm for close studding. The only ornamental framed building included in the sample has panels that are considerably smaller at just 261mm wide by 633mm high.

To validate the results from this sample a review of all buildings included in Brunskill's "Timber Building in Britain" (Brunskill, 1985) a seminal text on the typology, was undertaken. Measurement of panels sizes were undertaken of all photographs in the book using methodology 2. The results, presented in Table 11, show that for square framing and close studding there is very little deviation between those measured from the representative sample and those contained in Brunskill's book. It is perhaps not surprising however that the ornamental panels do differ significantly, due to the small population size in both samples (one in the 100 sample and eight in Brunskill). Given the larger population size in the Brunskill sample, this is probably a better representation of the panel size for this frame type.

Table 11. Infill panel sizes as measured from 100 representative sample and Timber-Framed Building in Britain (Brunskill, 1985) and deviation between the two.

Frame type	100 Sample Width (mm)	Brunskill Width (mm)	Deviation in Width (%)	100 Sample Height (mm)	Brunskill Height (mm)	Deviation in Height (%)
Square framed	785	766	2.4	950	892	6.1
Close studded	272	268	1.5	1661	1675	0.8
Ornamental	261	471	44.6	633	816	22.4

The measurements here are presented in metric units, which are not those in which they would have been built. When considering the average sizes in imperial units it can be seen that the width of a close studded panel is approximately 1 foot (304.8mm) by around 5’ 6” (1676.4mm) or a full storey height. Square framing is around 2’ 7” (787.4mm) which allowing for the width of the frame would allow 6 panels per bay based on bays one perch (16 foot or 4876.8mm) wide (Braun, 1940 p.13). Again, their height of around 3 foot (914.4mm) when doubled would form one storey approximately 6 foot (1828.8mm) high.

7.3 Conclusions

The analysis presented in this chapter has indicated the validity of pursuing a closer study of two aspects of the surviving timber-framed buildings in the UK, these being their orientation and the size of their timber panels. With regard to the orientation of these buildings, the results arising from this analysis would suggest that access to direct solar radiation, especially during the morning, was potentially an influencing factor in the planning of the buildings. In addition, the Southwest is less popular, probably due to the prevailing winds. Currently it is unclear if adjacent roads predate the buildings or were influenced by them; further research using historical documentation may be able to refine these conclusions. Another area for future research could include a more detailed study of the plans of each building to identify if solar gain and prevailing winds influence the interior room layouts.

Looking at panel sizes it can be seen that there is an almost 50-50 split between close studding and square framing, with close studding being more common in East Anglia and square framing in the West Midlands and the Welsh Marches. The average size for close studded panels is 272mm wide by 1661mm high (approx. 1’ x 5’6”) and for square framing 785mm wide by 950mm high (approx. 2’7” x 3’). These sizes match closely those buildings illustrated in Brunskill’s “Timber Building in Britain” (Brunskill, 1985). Ornamental panelling

is smaller with panels around 471mm wide by 816mm high. Whilst there can be seen to be a wide variation in the precise measurements from building to building, there does appear to be a reasonable degree of standardisation of this construction typology. A future study could be to see how closely timber-frames from the same age and location vary in size.

8 CASE STUDIES: INTRODUCTION

8.0 Introduction

In order to understand the implications of retrofitting historic timber-framed buildings, five case study buildings have been monitored. This chapter introduces each of the case studies, briefly outlining their history and retrofit strategies. The following chapter then goes on to present the methodology, both general and specific for the monitoring undertaken, the results and the analysis. The results of each case study are analysed individually, with partial conclusions drawn at the end of each sub chapter. A final summary brings together these results, drawing overall conclusions and suggesting areas for further research.

With many low carbon retrofits, the main objective is the reduction of greenhouse gas emissions, with the aim being to mitigate the effects of climate change. However, given the small percentage of the total domestic building stock represented by historic timber-framed dwellings, 0.24% (Nicol et al., 2014), reducing their emissions will have a minimal impact. The overriding aim of retrofitting these properties should therefore be to ensure that these buildings provide reasonable comfort to their inhabitants and by doing so enabling their continued occupation and survival. At the same time, it essential that any retrofit actions do not put at risk the historic building fabric nor damage the buildings heritage value.

8.0.1 Overview of case studies.

The five buildings chosen are, Hacton Cruck, a mediaeval peasant hall, now let as holiday accommodation; The Oaks, an estate cottage built over three centuries, now owned by the National Trust and let as a single-family residence; The Old Mayor's Parlour and No. 25 Church Street, two adjacent commercial properties whose origins date back to the 14th century, now managed by a charitable trust; Nos 25 & 27 Church Street Saffron Walden, a mediaeval hall house subsequently divided into two cottages and now reunited under the

ownership of the Technical director of SPAB; and Old Stokes Farm, a farm house dating from the 16th Century in private ownership. As such, the case studies represent a variety of ownership models, tenancies and uses. Hacton Cruck, The Old Mayor's Parlour and Old Stokes Farm have undergone substantial retrofits and display a variety of different panel infills, both old and new. In the case of Hacton Cruck and The Old Mayor's Parlour, this work was designed and overseen by a local, sole practitioner architect. In contrast, The Oaks has had minor retrofit interventions with no change to the existing panel infills, with the works specified by the Estate surveyor in line with the National Trust's environmental standards. In the case of the latter, monitoring was undertaken both pre and post-retrofit. At nos. 25 & 27 Church Street, Saffron Walden, no energy retrofit work has been undertaken.

8.0.2 Location

The first three case studies are all located in the county of Herefordshire, in the English West Midlands, or Welsh Marches, on the border with Wales. Whilst the fourth and fifth case studies are located in Essex and Suffolk, respectively, in East Anglia (Figure 126).

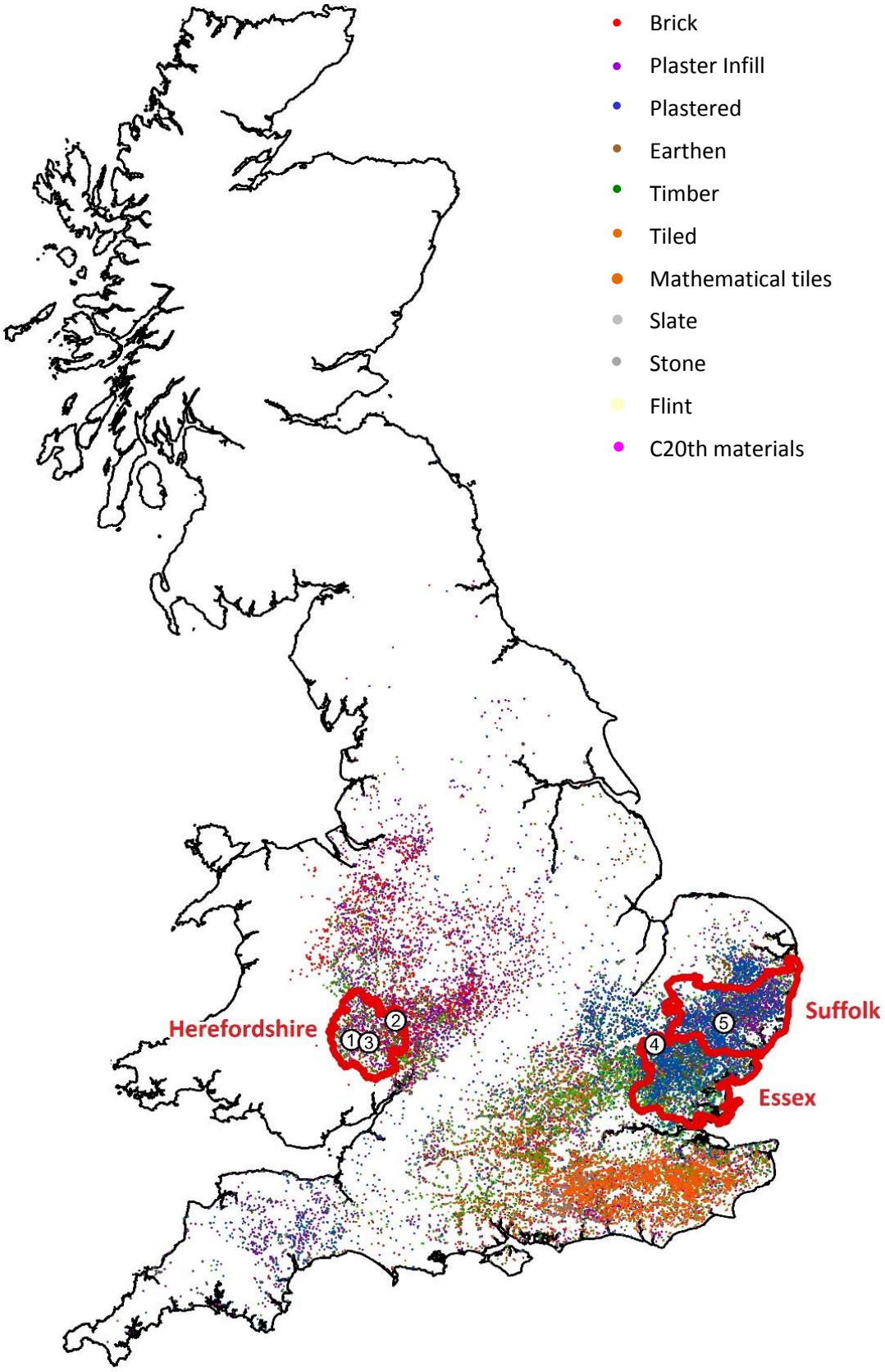

Figure 126. Distribution map of timber-framed buildings in Great Britain by infill material showing location of case studies and associated counties. Source: (Author's own based on data from (Historic England, 2014, RCAHMW, 2014))

Hacton Cruck (1) is situated in the west of Herefordshire, The Oaks (2) in the northeast and The Old Mayor's Parlour (3) in the heart of Hereford, the county town, which lies at the centre of the county[44]. Figure 126 illustrates that the county encompasses the southwest quadrant of the western concentration of timber-framed buildings in the UK. The predominant panel infill materials in Herefordshire are brick (47%), plaster (44%) and wattle and daub (8%). A high proportion of buildings with modern infill can also be found locally with 16% of those listed with twentieth century infills located within the county boundaries.

Nos. 25 & 27 church Street, Saffron Walden (4) are located in the North of Essex, with Old Stokes Farm (5) located in the centre of neighbouring Suffolk. Together Essex and Suffolk encompass most of the northeast quadrant of the eastern concentration of timber-framed buildings, and between them contain 29% of all surviving timber-framed buildings in the UK. The predominant panel infill materials in Essex and Suffolk are plaster (41%), followed by completely plastered buildings (35%) and timber clad buildings (20%). The remaining 4% are divided between brick, wattle and daub, tile-hanging, stone and modern infill.

8.0.3 Climatic Conditions

The majority of the UK is located in a temperate maritime climate with warm summers and cold winters. The climate is classified under the Köppen-Geiger climate classification system as Cfb (C-Warm temperate, f-fully humid, b-warm summers) (Kottek et al., 2006). The heating season typically lasts from November until March with no requirement for mechanical cooling during summer months. Figure 127 shows the climates generated using the software Meteonorm™ version 6.1 for Herefordshire, North Essex and Suffolk. Meteonorm™ uses the recorded data of multiple local weather stations to create averaged

[44] latitude 52.06 and longitude -2.72

values. For the creation of the data presented in Figure 127 the time period 1996-2005 was used. This was chosen to have more recent data rather than the longer but older time period of 1961-1990.

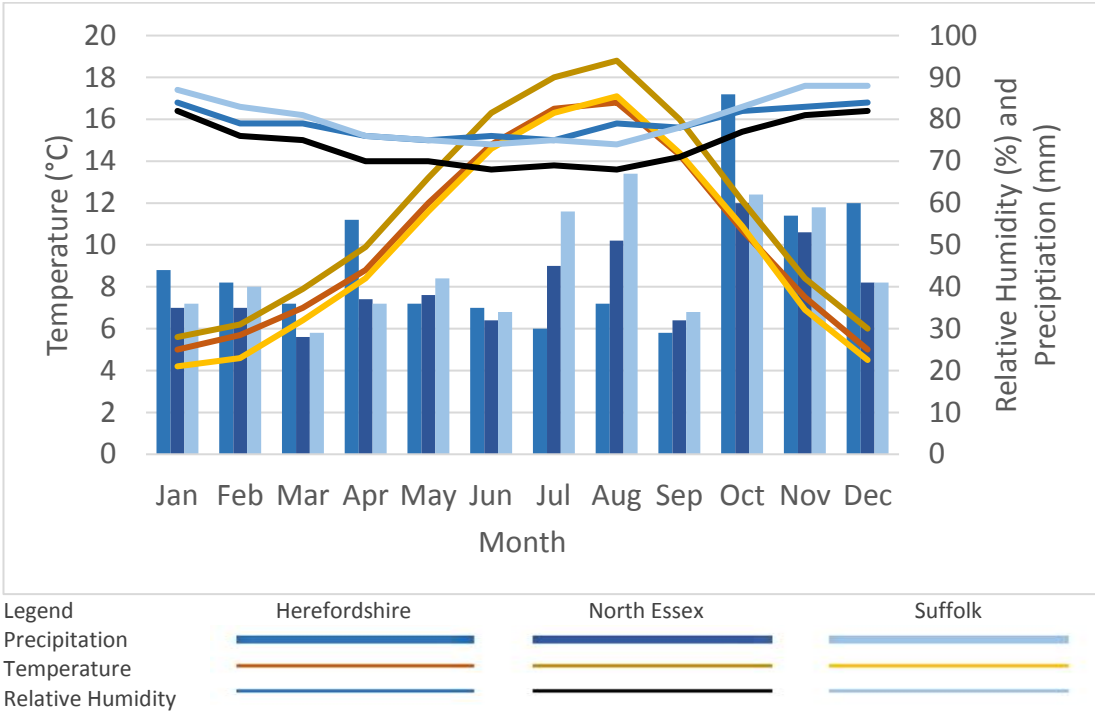

Figure 127 Climatic data for Herefordshire, North Essex and Suffolk. Source: (Meteotest, 2016)

It can be seen in Figure 127 that Saffron Walden in North Essex has the warmest, least humid climate, with a yearly average of 11.5°C, 74% RH, a monthly average of 19°C, 68% RH in August, and a maximum of 31.5°C recorded in the time period used to generate this data. Suffolk and Herefordshire have similar average temperatures (10°C) and levels of relative humidity (70% and 69% respectively). With regard to precipitation, Saffron Walden is again the driest with an average annual rainfall of 487mm, marginally higher than both Suffolk (538mm) and Herefordshire (546mm). However although these latter two may have similar yearly averages, the precipitation pattern for them differs considerably. In Battisford, Suffolk winter is relatively dry, with similar levels of precipitation as North Essex, however the maximum levels of precipitation are experienced in the summer months, a pattern shared by Saffron Walden to a far lesser extent. This increase in summer rainfall is

due to the summer thunderstorms that are more common in the east of the country (Manley, 1955 p.262). The peak precipitation for Herefordshire occurs in spring and autumn. It should be noted that Herefordshire has a fairly dry climate considering its western location. This is due to the rain shadow of the Welsh Mountains (Phillips, 2013 p.117).

8.1 Methodologies

There follows a description of the methodologies used for the selection of the case study buildings.

8.1.1 Selection of case studies

Gaining access to any building in order to undertake monitoring requires a degree of trust from both the owner and occupants. Therefore, where the possibility to monitor suitable buildings presents itself, this should be taken. Whilst the ideal would be to select the case studies via a scientific process, such as that used in the previous chapter, to ensure an accurate representation of UK timber-framed buildings, in reality the choice of these case studies has been more limited. The first and third of these case studies, Hacton Cruck and the Old Mayor's Parlour were discovered whilst attempting to track down the author of one of the replacement infill details published in SPAB technical pamphlet (Reid, 1989). Contact with the second case study, The Oaks, arose through contact with the National Trust following a conference on Responsible Retrofit, organised by the Sustainable Traditional Building Alliance (STBA). The fourth and fifth case studies resulted from contacts made during my teaching role on the MSc in sustainable Building conservation. Although a degree of serendipity was involved in their selection, the five case studies were pursued due to their specific characteristics and together they provide a varied cross-section of retrofitted timber-framed buildings in the UK.

Further case studies were considered at St Fagan’s Museum of Welsh Life, where there exists a total of three historic timber framed buildings, Abernodwydd Farmhouse, Hendre'r-ywydd Uchaf Farmhouse and Stryd Lydan Barn. However, due to these buildings being museum exhibits no longer in their original climatic and topographical context, in addition to the restoration work that has returned them to a representation of their original form, they were not pursued as case studies.

8.2 Hacton Cruck, Preston-on-Wye

Hacton Cruck is a 15th century cruck hall in the Wye Valley, Herefordshire, UK (National Grid Reference (NGR) SO 38783 41829). For much of the 20th century it lay abandoned and derelict, yet from 2000 until 2012 it was restored by its owner and now provides holiday accommodation. The renovation involved a number of different approaches and so allows the comparison of three different wall infill panels. These are; one original oak lath and lime plaster; one replacement wattle-and-daub; and one new panel with modern multi-foil insulation consisting of reflective foils separated by polyester fleece.

8.2.1 History

Located on the edge of the 11th century village of Preston-on-Wye (Williams, 2011), Hacton Cruck was constructed as a three bay, single hall dwelling in the late 14th or early 15th century (Williams, 2011). Its design is typical to many Mediaeval halls with a central hall open to the roof, flanked by the solar, or private room, to one end (high end) and the service accommodation to the other (low end), each with loft spaces, or gallery above (Harris, 2010). Originally, an open hearth would burn in the centre of the hall, the smoke escaping through a hole in the roof. Smoke-blackened timbers and a shortened rafter clearly mark the former location of this hole. The size, configuration and lack of ornamentation would suggest that the Hacton Cruck was what is now recognised as a peasant hall-house (Suggett and Dunn, 2014), although the owner suggests it was that of a yeoman (Williams, 2011). The three-bayed structure, open central hall and smoke hole can be clearly seen in the longitudinal section, running north-south, through a laser scan of the building (Figure 130). It should be noted that the left hand, southern bay is a modern reconstruction based on conjecture.

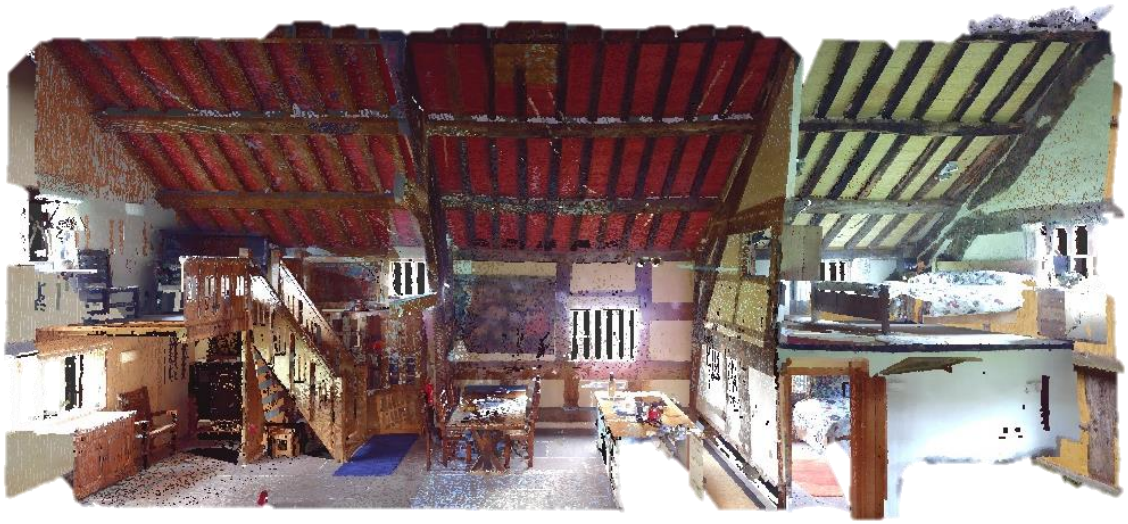

Figure 128. Hacton Cruck. Longitudinal section through laser scan of showing three bay structure and open central hall. Source: (Author's own, 2016)

It is unknown when the southern bay was lost, however at some time during the 18th-19th centuries the property was divided into two separate dwellings. The positioning of the doors and the stone wall added at the time of this division (Figure 129), may suggest that the southern bay had already disappeared by this time. Previous to this, in circa late 16th or early 17th century, a floor was added over the open hall dividing it into two storeys (Historic England, 2014). This has since been removed.

By the mid-20th century, the building was uninhabited, save for some pig and hens, and apples were stored upstairs (Williams, 2011). Its decline continued and the hall spent the latter half of the last century abandoned. Prior to restoration, much of the remaining fabric was in a poor state of repair. Over a period of 12 years, starting in 2000, the current owner undertook a process of restoration that resulted in what we see today (Figure 130).

Figure 129 Hacton Cruck in 2000. Source: (Williams, 2011)

Figure 130 Hacton Cruck Hall, east elevation. Source: (Author's own, 2015).

8.2.2 Restoration and Retrofit measures

With the site boundary just over a metre from the exposed central truss, in order to achieve the owner's desire to reconstruct the lost southern bay, it was necessary to relocate the building approximately 30 meters to the east (Figure 131). In addition to the technical and practical challenges this poses, both moving and reconstructing a building are controversial as they go against many generally accepted conservation principals. By moving a building, it's original relation to its site and context is lost, thereby reducing its authenticity, and the restoration to an earlier time produces an edited story that negates the changes and history of the building over time (SPAB, 2009). For this reason the SPAB, The Archaeological Society and the local planning department opposed the move. However, without this move it is questionable if the owner would have decided to repair the building and it may have been lost forever. Supporting this argument were English Heritage and the local conservation officer. In the end planning was granted for the relocation (Williams, 2011), however due to its relocation it was viewed by Building Control as a new-build construction and as such greater restrictions were placed on the thermal performance of the building envelope.

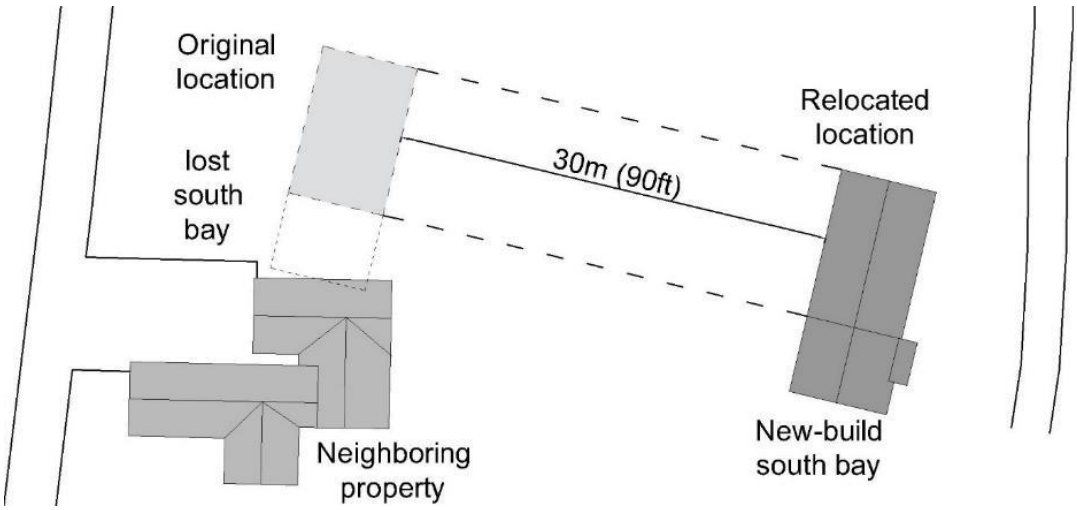

Figure 131 Hacton Cruck. Plan showing relocation of from original to current site. Source: (Author's own, 2016)

Figure 132 Hacton Cruck following demolition of 18th/19th century stonework. Source: (Williams, 2011).

Prior to relocation, the 18th/19th century stonework (Figure 129) was demolished (Figure 132) and the timber-frame repaired in its original location. Some missing timbers were required to be replaced, as there were some that were beyond repair. However, most of the surviving timber-frame was saved, in addition to all the original lath and plaster infill panels in the north wall that had been protected by a lean-to pigsty and weatherboarding (Williams, 2011). Once stable, a steel platform was constructed beneath the timber-frame and a vintage Matador timber crane was employed to haul the frame 30m across the flattened ground, to marry-up with a new southern bay, built in lime rendered concrete block, and a chimney built from the demolished stonework. The east and west walls of the new southern bay are of single leaf concrete block, uninsulated to match the thickness of the timber-frame, whereas the south wall is a cavity, insulated, two-leaf construction. Once secured in its new location, there was a hiatus in the restoration process and the building was clad in corrugated to protect it from the elements.

The work recommenced a couple of years later with the thatching of the roof. The original proposal for the restoration of the house was with clay tiles. However, as thatch was believed to be the original roofing material, the owner decided to follow this tradition using reed from the Tay Estuary and Sedge, for the ridge, from the Norfolk Broads (Williams, 2011). He believed that the thatch would "*give good insulation and allow the building to breathe*" (Williams, 2011). The impact of this theory will be tested by the results of the monitoring. The underside of the thatch was exposed internally, with no "torching" (plastering) in the central two-story bay. Although most of the original infill panels had been lost, those previously mentioned to the north wall survived. These remaining panels were of lime plaster on traditional riven oak lath and are believed by the owner to date from the 18th century (Williams, 2011). With minor repair work, all but the top-most panel were saved. Elsewhere, in order to provide improved thermal resistance, the majority of the new infill panels incorporated a multi-foil insulation (Triso Super 9), sandwiched between finishes of lime plaster on expanded metal lath. In some parts however, the external timber-frame walls members were barely 76 millimetres wide. In these locations, new panels of wattle and daub (earthen render on slit oak timber lath) were installed. Figure 133 shows the extent and location of each of these panel types, and Table 12 the surface area and percentage coverage. This shows that almost half of the infill panels incorporate Triso Super 9 (46%), although this accounts for only 13% of the wall surface and 8 % of the external building envelope (excluding the floor). The presence of the three panel types in one building presented the opportunity to monitor three different constructions under the same climatic conditions. This is further discussed in the next chapter along with the methodology employed.

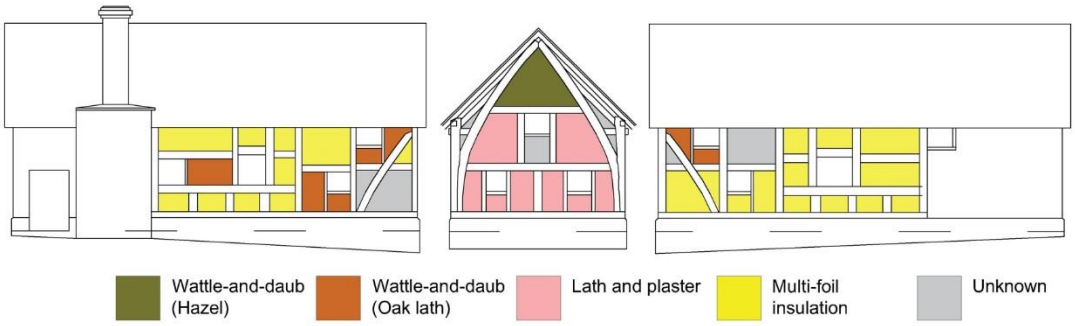

Figure 133 Hacton Cruck. Diagram showing location of each infill panel type. Source: (Author's own, 2016)

Table 12 Surface area of external envelope materials expressed as percentage of building envelope, wall and infill panels.

Material	Surface area (m^2)	Percentage of building envelope* (%)	Percentage of wall (%)	Percentage of infill panels (%)
Wattle and daub (Hazel)	2.96	1	2	7
Wattle and daub (Oak lath)	4.64	2	3	11
Original lath and plaster	8.98	4	6	22
Plaster on metal lath + Triso Super 9	19.27	8	13	46
Unknown panel infill	5.67	2	4	14
Timber-frame	28.78	12	20	
Insulated concrete blockwork	22.79	9	16	
Uninsulated concrete blockwork	15.03	6	10	
Stone	24.07	10	17	
Windows (single glazed)	8.83	4	6	
Doors	2.68	1	2	
Thatch- untorched	37.65	26		
Thatch- torched	64.40	15		

*External building envelope excludes the ground floor as this is in contact with the ground and has minimum heat loss.

Heating is provided at Hacton Cruck by a ground-sourced heat pump with radiant underfloor heating to the ground floor only. This is supplemented by a log burner located in the newly constructed fireplace.

8.3 The Oaks, Brockhampton

The Oaks (NGR: SO 70112 55441), is a National Trust let property on their Brockhampton Estate, Herefordshire. The small, two bedroom, timber-framed cottage has sections dating from the 16th, 17th and 19th Centuries (Coope, 2015). Following the end of a long lease, the property was in need of complete refurbishment. This gave the opportunity to include measures to improve the dwelling's energy efficiency with the fitting of secondary glazing and installation of roof insulation. Pressure testing and thermography[45], undertaken before and after these improvements, enables an evaluation of their efficacy.

8.3.1 History

The Brockhampton Estate lies to the east of Bromyard, in Northeast Herefordshire. Dating from the 12th century (Lello and Williams, 2011), the 687 hectare farmed estate is most noted for the 15th century moated timber-framed manor house Lower Brockhampton and its close-studded 16th century gatehouse (Figure 134).

Figure 134. Lower Brockhampton, 15th century moated manor house and 16th century gatehouse. Source: (Author's own, 2015)

[45] The use of a camera that measures infrared radiation (Young, 2015)

The estate was bequeathed in 1946 to The National Trust (Lello and Williams, 2011), who now lease out many of the smaller estate properties, in addition to providing public access to the manor house and surrounding parkland. The Oaks (Figure 135) is one of these small estate cottages located towards the eastern boundary of the estate, just north of the A44. The oldest section of the house is the single-storey, box frame construction to the south (on the left in Figure 135). Believed to date from the 16th century (Coope, 2015), the panel infill was unknown. The other timber-framed element to the north (right-hand side Figure 135) is believed to date from the 17th century (Coope, 2015). Again, the infill material was unknown. The central stone section and the second floor are believed to date from 19th century (Coope, 2015) and most probably replace an earlier construction.

Figure 135 The Oaks, Brockhampton Estate, Bromyard, Herefordshire. East façade. Source :(Author's own, 2015)

8.3.2 Retrofit

Under the "Energy Efficiency (Private Rented Property)(England and Wales) Regulations" (2015) from the 1st of April 2018 all let properties in England and Wales must achieve an Energy Performance Certificate (EPC) rating of E or above. In addition to the 300 historic buildings open to the public, The National Trust owns 52 villages and has a let property

portfolio of over 5000 homes. Whilst since January 2013 listed buildings have been exempt from requiring an EPC, not all of the National Trust's private rented accommodation is listed. In order to address the challenge set by the upcoming EPC minimum standards legislation, The National Trust launched a new set of environmental standards in February 2015 specifically for their let estate (National Trust, 2015). These standards aim to ensure that their housing is healthy and affordable to heat, has a lower environmental impact, and achieves an EPC of E or above. At the same time, they acknowledge that the heritage of the buildings must be respected, and that any measures to improve the environmental performance must be appropriate to, and enhance these special places (National Trust, 2015). Following the end of a long lease, the necessary refurbishment of The Oaks provided the opportunity to bring this property in line with these new environmental standards. The most economic and least intrusive measures identified for achieving an EPC of E were the installation of metal framed, single glazed, internal secondary glazing and roof insulation.

In addition to these retrofit measures aimed at improving the building's performance, other alterations to the property were undertaken. These included a new concrete screed to the semi-basement cellar floor and the relocation of the bathroom from the back, beyond the cellar-head lobby (Figure 136 top right), to the room on the half landing previously the parlour (Figure 136 bottom right). The work was undertaken by a standard building contractor but overseen by the National Trust's Estate Surveyor.

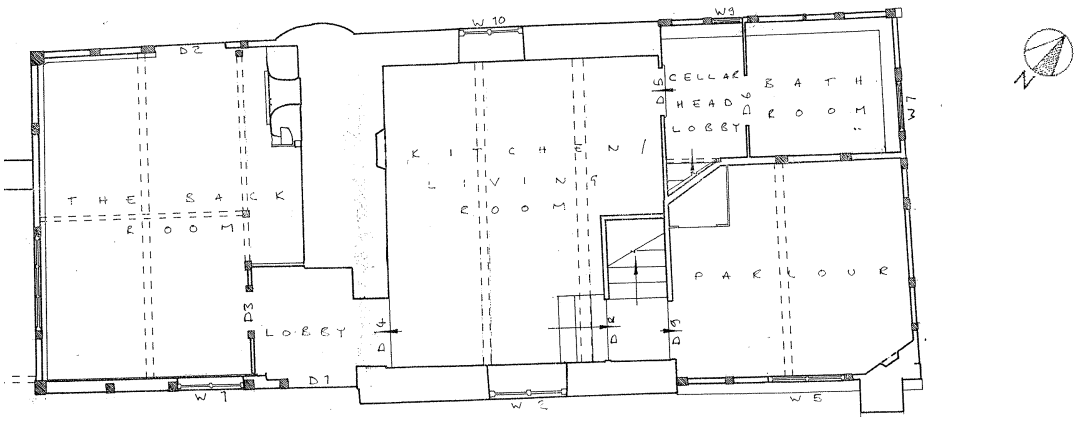

Figure 136 The Oaks, Bromyard. Ground floor plan, pre-retrofit. Source: (National Trust, Knox, 1987)

8.4 The Old Mayor's Parlour and No.25 Church Street, Hereford

Figure 137. Nos.24 and 25 Church Street, Hereford. Source: (Author's own, 2016)

Figure 138. Detail of plaster ceiling, Old Mayor's Parlour. Source: (Author's own, 2016)

The Old Mayor's Parlour, 24 Church Street, Hereford is a gallery space owned by the Church Street Charitable Trust, together with the adjacent property, 25 Church Street (Figure 137) (NGR SO 50981 39895). Currently the building is divided into three separate entities; The Old Mayor's Parlour, located on the first floor of 24 Church Street (the left-hand gable in Figure 137), accessed via a staircase located within 23 Church Street; "Rocket", a café on the ground floor of no.24 and "Layers" a women's' clothes store occupying no.25, with the sales area on the ground floor and storage and office space on the first. The interconnecting door between The Old Mayor's Parlour and the first floor storage area of no.25 was locked shut at all times and was sealed during pressure testing.

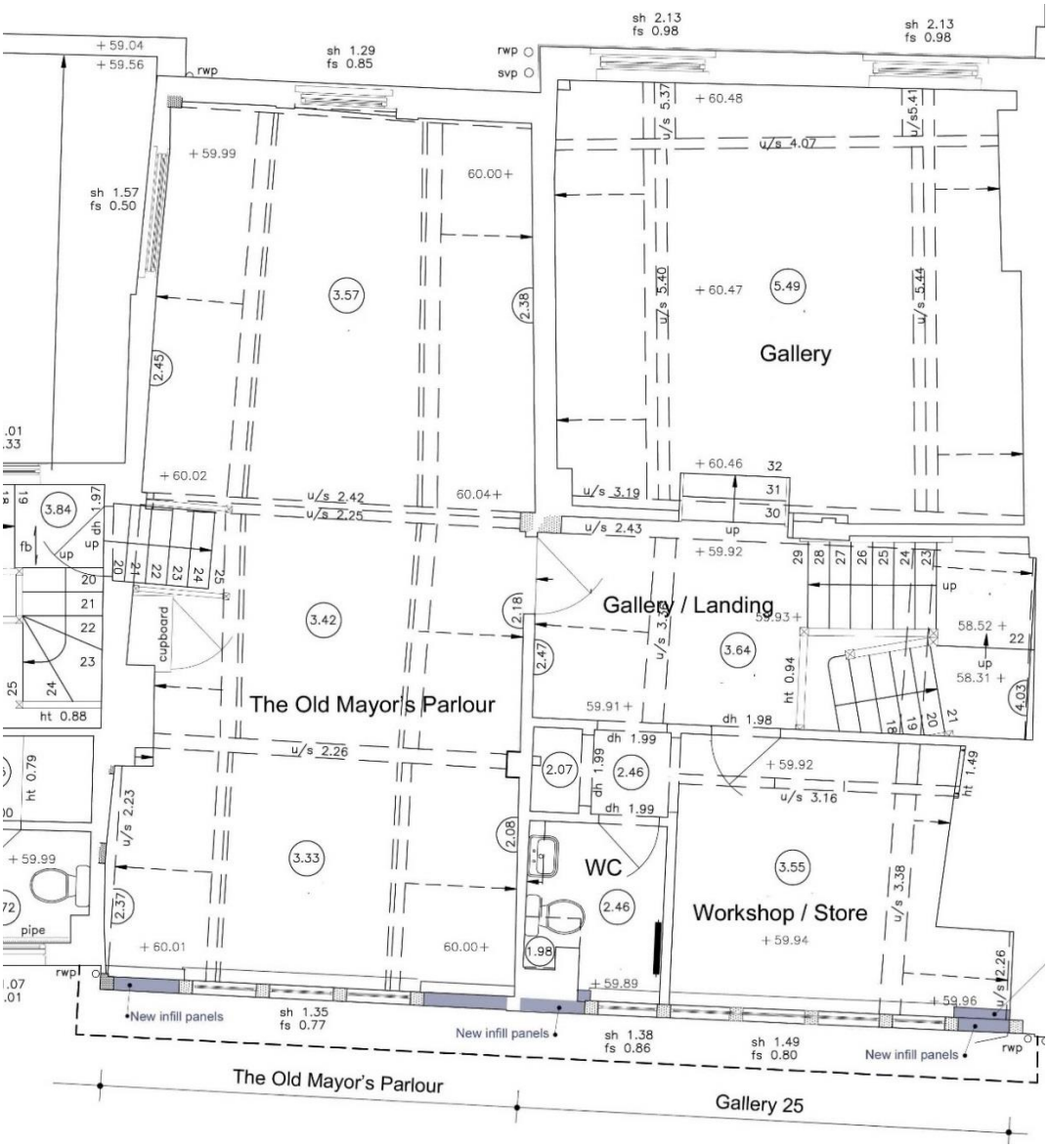

Figure 139 First floor plan of 24 and 25 Church Street. © Jacqueline Demaus Architect. Larger image in appendix C3

8.4.1 History

According to the designation description, the buildings date from the early 17th century (Historic England, 2014), however, other sources state that the buildings are 14th century (BBC, 2014, The Church Street Charitable Trust, 2016). This confusion is to some extent clarified by the original description by The Royal Commission on Historical Monuments (Royal Commission on Historical Monuments, 1931) which records the building as probably built early in the 16th century but with a stone-built cellar under the north part of the

building, containing 15th century doorways (ibid). The east façade onto Church Street is timber-framed at first floor with underbuilding and 20th century shopfronts. It is claimed that it once belonged to, and was used by the *Custos Rotulorum*, the keeper of the rolls, and the Vicars Choral (the men of the Cathedral Choir) (The Church Street Charitable Trust, 2016). Its most notable feature is the ornate early 17th century plaster ceiling to the gallery space (Figure 138), decorated with geometric designs, foliage, leopards heads and fleur-de-lis and a fresco of what is believed to be Hereford Castle (The Church Street Charitable Trust, 2016). The building was saved from demolition in 1969 with help from Ivor Bulmer and the Ancient Monuments Society and has recently been refurbished (BBC, 2014, Demaus, 2015).

8.4.2 Retrofit

The most recent refurbishment work was carried out in two phases. The first phase consisted of internally lining the east wall of just the Old Mayor's Parlour. Originally, it was not intended to replace the infill panels, however, during the first phase of work it was discovered that the infill was of very loose concrete blockwork, rendered with a cement lime render externally and gypsum plaster internally (Demaus, 2015). It was decided that this would require replacement during a second phase of work. The architect explains that "*as all other materials in the OMP (apart from the ceiling) were modern, PIR* [Polyisocyanurate] *insulation was used for the lining and the wood wool was plastered with gypsum plaster*" (Demaus, 2015).

For the second phase of the refurbishment, concrete block infill was removed from the timber-framed east façade of both the Old Mayor's Parlour (no.24) and no. 25 and replaced with wood-fibre insulation using the detail published by Historic England (McCaig and Ridout, 2012) .

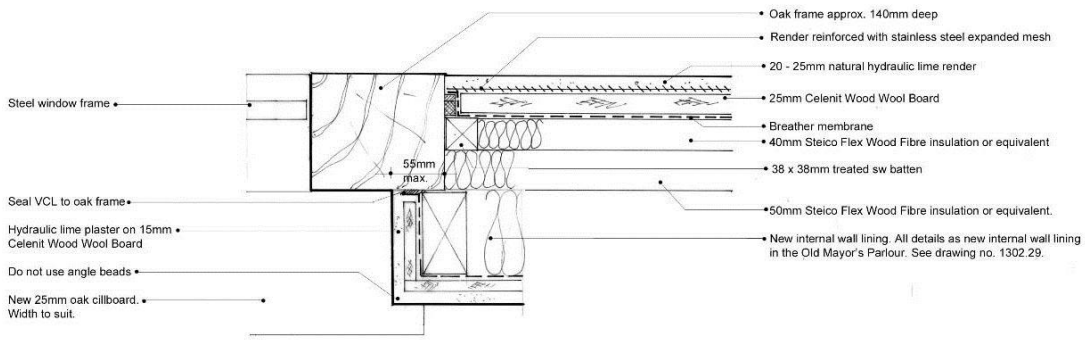

Figure 140 Old Mayor's Parlour. Replacement panel infill detail showing internal lining. Source: (Jaqueline Demaus Architect, 2014)

At the same time an internal lining to the first floor of no.25 was inserted using mineral wool insulation (Demaus, 2015). Whilst installing the Historic England replacement infill detail, the contractor, Colin Richards of CJR Heritage Services Ltd, found the wood fibre insulation difficult to use, as expressed in this excerpt from an email describing their experience:

> "*Our recent experience with the EH spec in Church Street in Hereford has proved interesting and thrown up some issues. Firstly the wood fibre insulation was very fragile and required an absolute precision fit as any pressure pressing it into place caused it to break up and … time needed to be spent cutting fine slivers to fill any gaps. Old nailheads or splinters of timber were sufficient to snag the panels... Overall I think it should work but it is labour intensive and with elements such as the mastic and compriband which need (up to 24 hours) setting time an unscrupulous contractor could cut corners through rushing and thus compromise the layered defences inherent in the design*." (Richards, 2014).

In addition to the technical issues identified by the contractors, in the opinion of the author, the regularity of the finish created by the board substrate lacks something of the character present in panels with a wattle or lath background.

8.5 25-27 Church Street, Saffron Walden, Essex

Figure 141 North elevation of Nos.25 (left) and 27 Church Street, Saffron Walden, Essex. Source: (Author's Own, 2017)

Pevsner described nos. 25-27 Church Street (Figure 141) and their directly adjoining neighbours as being "*amongst the most precious of Saffron Walden*" (Pevsner et al., 2007 p.665). The Grade I listed building is notable for its elaborate pargetting applied in 1676 (Kent, 2015) which depicts foliage , birds, fruits (Figure 142), a stocking and over the carriageway two figures (Figure 143). The figures have been interpreted as either the pre-Conquest giant slayer (Jacobs, 1894) Thomas Hickathrift and his foe the Wisbech Giant, or the biblical Gog and Magog (Pevsner et al., 2007). Today the two properties are both in the private ownership of the technical director of SPAB and are in the process of an ongoing conservation project.

Figure 142. Jettied bay of no. 27 Church Street. Source: (Author's own, 2017)

Figure 143. Jettied bay over carriageway of no.25 Church Street. Source: (Author's own, 2017)

8.5.1 History

Nos 25-27 Church Street were original built as one single mediaeval hall house in the late 14th Century (Kent, 2015, Historic England, 2014) (Figure 144). The central section, currently the sitting room of no. 25, would have been a double height hall with a central hearth and a smoke hole in the ceiling (Kent, 2015), much like that at Hacton Cruck. To the east was the low service cross-wing (Historic England, 2014), typically containing the buttery and pantry at ground level and a chamber above (Forrester, 1976 p.1), with the taller, high-end, cross-wing to the west, typically containing the solar at first floor with possibly a parlour or wardrobe below (ibid). In possibly the 16th Century a brick chimney was inserted, with the hall being floored over at first floor at around the same time (Kent, 2015). A little later, the ground floor of the solar cross-wing was opened up to form a carriageway probably linking to stables to the rear of the property (ibid). As previously noted, the pargetting was applied in 1676. This is believed to be at the point that the original hall house, along with the neighbouring property no 31 Church Street, became the Sun Inn (Pevsner et al., 2007 p.665).

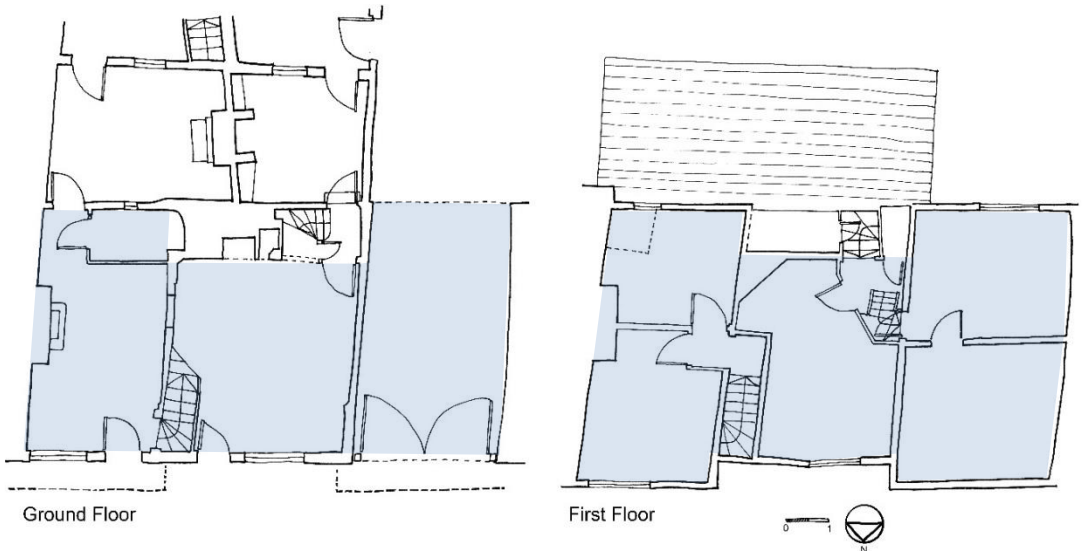

Figure 144. Current Ground and First Floor Plans of Nos. 27 and 25 Church Street, Saffron Walden, Essex, with overlay in blue showing original hall-house. Source: (Author's own based on drawings by (Kent, 2015)

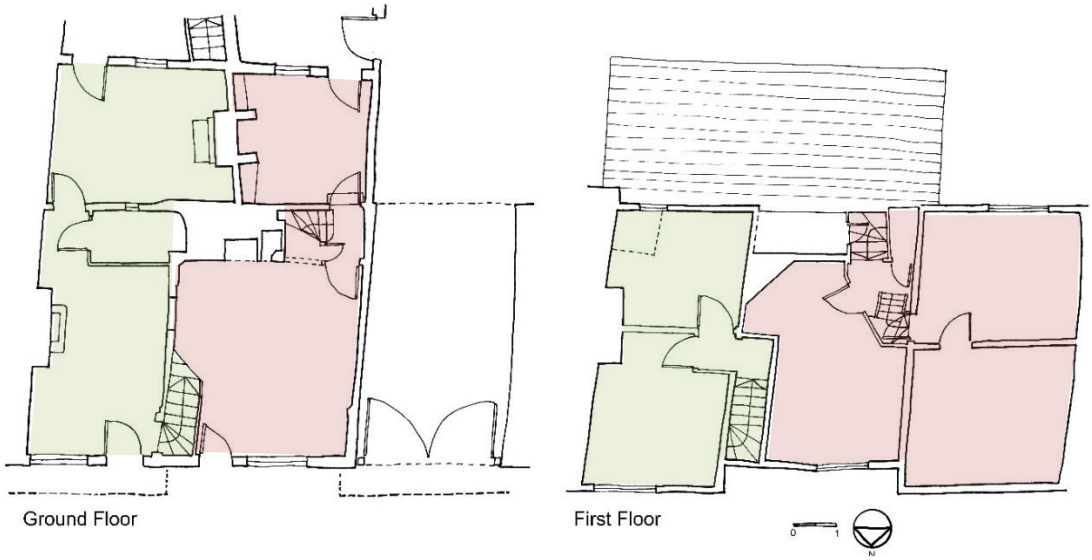

Figure 145. Current Ground and First Floor Plans of Nos. 27 (green) and 25 (pink) Church Street, Saffron Walden, Essex. Source: (Author's own based on drawings by (Kent, 2015))

During the Georgian period, the hall house was subdivided (Figure 145) to form two cottages no. 25 and no. 27 both related to the inn until it closed in the 1870s. At this time, the owners, a prominent Quaker family the Gibsons, extended the two cottages to the south with a single storey outshut to provide kitchen facilities (ibid). Tudor style windows and doors were also fitted to the main elevation around this time (Historic England, 2014). In the 1930s, ownership of the property passed to SPAB, which in turn vested the freehold

to the National Trust, who own it to this day (Kent, 2015). The leasehold for both properties was then acquired by the current owner in 2009. Up until this time no.27 had been occupied by an elderly lady, however no.25 had been uninhabited since the 1960s and had never had electricity installed.

8.5.2 Built Fabric

The structure of the main building is timber-frame, although the ground floor has been underbuilt with brick. The Victorian outshut is also of brick construction. The infill panels to the upper stories is mainly wattle and daub, although some brick nogging has been identified by the owner. The roof is covered with clay peg tiles, except for the roof of the outshut, which is slated. The exterior of the main façade is covered in lime pargeting, with the previously mentioned decorative motifs at first floor level.

8.5.3 Conservation

The aim of the ongoing conservation of the two cottages is to return them to being one house fit for 21st century residential occupation. Internal bathroom facilities are to be installed along with heating. As would be expected of SPAB's technical director, the work is being governed by SPAB's philosophy of "conservative repair". Where possible original and historic fabric will be retained and repaired. To date the major work has been the conservation of the pargeting at a cost of £29,000 (Kent, 2015). Internally 20th century wall finishes have been removed and a doorway has been opened up between the two cottages. Conservation heating is provided by electric radiators; however, the house is currently uninhabited.

8.6 Old Stokes Farm

Figure 146. North entrance elevation of Old Stokes Farm, Battisford, Suffolk. Source: (Author's own, 2017)

Figure 147. South elevation towards rear garden of Old Stokes Farm, Battisford, Suffolk. Source: (Author's own, 2017)

Old Stokes Farm, Battisford, Suffolk (Figure 146 & Figure 147) is a Grade II listed former farmhouse, whose origins date back to the 16th century (Historic England, 2014). The property is now a private residence with two occupants.

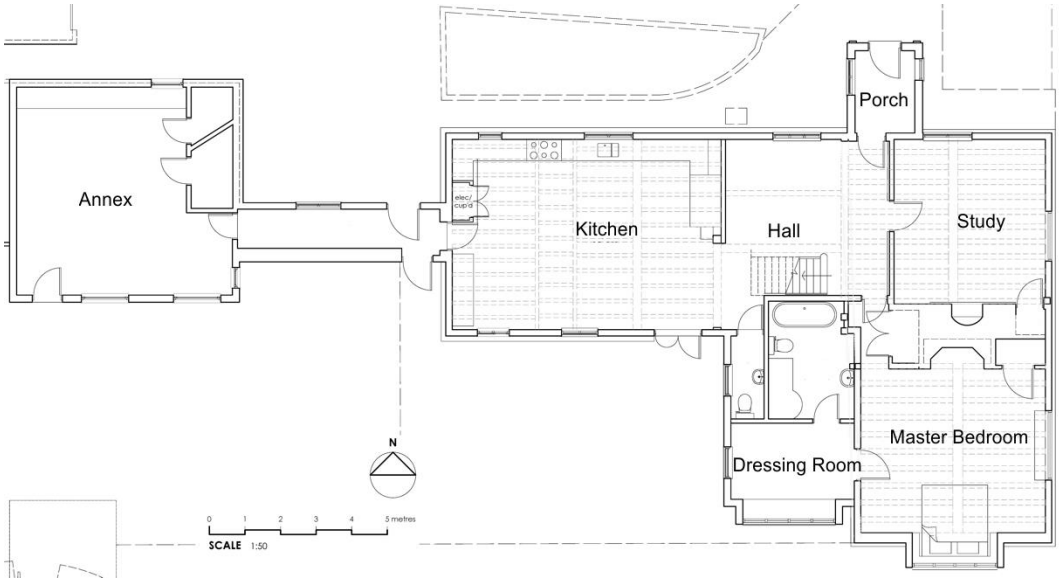

Figure 148. Ground floor Plan. Old Stokes Farm, Battisford, Suffolk. Source: (Andrew Faulkner Associates Ltd, 2016). A larger scale plan is available in appendix C6

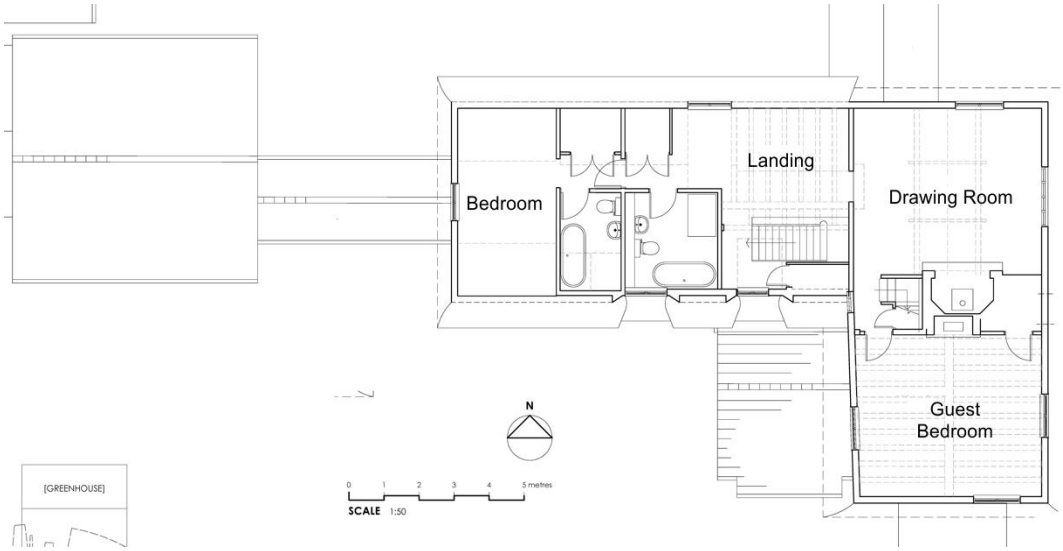

Figure 149. First floor Plan. Old Stokes Farm, Battisford, Suffolk. Source: (Andrew Faulkner Associates Ltd, 2016) A larger scale plan is available in appendix C6

8.6.1 History

The oldest section of the house is the lower wing (to the right in Figure 146) that contains a small section of 16th Century plain crown post roof structure (Historic England, 2014). A second, taller wing was then constructed at right angles to the first in around the 17th century, with an axial red brick chimney with sawtooth shaft (ibid). Subsequent additions were added in the 1980s with a porch to the north (Figure 146), an en-suite bathroom at the junction of the two wings (Figure 147) and a service block to the west.

8.6.2 Built Fabric

The timber-frame was overclad in cement render sometime in the early to mid-20th century. At some point, the timber sole plates have also been encased in concrete and the interior faces painted with an impervious resin. In around 2005 most of the panel infills were replaced with rigid polyisocyanurate (PIR) thermal insulation (Figure 150). In this detail, the cold-bridging of the historic timber-frame is exacerbated by the introduction of additional timber battening both sides to take the plasterboard. In addition, the PIR insulation is not mechanically fixed or bonded and is left free-standing within the opening with large gaps around the sides in many instances (Figure 151).

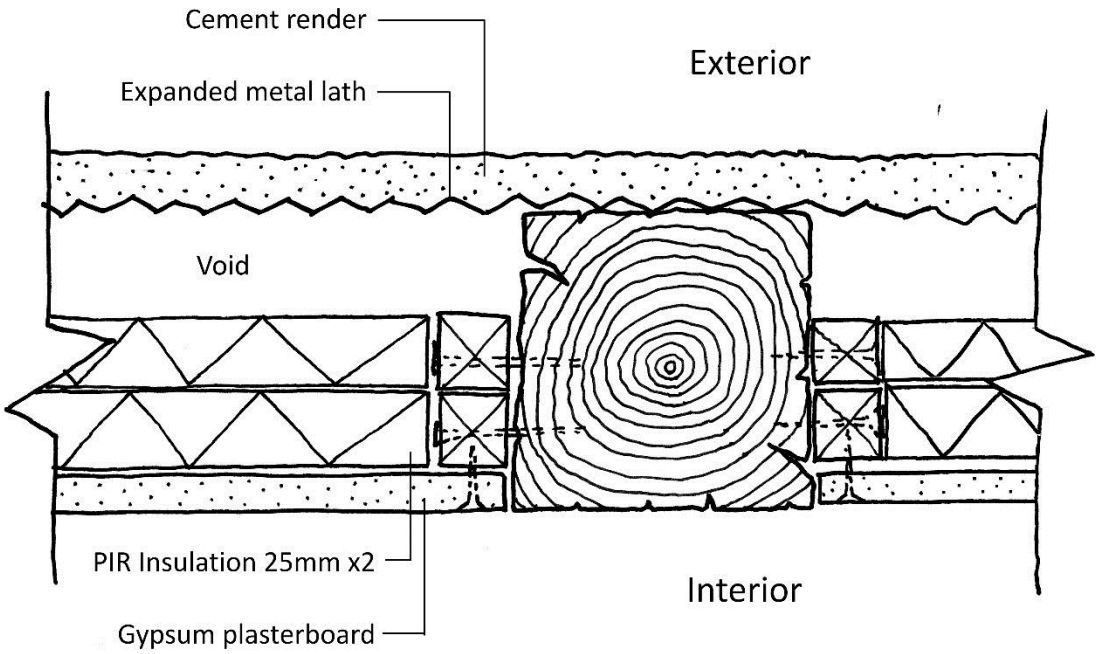

Figure 150. Sketch plan detail of replacement panel infill at Old Stokes Farm. Source: (Author's own, 2017)

On opening up the walls, it can be seen that the expanded metal lath used to carry the cement render has in many places completely corroded away and the original oak laths are also in a state of advanced decay (Figure 152). In addition, there are areas where the external cement render is cracked allowing rain penetration into the wall and building interior (Figure 153).

Figure 151. Replacement infill PIR insulation with plasterboard removed. Old Stokes Farm. Source: (Author's own, 2016)

Figure 152. Internal face of external cement render with internal plasterboard and insulation removed. Source: (Author's own, 2017)

Figure 153. Cracking to external cement render on southern façade. Source: (Author's own, 2017)

The cement render would have been applied to reduce the maintenance of the lime render that probably previously covered the building and the PIR insulation has been installed to improve internal comfort conditions and reduce energy consumption. Both actions were presumably undertaken believing that they were improvements; however, neither have been undertaken with a full understanding of the historic built fabric and have now resulted in the poor current condition of the building. Today many of the timbers are rotten and will require replacing and the cement render is in danger of collapse.

8.6.3 Proposed Renovation

The current owner is currently proposing to strip off all the external cement render and remove all new rigid PIR thermal insulation and gypsum plasterboard infill. The timber-frame will then be fully assessed and any necessary repairs will be undertaken. Whilst they are certain that they will re-render the house in lime render on oak lath, some uncertainty over the preferred insulation material remains. Sheep's wool insulation finished with lime plaster on oak laths is currently the preferred option.

8.7 Summary

The five case studies presented in this chapter show a diverse range of approaches to the continuing occupation of historic timber-framed buildings in two of the principle concentrations of surviving examples of this construction typology. They range from conservative repair at nos. 25 & 27 Church Street, Saffron Walden, to restoration at Hacton Cruck, to limited intervention at The Oaks, more invasive retrofit measures at The Old Mayor's Parlour and near destruction at Old Stokes Farm. In each of the cases, those instigating the alterations and those advising them has a direct bearing on the resulting outcomes.

In the case of nos.25 & 27 Church Street, Saffron Walden, it is unlikely that many people other than the technical director of SPAB would have taken the time and attention to detail over the conservative repair of their property. Samples of paint and internal finishes have been analysed, original fabric preserved and significant sums have been spent on the conservation of the pargeting, prioritising this over the buildings habitability. At Hacton Cruck the enthusiasm for rescuing an almost lost building and restoring it to its original configuration has manifested itself in a hands on approach by the building owner. Although aided by a professional conservation architect and conservation contractors, the slow process of restoring the building has an element of experimentation. The Oaks on the other hand shows the clinical consideration of minimum intervention and cost, versus maximum benefit, that is to be expected from a large institution with expert advisers and a considerable historic property portfolio. Whilst at Old Stokes Farm the opposite is the case. A series of uninformed private owner-occupiers have undertaken major changes that will require significant intervention to reverse and rectify, and have resulted in the substantial loss of historic fabric. It is highly unlikely that these decisions were taken out of malice but

instead stem for a homeowner's desire to improve their living environment, and reduce outgoings and labour intensive maintenance.

It is clear that education and guidance is therefore essential for the owners and guardians of these historic buildings. This however cannot be generic but must acknowledge the variety of drivers and motivations that lie behind the motivation for individuals and organisations to buy, occupy and caring for these buildings.

In the following chapters, the performance of these buildings will be evaluated through in situ monitoring and digital simulation.

9 CASE STUDIES: MONITORING

9.0 Introduction

This chapter presents the methodologies employed in monitoring the previously described case study buildings, and the ensuing results. The results of each case study are analysed individually, with partial conclusions drawn at the end of each sub chapter. A final summary brings together these results, draws overall conclusions and suggests areas for further research.

9.1 Methodologies

There follows a description of the general methodologies used for the monitoring of the case study buildings. Site-specific methodologies, including the specific instrumentation used, the timing and duration of the monitoring are included at the beginning of each sub-chapter. Where possible the relevant British and International standards have been followed and best practice guidelines consulted in order to maximise the validity of the data collected. This chapter focuses only on the in situ monitoring and measurement of the buildings. Simulations of energy use are presented in the following chapter.

9.1.1 In Situ U-value

The methodology employed for the in situ monitoring of U-values was according to BS ISO 9869-1:2014 “Thermal Insulation- Building elements- In-situ measurement of thermal resistance and thermal transmittance. Part 1: Heat flow meter method” (British Standards Institution, 2014). For this method, three variables must be measured. These are the heat flux (W/m²) through the element in question; the internal ambient dry-bulb air temperature (˚C) directly adjacent to the internal surface at the point of measurement; and the external ambient dry-bulb air temperature (˚C) directly adjacent to the external surface at the point corresponding to the internal measurement location (Figure 154).

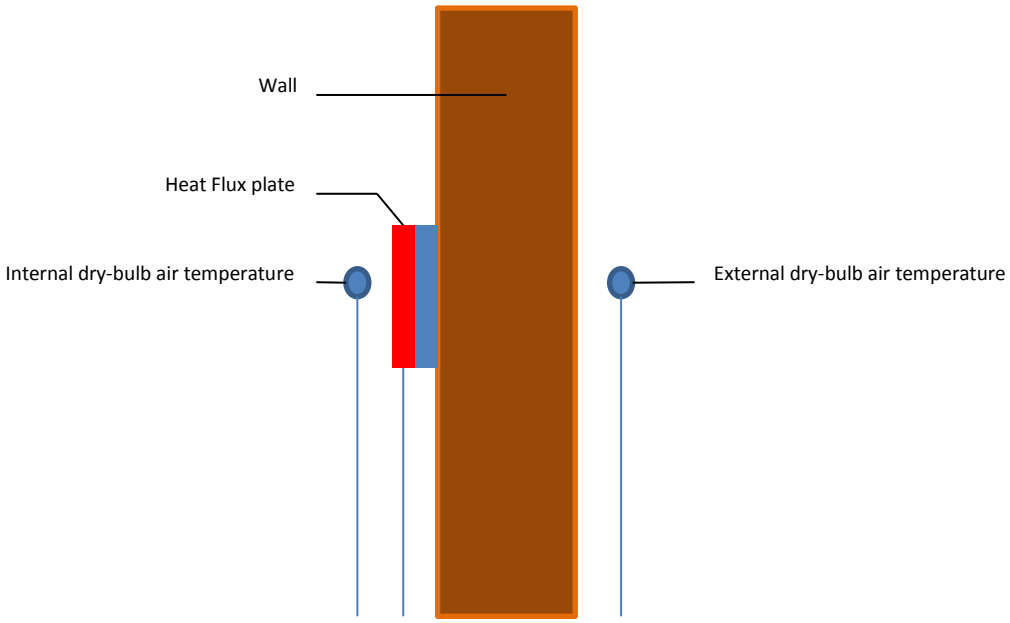

Figure 154 Diagram of instrument set-up used for in situ U-value measurements according to BS ISO 9869-1:2014. Source: (Author's own)

Using the data collected, the U-value was calculated according to the averaging method, which utilises following equation to produce cumulative averages.

$$U\ Value = \frac{\sum_n Q}{\sum_n (ti - te)} \quad (1)$$

Where:

Q is the mean heat flux (W/m^2)

t_i is the mean Internal Temperature (°C)

t_e is the mean External Temperature (°C)

The standard recommends that analysis should exclude data obtained during periods when the external wall surface is exposed to direct solar radiation. Data collected one hour after sunset or one hour after the surface has passed into shade should therefore be utilised. The U-value is deemed to be that calculated when there is a deviation of no more than ±5% from that calculated for the previous 24hr period.

The standard deviation is calculated from moving weekly averages, as suggested by Baker (2011, p.37).

In each of the individual cases, the heat flux (W/m²) was measured with Huxeflux HFP01 heat flow meter plates, held by pressure against the wall surface with a flexible plastic clip. The surface of the plate was covered with petroleum jelly to ensure complete physical contact, with the use of thin PVC film to avoid damage to the internal wall finish.

Project-specific methodologies, including measurement locations and specification of equipment used are detailed for each case study. In situ U-value monitoring was undertaken at all case studies except The Oaks where it was not possible due to the personal circumstances of the tenant.

9.1.1.1 Assumptions and limitations

The measurement of in situ U-values using this methodology is suitable for elements with "quasi-homogeneous layers perpendicular to the heat flow" (British Standards Institution, 2014). The BS defines "quasi-homogeneous" as being when any inhomogeneity close to the location of measurement is smaller than its lateral dimensions and does not form a thermal bridge. Whilst thermography has been used on all measurement locations to ensure no obvious thermal bridging is present, it could be argued that wattle, laths and staves in reality form heterogeneous layers. It has however been assumed for the purposes of this research that due to the small gaps between most of these elements, the inhomogeneity has only a minor influence on the measured result.

It should also be noted that the walls monitored in these case studies are heterogeneous at a larger scale with the timber-frame forming thermal bridges at the perimeter of the infill panels. The BS states that heat flux sensors "shall not be installed in the vicinity of thermal bridges, cracks and similar sources of error" (British Standards Institution, 2014). Whilst it

does not specify a specific distance, it could be taken that due to the size of the panels, the surrounding timber-frame constitute such a source of error. This is however, a problem common to timber-frame infill panels in general and all those measured in these case studies. Direct comparison between panels can therefore be made, however care should be taken in comparing these measured results with those from solid wall constructions, such as those undertaken by Baker for Historic England (Baker, 2016) and Historic Environment Scotland (Baker, 2011) and by Archimetrics for SPAB (Rye et al., 2012a), which do not have timber-frames and the associated errors.

9.1.2 Pressure Testing

For all case studies, the following methodology was used to measure the air permeability index ($m^3/hr/m^2$) and air change rate of each property. The methodology as prescribed by BS EN ISO 9972:2015 (British Standards Institution, 2015b) requires all intentional openings in the building envelope, that is to say fixed vents, drains and fireplaces, to be sealed. All doors and windows must also be closed. The sealing of intentional openings is achieved with the use of polythene sheeting and adhesive tape. A fan (see section 9.1.2.2) is then fitted to the main door of the property and used to depressurize the building to an induced pressure difference of over 50 Pascal, taking readings of fan pressure (q_r) and the induced building pressure difference (Δp) on the way up and on the way down. In addition to these readings, the following parameters must also be measured:

- Average dry bulb internal (T_{int}) and external (T_e) air temperatures. Readings are taken before and after the pressure testing and an average calculated.
- Average barometric pressure. For convenience, these readings were taken from the closest weather station to each case study.

- Internal volume (V), calculated as the overall internal volume with no subtraction of internal elements such as internal floors, walls or other volumes such as voids or furniture etc. (British Standards Institution, 2015b).
- External Envelope Area (A_E), calculated as the overall total area of walls, floors and ceilings bordering the internal volume with no subtractions for internal elements as defined above.

9.1.2.1 Pressure Testing Calculations

Together these readings and measurements are used, according to the methodology as defined by BS EN ISO 9972:2015 (British Standards Institution, 2015b), to calculate the air permeability index ($m^3/h/m^2$), the air change rate at 50 Pascal (/hr) and under normal unpressurised conditions, and the effective leakage area. Full details of these calculations are presented in appendix D.

9.1.2.2 Instrumentation

For all five properties a Minneapolis Blower Door (Figure 155), was used to depressurise the building. This consist of a rigid adjustable timber-frame with rubber gaskets on its outer edges, over which an airtight fabric screen is stretched, into which a large electric fan with adjustable speed is set. Magnehelic analogue pressure gauges (Figure 156) were used to measure both the house pressure (top gauge) and the fan pressure (bottom gauges), with two gauges used for the latter to achieve precision at both low and high pressures. Once installed, and prior to testing, a cover is placed over the fan and the gauges are zeroed. The normal procedure is to start with an eight-holed blanking plate to restrict the airflow. The fan is started and the speed gradually increased in steps, allowing time for the pressure to stabilize at each step and readings to be taken. Once a pressure of >50Pa has been achieved the fan speed is decreased in steps, again taking readings after pressure has stabilized. If sufficient pressure (<50 Pa) is not achieved the eight-holed blanking plate is

removed and the process repeated. A detailed methodology for each case study is included in each of the following sections.

Figure 155. Minneapolis Blower Door, installed at The Oaks. Source: (Author's own, 2015)

Figure 156. Magnehelic pressure gauges, installed at Hacton Cruck. Source (Author's own, 2015)

9.1.3 Thermography

In order to study both the heat loss through the building fabric by conduction and that by air infiltration, thermography was undertaken on all case studies. Given that no British Standard exists for infra-red thermography of buildings, the Building Research Establishment (BRE) guide "Practical guide to infra-red thermography for building surveys" (Hart, 1991) and Historic Environment Scotland's "Short Guide 10: Thermal Imaging in the Thermal Environment" (Young, 2015) were consulted in the creation of this methodology.

The BRE guide recommends that there is a minimum temperature difference between inside and outside of 10°C or 5°C if the building is mechanically pressurised or depressurized (Hart, 1991 p.17-18). It is recommended that this temperature difference is maintained for a 24 hour period prior to the commencement of the monitoring, with a variation of external temperature of >±2°C. This in reality is often difficult to achieve. The Historic Environment Scotland guidance is less stringent, only stating that a "significant temperature difference" is achieved, with a recommendation of a minimum difference between internal and external temperatures of 5°C (Young, 2015 p.23). In addition to the temperature difference, there are other climatic factors that should be taken into consideration, such as wind and more importantly direct solar radiation. The BRE guidance states that during thermography and preferably for 24 hours prior to commencement, there must be no direct solar radiation on the façades under investigation (Hart, 1991 p.18). This is not always possible to achieve, especially for a south facing façade. Although not specified by the guide, in order to minimise the effects of solar radiation and to maximise the temperature difference, thermography is best undertaken just prior to sunrise. The timing and temperature difference for each case study is stated alongside the results for each of the case studies.

For thermography of external surfaces, all buildings were pressurised with the aid the previously described Minneapolis Blower Door. For the thermography of internal surfaces, the buildings were depressurised using the same apparatus.

Once pressurised or depressurised a thermal imaging camera was then used to take infrared thermal images. A detailed methodology, including the model of camera used is provided for each case study in sections 9.2.3, 9.3.2, 9.4.3, 9.5.3 and 9.6.3.

9.1.3.1 Assumptions and limitations

There are some instances where care must be taken with thermography to avoid misdiagnosis when undertaking analysis. These include, variations in surface emissivity, thermal influences from building services, both heating and electrical, and genuine variations in temperature which must be expected due to the physics of heat flow, such as at the corner of walls, and the junction between floors and ceilings (Hart, 1991 p.19-21, Young, 2015 p.15). Emissivity is a surface's ability to emit thermal radiation, and is measured on a scale of 0-1, with zero being no ability to radiate. The emissivity for many building materials is fairly similar (timber 0.85, plaster 0.92, brick 0.90 (Hart, 1991 p.46)), however some materials, especially unpainted metals have values closer to zero (aluminium foil 0.09). As such, these materials will appear to have a lower surface temperature in thermographic images. This must therefore be considered when analysing these images. Care must also be taken over reflective surfaces such as glazing, as measurements will be of the objects reflected and not the surface itself (Young, 2015 p.17).

9.1.4 Internal Hygrothermal Comfort

Although all the previously detailed measurements are important to understand the performance of the building, ultimately it is the hygrothermal (heat and moisture) comfort of the building's occupants that is the most tangible and important factor to be monitored. As previously mentioned, unlike many low carbon retrofits, the main objective with these buildings is achieving affordable comfort, thereby ensuring continuing use, rather than lowering greenhouse gas emissions. Due to their small numbers, even if it were possible for all historic timber-framed buildings to be made zero carbon, this would have a minimal impact on the overall emissions of the UK. It could therefore be argued that ensuring the

ongoing habitation of these historic buildings is the priority. Satisfying or managing 21st century hygrothermal comfort expectations is therefore critical to achieving this goal.

The problem is that hygrothermal comfort is highly subjective, varying from person to person, and is complex and continually changing bringing in factors such as time, season, climate, built form, clothing, physique, metabolism, activity, social conditioning, economic and other factors (Nichol et al., 2012 p.7) and is the subject of significant studies beyond the scope of this thesis. Added to this is the concept of "thermal delight". This acknowledges that rather than a steady state of comfort, dynamic changes in temperature can be a source of pleasure. De Dear (de Dear, 2011) argues that this is particularly the case in environments already outside an individual's thermal comfort zone. For example, a cool breeze will feel delightful on a hot day, just as does entering a warm house on a frosty evening. These positive "*alliesthesia*" depend on stimuli that return the body to its equilibrium (ibid). As such, the standard methodology for assessing hygrothermal comfort conditions involves field surveys, questioning occupants at different times of day and year, preferably incorporating responses from as many occupants as possible to arrive at a range of temperatures comfort is achieved in the building (Nichol et al., 2012 p.23-25). Unfortunately, in all but two of the case studies presented in this thesis, it was not possible to interview the building occupants. Even in the two properties where it was possible, the interviews were limited to one inhabitant at The Oaks and two inhabitants at Old Stokes Farm. In these two cases a simple questionnaire was devised following the guidance given by Nichols et al (Nichol et al., 2012) using an adaption of the Bedford comfort scale from 1-very cold, to 7 very hot (Bedford, 1936) and including observations on the occupants current and typical behaviour with relation to their thermal comfort. A copy of the questionnaire can be found in appendix F.

At Hacton Cruck, the use of the guest book has provided some insight into user satisfaction, however in all other cases (except for The Oaks) measurements of dry bulb air temperature (°C) and relative humidity (%) have been used in order to assess the resultant internal hygrothermal comfort.

According to the international standard ISO EN 7726: 2001 "Ergonomics of the thermal environment—instruments for measuring physical quantities" (ISO, 1998) sensors for monitoring hygrothermal comfort should be mounted at 0.1m, 1.1m and 1.7m above finished floor level in the centre of the space being investigated, or close to the typical location of the occupant(s). This however is completely impractical for long-term measurements within an occupied space, where sensors placed in such a way would be intrusive and subject to possible interference. This is particularly the case in buildings with multiple or unknown occupants. In reality, the sensors were located in discrete locations, selected to minimise both the influence of localised microclimates and inadvertent disturbance by the occupants. Whilst not ideal, this methodology enabled monitoring to occur over a longer period of time and undisturbed. The sensors used were TinyTag Ultra 2 TGU-4500 sensors (Figure 157). These monitor temperatures ranging from -25 to +85°C, and relative humidity from 0 to 95% using built-in sensors. These have an accuracy of ±0.4-0.8°C (dependant on temperature range) and ±3% humidity, and a resolution of 0.01°C and 0.3%. They do however have the disadvantage of sticking at 100% humidity if exposed to these conditions for extended periods. These erroneous readings were therefore deleted from the results. An additional disadvantage is there relatively large size at 72x60x33mm. Due to concerns from the trustees of The Old Mayor's Parlour, long term monitoring at this particular case study was continued with Maxim Hygrochron iButton DS1923 Sensors (Figure 158). With a similar accuracy but a reduced resolution (0.5°C and 0.6%), their main advantage is there unobtrusive design and small size at less than 20mm diameter.

Figure 157 TinyTag Ultra 2 TGU-4500

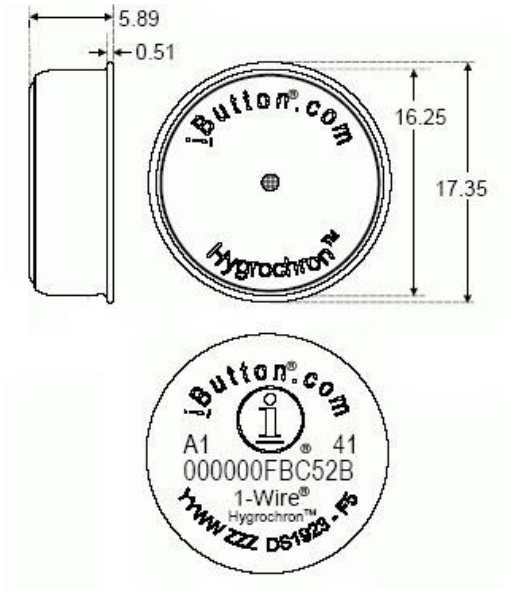

Figure 158 Maxim Hygrochron iButton DS1923. Dimensions in mm

The measurements recorded were then used to assess the hygrothermal comfort conditions of each case study. To achieve this, a number of alternative definitions of thermal and hygrothermal comfort were considered. The first was the American Society of Heating, Refrigerating and Air-Conditioning Engineers' (ASHRAE) standard 55-2013, acceptable operative temperature ranges for naturally conditioned spaces (ASHRAE, 2013 p.12) (Figure 159).

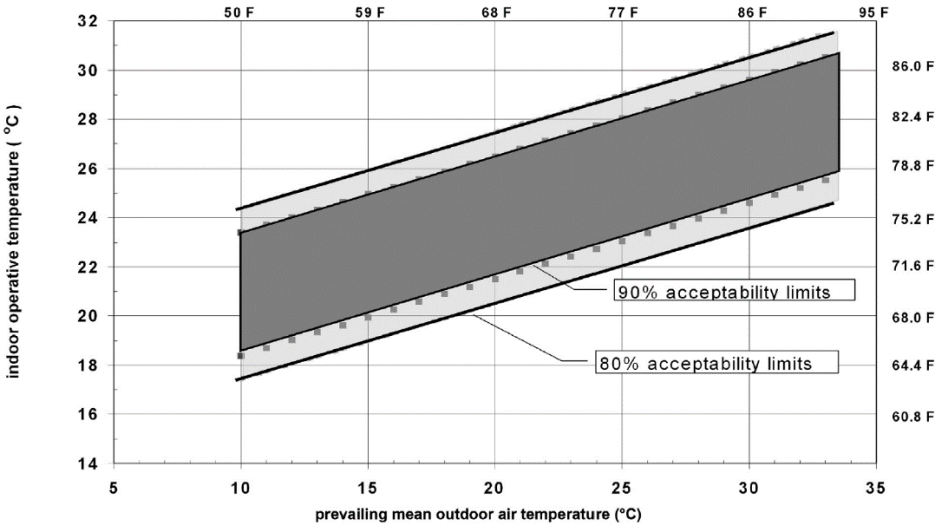

Figure 159. ASHRAE 55-2013 acceptable operative temperature ranges for naturally conditioned spaces. Source: (ASHRAE, 2013 p.12)

This allows the plotting of mean outdoor temperatures against indoor temperatures, with those deemed to meet thermal comfort falling within the dark grey shaded area. However, this methodology uses only temperature measurements and does not include the influence of relative humidity.

At the other extreme the equations of Fanger (Fanger, 1973) are extremely complex and require the measurement of many parameters including air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate, and clothing insulation. Due to limitations of available equipment, Fanger's methodology was not adopted for this research. A simpler tool for evaluating comfort conditions is the bioclimatic chart, which plots dry bulb temperature against wet bulb temperature or relative humidity. Versions of these charts were developed by Olgyay (Olgyay and Olgyay, 1963 p.22) who places the comfort zone between 20°C and 30°C depending on relative humidity and Givoni (Givoni, 1998 p.38) who defines the comfort zone between 17°C and 27°C, with a range of relative humidity between 20% and 70% (Figure 160).

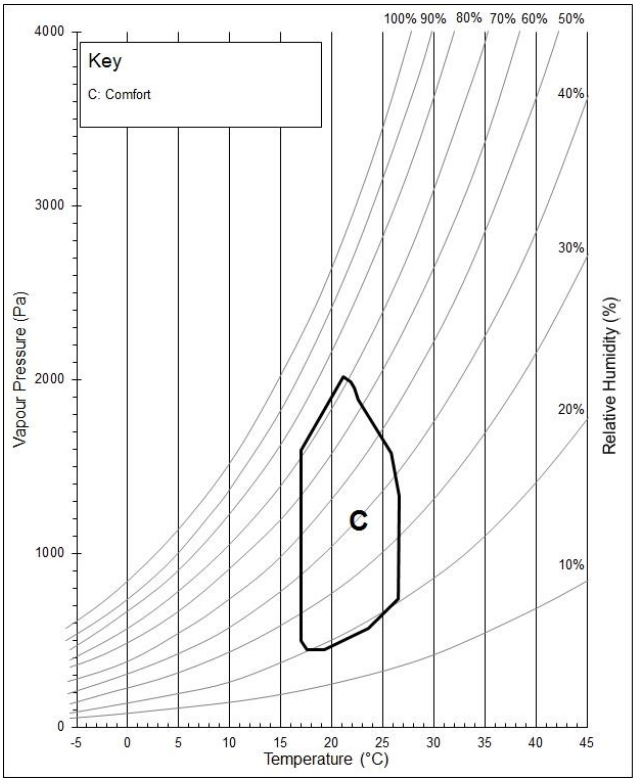

Figure 160. Psychrometric chart showing the comfort zone as defined by Givoni. Source: based on (Givoni, 1998).

For the purposes of this thesis, the psychrometric chart of Givoni was used for the analysis of the internal hygrothermal comfort conditions within each case study. Further detailed methodologies, including monitoring positions are included in the methodology for each case study.

9.1.5 Timber Moisture Measurements

9.1.5.1 Surface Moisture Measurements

There exist a number of different methods for measuring the moisture content of building materials. These include carbide testing, gravitational method, electrical resistance and capacitance, relative humidity, microwave, radar, x-ray, thermography and nuclear magnetic resonance (NMR) (Phillipson et al., 2007). These can be categorized as in situ or laboratory; destructive, semi-destructive or non-destructive; and absolute or comparative and give either punctual or continual measurements. The choice of method depends on the application in question. For punctual measurements of surface moisture of timber, the simplest method is electrical resistance using a wood moisture meter calibrated for oak. Non-destructive methods such as the use of ultra-wideband radio waves are also of interest, however these currently remain to be developed beyond laboratory prototypes (Healy, 2006).

At The Oaks and Old Stokes Farm, a Testo 606-2 resistance meter was used. This meter calculates moisture content as a weight percentage based on the dry mass, by measuring the electrical resistance of the timber. The meter has been calibrated for six different timber species. For the measurements presented in this thesis the calibration was set to "2-*oak, pine, maple, ash-tree, douglas fir, meranti*" (Testo, 2007). The specifications for the meter state that it has an accuracy of ±1 %, a resolution of 0.1 and a measurement range for oak of 7 to 47.9% (ibid).

Ideally, the serial number of the Testo 606-2 resistance moisture meter should have been noted at the time of each of the first measurements to ensure that the same instrument was used for all measurements. Unfortunately this did not occur. In order to assess the potential variation between the two available Testo 606-2 meters a simple experiment was undertaken of taking readings with both meters of a variety of wood samples at varying moisture contents. The results were then plotted and are presented in Figure 161.

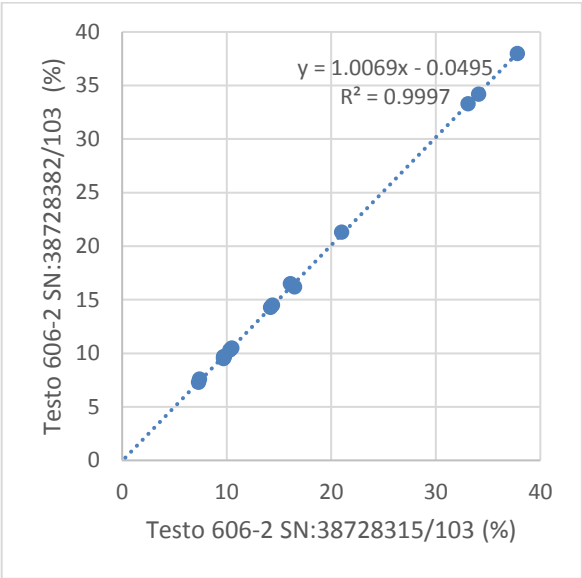

Figure 161. Surface moisture readings taken with two Testo 606-2 resistance moisture meters, serial numbers SN:38728315/103 and SN:38728382/103 to calculate error margin. Source: (Author's own, 2015)

The two sets of readings show a close correlation with a coefficient of correlation[46] (R^2) of 0.9997 and a linear equation of $y = 1.00069x - 0.4950$. The maximum measured deviation between readings was 0.3 and a mean deviation of 0.07. Although this procedure could have been avoided by the careful notation of the serial number at the time of the experiment, it does show that the error between using both meters is negligible.

[46] A coefficient of correlation (R^2) of 1 would show a perfect correlation.

9.1.5.2 Interstitial Moisture Measurements

Electrical resistance has previously been used by researchers monitoring moisture levels within solid masonry construction (Gandhi et al., 2012) using the insertion of timber dowels. There are however both physical constraints, and limitations in the accuracy of this method. For absolute readings, the method must be calibrated to measure the electrical resistance across two electrodes embedded in the timber, noting both the distance between the electrodes and the specific species of timber. The direction of the grain should also be noted as the conductivity along the grain, across the grain, and tangential to it are related by the approximate ratio of 1.0:0.55:0.50 (Simpson and TenWolde, 1999). In order to attach the electrodes to timber within the wall, or introduce a timber dowel where no timber exists, a hole must be drilled. This is problematic in historic buildings due to the damage and loss of historic fabric. The hole also drastically alters the conditions within the wall, providing a conduit for the transfer of moisture and heat by both convection and conduction. Within a solid masonry wall, these changes may be deemed to be negligible due to the shear bulk of the wall. This is not however the case with the thinner walls of timber-frame.

Monitoring relative humidity can be another method of measuring the moisture content within walls. This method has been used on the Parnassus project to monitor moisture in historic walls (Erkal et al., 2013, Didem Aktas et al., 2015, D'Ayala and Aktas, 2016). The method has the advantage over electrical resistance monitoring in that a narrower hole can be used to insert the sensor, the dimensions of which are smaller than a wooden dowel. In order to convert relative humidity to moisture content the sorption profile of the material in question must be known. In the case of the Parnassus project this was acquired by the use of Dynamic Vapour Sorption (DVS) analysis on the dust removed when drilling. Given the large surface area of the dust it must be questioned if the sorption profile is a true match to the consolidated material within the wall. In addition, many materials have

different absorption and desorption profiles, known as hysteresis. It must therefore also be known if the wall is in the process of wetting or drying. It should also be noted that some researchers using relative humidity probes embedded inside cavities within the wall depth, have recorded constant readings of 100% even when the wall has been shown to be dry by other methods (Pinchin, 2008).

In all but one of the case studies it was not possible to drill holes or open up the panel infills to insert interstitial monitoring equipment. However, given that work is proposed at Old Stokes Farm and that the infill dates from the 20th century, it was possible to open up two sections of wall and install electrical resistance moisture monitoring equipment. GE Sensing Hygrotrac® type 4 sensors were used. These allow for the monitoring of moisture through the measurement of the electrical resistance across two stainless steel screws inserted into the timber-frame 20mm apart, in addition to temperature and relative humidity. Further details on the monitoring positions are included in the section on Old Stokes Farm.

9.1.6 Co-heating test (not undertaken)

These tests involve heating a building at a constant temperature over a given period, measuring the energy required to maintain that temperature, taking into account the internal-external temperature difference and incident solar radiation (Baker, 2016). As such, it is possible to calculate the heat-loss coefficient of the building envelope as a whole.

Co-heating tests were not undertaken due to two principal factors both stemming from the required duration of such tests. It has been shown that the levels of accuracy for co-heating tests increase with the length of test period (Alexander and Jenkins, 2015). To achieve an accuracy of greater than 10% a test period of between 6 and 8 weeks is required (ibid p.1736) unless the test takes place during the six weeks of mid-winter, in which case the duration can be reduced to 3 weeks (ibid). During the monitoring period, the house must be unoccupied to avoid uncontrolled changes in temperature, internal gains and

airtightness. As such, even with the shorter test period of 3 weeks, the only case study where an unoccupied period might have been possible was Hacton Cruck.

In the case of Hacton Cruck an approximation of heating costs required to maintain an indoor temperature >20°C was undertaken based on measured U-values and air change rates. The resulting estimate suggested a cost of £59 per day or £1239 for three weeks. In addition, a SAP calculation showed that the building fabric accounted for only 48% of the overall heat-loss, the rest resulting from the excessive air change rate. It was therefore decided not to undertake any co-heating tests as part of this thesis. This could be an area for future research.

9.2 Hacton Cruck, Preston-on-Wye

For this holiday rental cottage, where the principal retrofit actions were the relocation of the timber-frame to a new south bay and floor slab, and the repair and replacement of infill panels, the following monitoring was undertaken:

- In situ U-value measurements
- Pressure Testing
- Thermography
- Hygrothermal monitoring

Timber moisture monitoring was not undertaken due to the time constraints imposed on visits by the departure and arrival of guests.

9.2.1 In Situ U-value measurements

9.2.1.1 Detailed Methodology

Measurements at three monitoring positions were undertaken at Hacton Cruck as shown in Figure 162. Monitoring position M1 measured the in situ U-value of repaired pre-existing lath and plaster panel, M2 a new wattle-and-daub panel and M3 a new panel with multi-foil insulation.

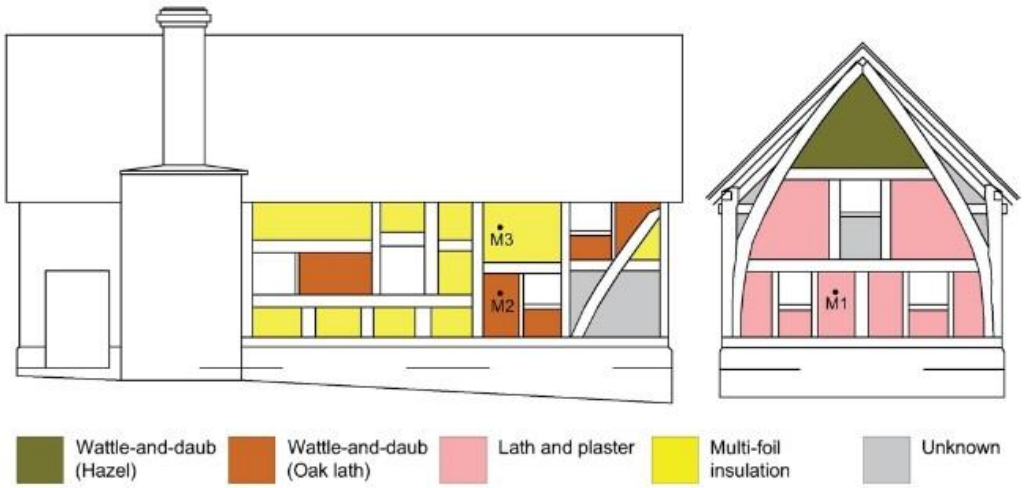

Figure 162. East elevation (left) and north elevation (right) of Hacton Cruck showing monitoring positions M1, M2 and M3 in relation to panel infill types. Source: (Author's own, 2015)

9.2.1.1.1 Instrumentation

The outputs of the heat flux plates were connected to Eltek® wireless telemetry transmitters with inputs for voltage. These in turn relayed the data to an Eltek® Squirrel® data logger with the voltage recorded at 5-minute intervals. The internal ambient air temperature (˚C) directly behind each heat flow plate was measured with an Eltek® wireless telemetry transmitter with built in temperature and relative humidity sensors, with measurements recorded at the same frequency as the voltage. The external ambient air temperatures (˚C) were measured using thermistors connected to an Eltek® wireless telemetry transmitter with inputs for external thermistors, also transmitting to the Eltek® Squirrel® data logger with readings at the same frequency of 5 minutes.

9.2.1.1.2 Time and duration of monitoring

The in situ U-value (thermal transmittance) monitoring was undertaken towards the end of the heating season, between 6th and 17th March 2015. It had been intended that the monitoring would continue until 25th March giving 17 days of results. However, due to a power cut on the 17th March, the monitoring period was reduced to 11 consecutive days.

9.2.1.2 Results and Analysis

In accordance with BS ISO 9869-1:2014 (British Standards Institution, 2014) only night time readings (one hour after sunset until sunrise) were included in order to remove the influence of any direct solar radiation. A variation of no more than ±5% of the final value was reached and maintained on the 14/03/2015 (Figure 163), 4 days before the completion of the monitoring. The average U-values over this final period and the standard deviation are presented in Table 13. U-values calculated according to BS EN ISO 6946:2007 (British Standards Institution, 2007b) with values taken from BS EN 12524:2000 (British Standards Institution, 2000) are also presented in the same table.

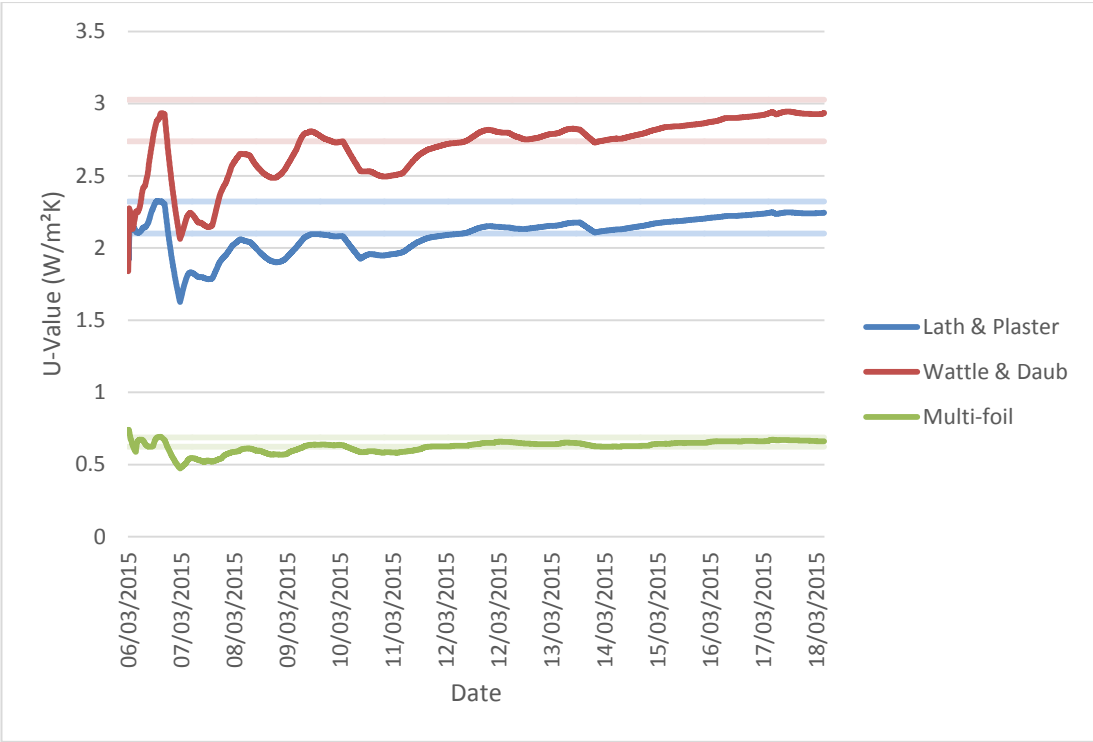

Figure 163 Cumulative averages of measured U-values of three infill wall panels measured 6th-17th March 2015

Table 13 Thermal transmittance and thermal resistance of wall panels calculated from data measured 13th-16th March 2015

Wall Panel Infill	Measured U-value (Thermal transmittance) (W/m²K)	Standard deviation (W/m²K)	Calculated U-value (W/m²K)	Percentage difference Measured to calculated (%)
Lath and Lime Plaster	2.21	±0.11	2.40	+4.4
Wattle-and-Daub	2.88	±0.17	2.99	+8.0
Multi Foil Insulation	0.66	±0.03	0.41	+42.0

The results show that the repaired pre-existing lath and lime plaster panel performs reasonably well with a U-value equivalent to that of a historic solid brick wall (Rye et al., 2012b). The new wattle-and-daub infill performs less well and is higher than those measured for wattle and daub infill panels by Rye et al (2012b) that were found to be 1.69W/m²K and 2.03 W/m²K (ibid). However, the infill panels measured by Rye et al. were thicker (144mm and 125mm respectively) than the panel measured here at Hacton Cruck

that only had a thickness of 88mm, although this does not fully account for the difference[47].

The new panel with multi foil insulation sandwiched between lime plaster on metal lath performs the best, with a U-value equivalent to that of a typical modern timber-frame building insulated with 50mm of mineral wool, allowing through only 28% of the heat that is conducted by the original lath and lime plaster.

The comparisons with the calculated U-values show that the measured values for the lath and plaster and wattle-and-daub are lower, therefore better performing, than those calculated. This is in line with other research that has shown that in general the measured in situ U-values of traditional and historic constructions outperform their calculated values (Rye et al., 2012b, Baker, 2011). The measured value for the new panels with multi-foil insulation is however worse than the calculated. This is perhaps due to the cold-bridging of the vertical timber staves within the panel that hold the foil in a central void, in conjunction with a poor junction between insulation and frame at the perimeter.

The resulting measured U-values are used in simulations, presented in chapter 10, to calculate the energy demand and the reductions achieved.

9.2.2 Pressure Testing

9.2.2.1 Detailed Methodology

Pressure testing following the previously described standard methodology took place on 25th March 2015 and again on 21st November 2015.

[47] The combined coefficient of thermal conductivity for the wattle and daub panels measured by Rye et al. would be 0.341 W/mK and 0.387W/mK respectively yet that for Hacton Cruck would be 0.497W/mK.

9.2.2.2 Results and Analysis

On the first attempt on the 25th March 2015, even with the fan on full, with no blanking plate, and with all vents, drains and fireplaces sealed, it was difficult to achieve a pressure difference of even 4 Pascal. Whilst limited in number (Figure 164), those readings taken[48] would suggest that the house had an air permeability index of 154 m³/hr/m², an air change rate at 50 Pascal of 130 changes per hour, an estimated air change rate unpressurised of 6.5 air changes per hour and an effective open area of 32.6 m².

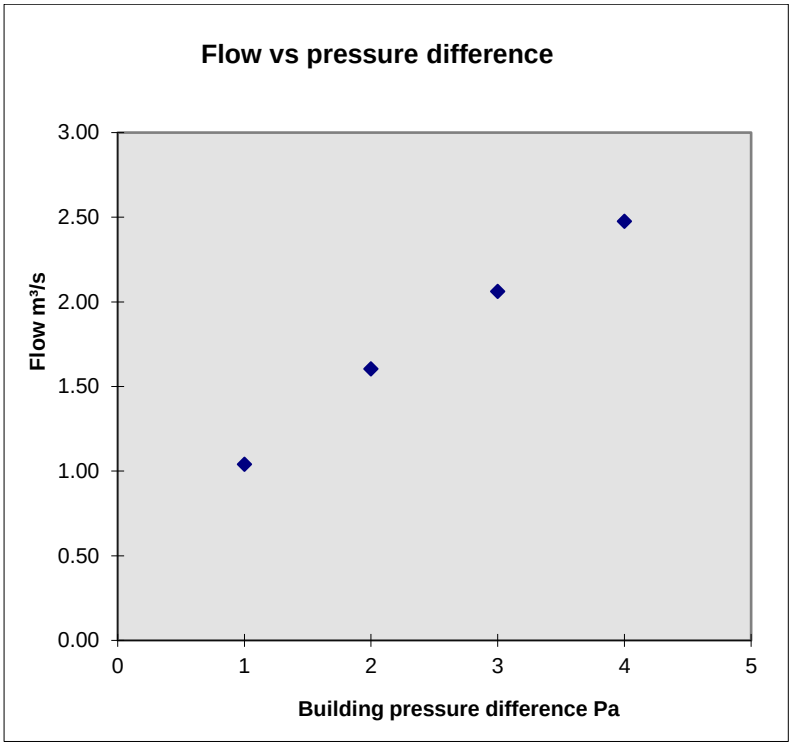

Figure 164 Hacton Cruck. Diagram of measured flow vs pressure difference 25th March 2015

To put the estimated air change rate in context, according to the UK building regulations new-build dwellings must achieve an air permeability index of no more than 10 m³/hr/m² (HM Government, 2016c), although it should be noted that this requirement does not apply to works to existing buildings. The effective open area of 32.6 m², measured at

[48] The coefficient of determination (R^2) of the best fit line of the plotted logarithm of the airflow rate through the building envelope and the building pressure difference has a value of 1 showing the closest fit possible

Hacton Cruck, is the equivalent of having 19 open doors. One area responsible for these high infiltration rates has already been identified, that of the junctions between panels and timber and between timbers themselves. However, a much more significant element contributing to this lack of air-tightness is the unlined thatched roof (Figure 165). Thermography of this element clearly showed the difference between the unlined (Figure 166) and the torched (lime plastered) roofs (Figure 307) to either end of the building. The owner of the property was informed of this by the author and in late October 2015 decided to improve the air-tightness by torching (lime plastering) the central section of the ceiling. The lime plaster finish was applied to the entire underside of the thatch except a central square, left to represent the original presence of a smoke-hole before the construction of a chimney.

Figure 165 Hacton Cruck, interior view of central hall with bedroom beyond showing unlined thatch roof, 2015

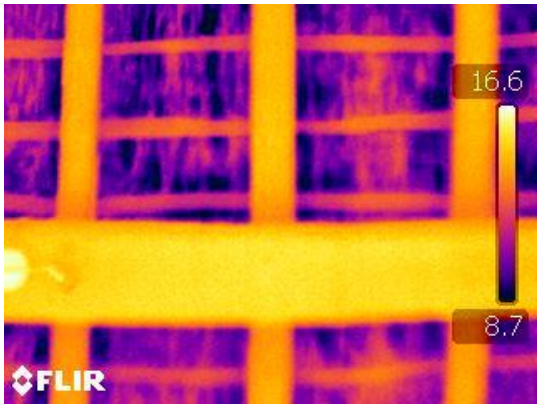

Figure 166 Hacton Cruck, thermography of unlined thatch. Source: (Author's own, 2015)

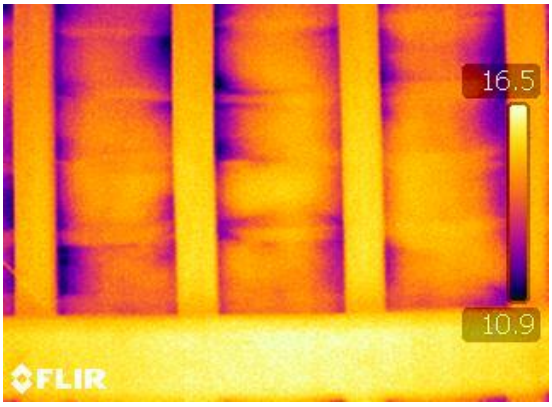

Figure 167 lined thatch over bedroom. Source: (Author's own, 2015)

The plaster was not continued right up to the ridge beam but stopped short to allow some air movement to aid in drying the external thatch. Following the completion of this work the pressure testing was repeated. This second time a maximum pressure of 11 Pascal was achieved. Whilst not the 50 Pascal required by the official methodology, this was however, an improvement. This increased pressure allowed for more readings to be taken leading to a greater reliability of the results. These showed an air permeability index of 80 $m^3/hr/m^2$, an air change rate at 50 Pascal of 68 changes per hour, an estimated air change rate unpressurised of 3.4 air changes per hour and an effective open area of 15.8 square meters[49]. Even with the uncertainty of accuracy of the original measurements due to the limited readings achieved, the results of the second pressure test show a marked improvement of approximately 50%.

Table 14. Hacton Cruck. Results of pressure testing pre and post-torching. (25/03/2015 & 21/11/2015)

	Air Permeability Index ($m^3/h/m^2$)	**Effective Leakage Area (m^2)**	**Air change Rate @50 Pa (/hr)**	**Air change rate unpressurised (/hr)**
Pre-Retrofit	154	32.6	130	6.5
Post-Retrofit	80	15.8	68	3.4
% post to pre	52	48	52	52

[49] (R^2) of this best fit line = 0.99 showing an almost perfect fit.

9.2.3 Thermography

9.2.3.1 Detailed Methodology

At the end of the two-week in situ U-value measurement period, thermography of the property was undertaken on the 25th March 2015 using a FLIR B250 thermal imaging camera. The images were taken at 5:30am, half an hour before sunrise, for maximum temperature differences between the internal (15˚C) and external environments (1˚C) and to avoid any influence of direct solar radiation (Hart, 1991 p.18). Additional electric fan heaters were used for an hour prior to taking the images to achieve this temperature difference. To enhance the transfer of heat, the building was first pressurized using the previously mentioned Minneapolis Blower Door for thermography of the exterior of the building, then depressurized for the thermography of the interior.

9.2.3.2 Results and Analysis

The images show the differing thermal performance of the various infill panels, with the lighter, warmer colours indicating areas of higher heat loss. In Figure 168 two of the new wattle-and-daub panels can be identified in paler orange (a and b) due to their higher surface temperature. One is between the two windows on the left (a) and the other is L-shaped adjacent to the right-hand window (b). Thermal-bridging formed by the upright timber staves within the panels is visible as the lighter vertical lines in the middle of each panel. The image also indicates the lack of sufficient perimeter insulation to the concrete floor slab containing underfloor heating.

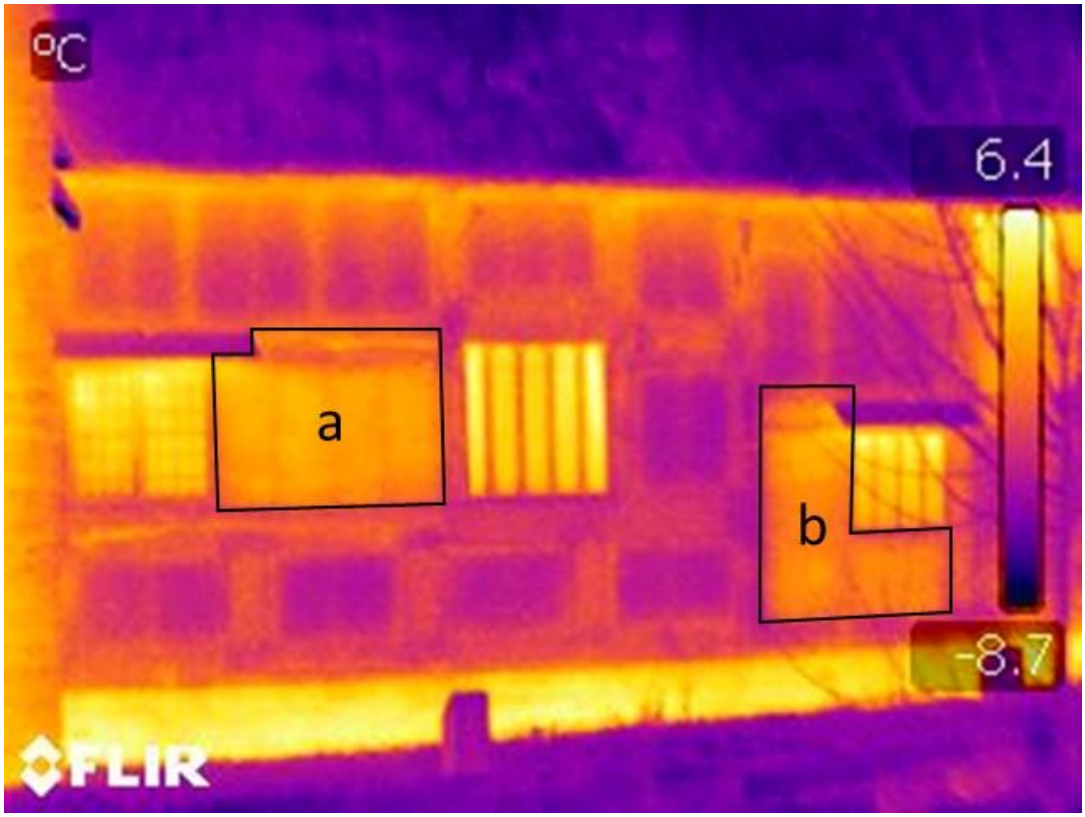

Figure 168 Hacton Cruck, thermographic image of external view of east elevation, 5:30am 25th March 2015. Lighter colours indicate greater heat loss. New wattle-and-daub panels a and b show more heat transfer than surrounding panels insulated with multi-foil insulation.

Whilst the external thermography visibly demonstrates the different thermal performance of the various infill panels, the internal thermography made evident the heat loss via air infiltration through the perimeter joints between panel and frame, joints between timbers, through peg holes within the timber members themselves (Figure 169) and as previously described, most notably through the unlined thatch ceiling. This, together with the pressure testing suggests that whilst the inclusion of multi foil insulation within most of the new panels will have improved their individual performance, there are other factors influencing the overall efficiency of the building as a whole.

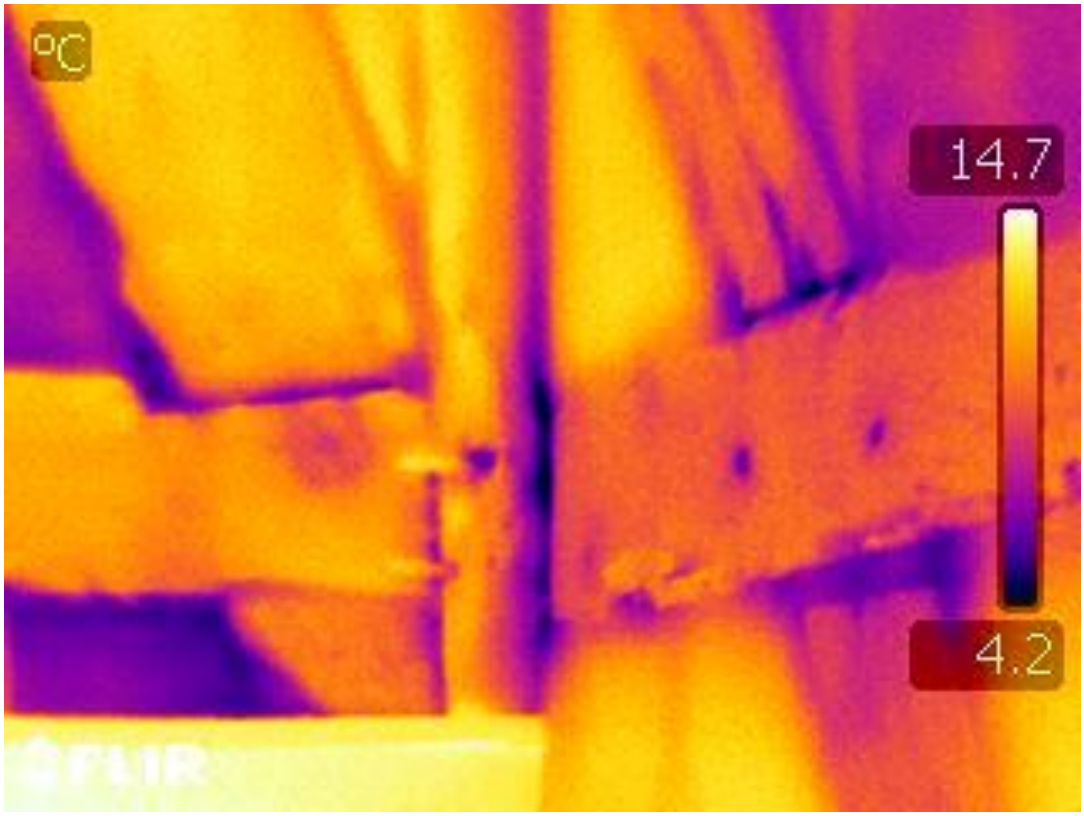

Figure 169 Hacton Cruck, thermographic image of internal northeast corner, 5:45am 25th March 2015.

9.2.4 Hygrothermal Comfort

9.2.4.1 Detailed Methodology

In order to assess the hygrothermal comfort conditions (temperature and relative humidity) that are currently achieved within the house, TinyTag Ultra 2 hygrothermal sensors were mounted in five internal locations, covering all habitable rooms (Figure 170), and one external location, protected from precipitation and direct solar radiation, to monitor ambient air temperature (˚C) and relative humidity (%). In November 2015, it was realised that the sensor for the upstairs bedroom was being affected by the microclimate created by the adjacent hot water tank. This was therefore relocated to below the bed and only readings post-November 2015 are presented. Following one full year of data collection, the sensors were removed in March 2016. It was however decided that in order to enable a comparison of the conditions pre and post-torching of the thatch ceiling that

further measurements were required. The sensors were reinstalled July 2016 and an additional year of monitoring was undertaken.

Figure 170. Hacton Cruck, ground (left) and first (right) plans showing location of hygrothermal sensors. Source: (Based on Jacqueline Demaus Architect, 2001)

9.2.4.2 Results and Analysis

Figure 172 and Figure 173 (overleaf) show a comparison for the months March-September, pre and post-torching of the hygrothermal comfort as defined by Givoni (Givoni, 1998) for those days when the house was occupied[50]. A comparison is only possible for these seven months due to these being the only months monitored pre-torching. The results show an

[50] Occupation data based on the booking register obtained from house caretaker and from visitors' book entries

overall shift upwards in the internal temperature in addition to some dryer conditions in the second bedroom on the ground floor.

The improvement in hygrothermal comfort conditions is most evident when comparing the percentage of time that hygrothermal comfort conditions were achieved (Figure 171). These show that although the external conditions achieved hygrothermal comfort conditions for less of the time during the March-September post-torching, there was a general improvement in the indoor climate.

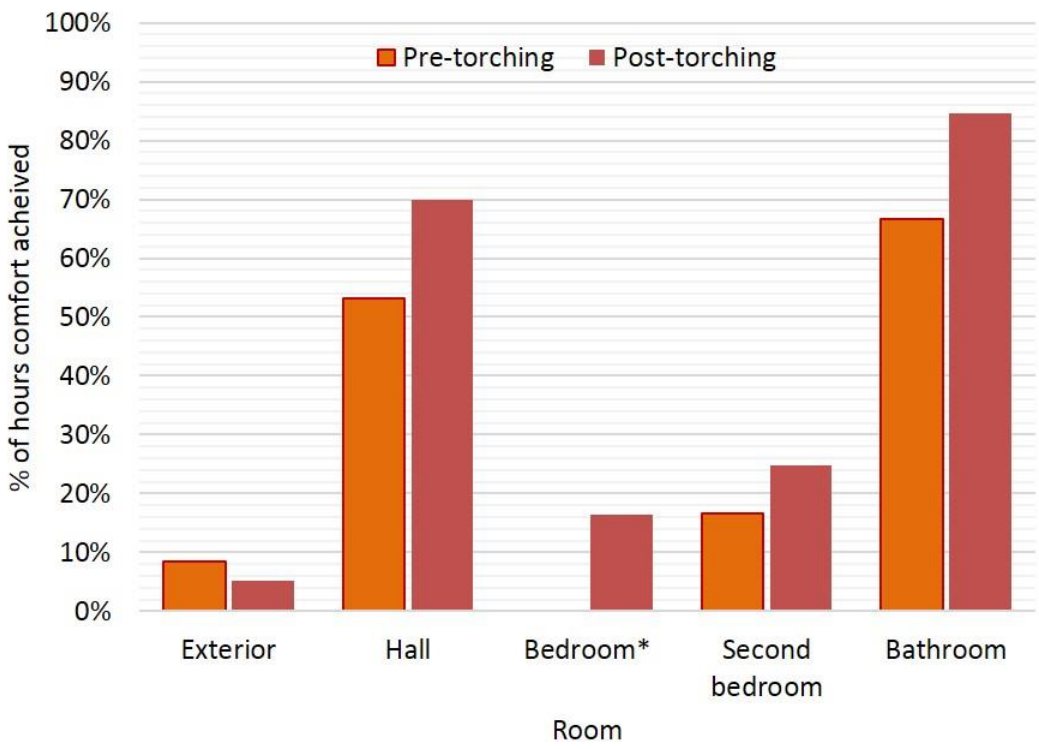

*Figure 171 Hacton Cruck. Percentage of occupied hours where hygrothermal comfort is achieved. March-September pre and post-torching. *No data is shown for bedroom pre-torching due to errors in measurements. Source: (Author's own, 2017)*

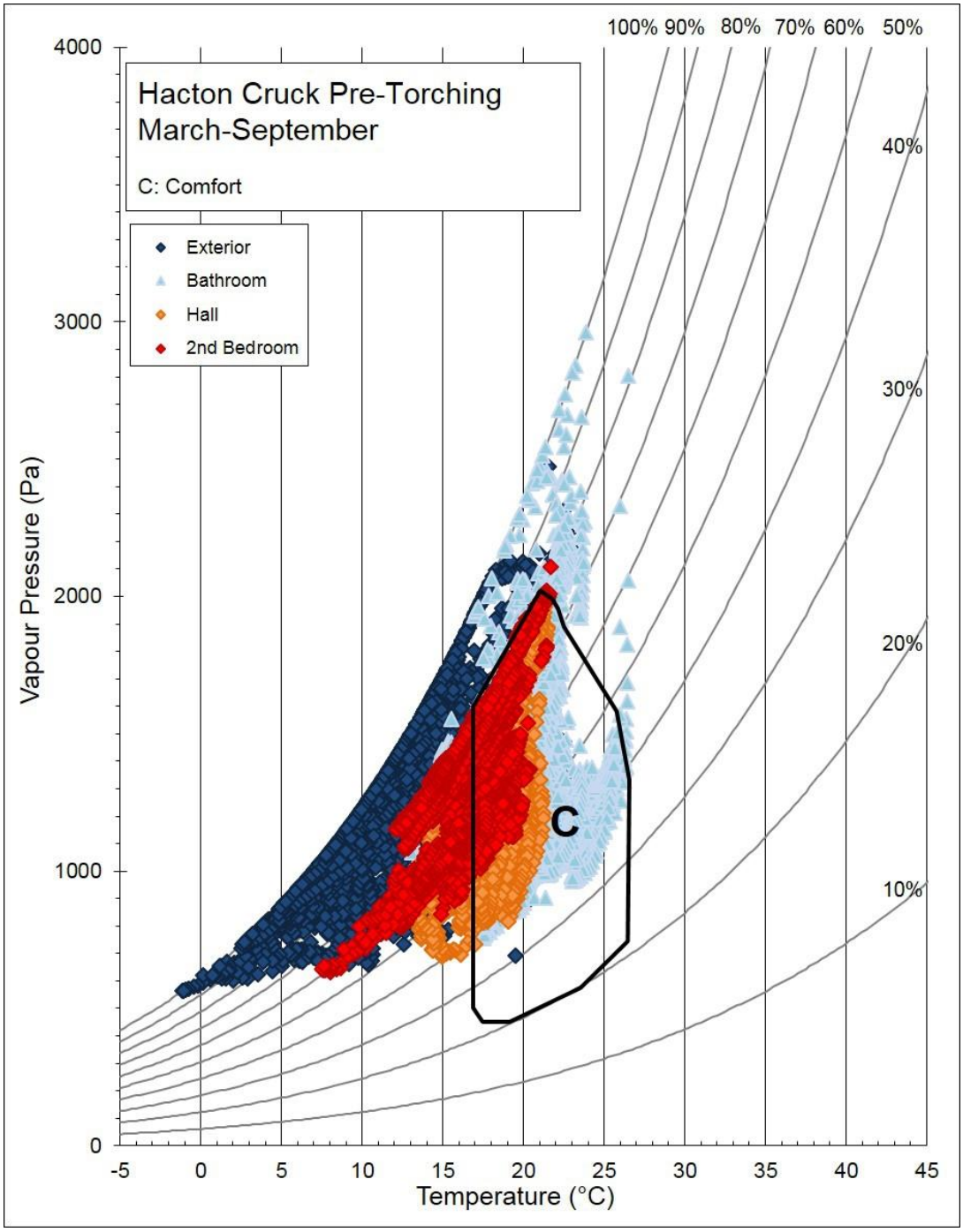

Figure 172. Hacton Cruck. Psychrometric chart according to Givoni showing hygrothermal comfort during occupied days March 2015 –September 2016 prior to torching of thatch ceiling. Source: (Author's own, 2017)

The warmest room in the house, both pre-torching and post-torching is the ground floor bathroom (Figure 171). This is perhaps to be expected as the room is small, has only one external wall (with repaired lath and plaster infill) and underfloor heating.

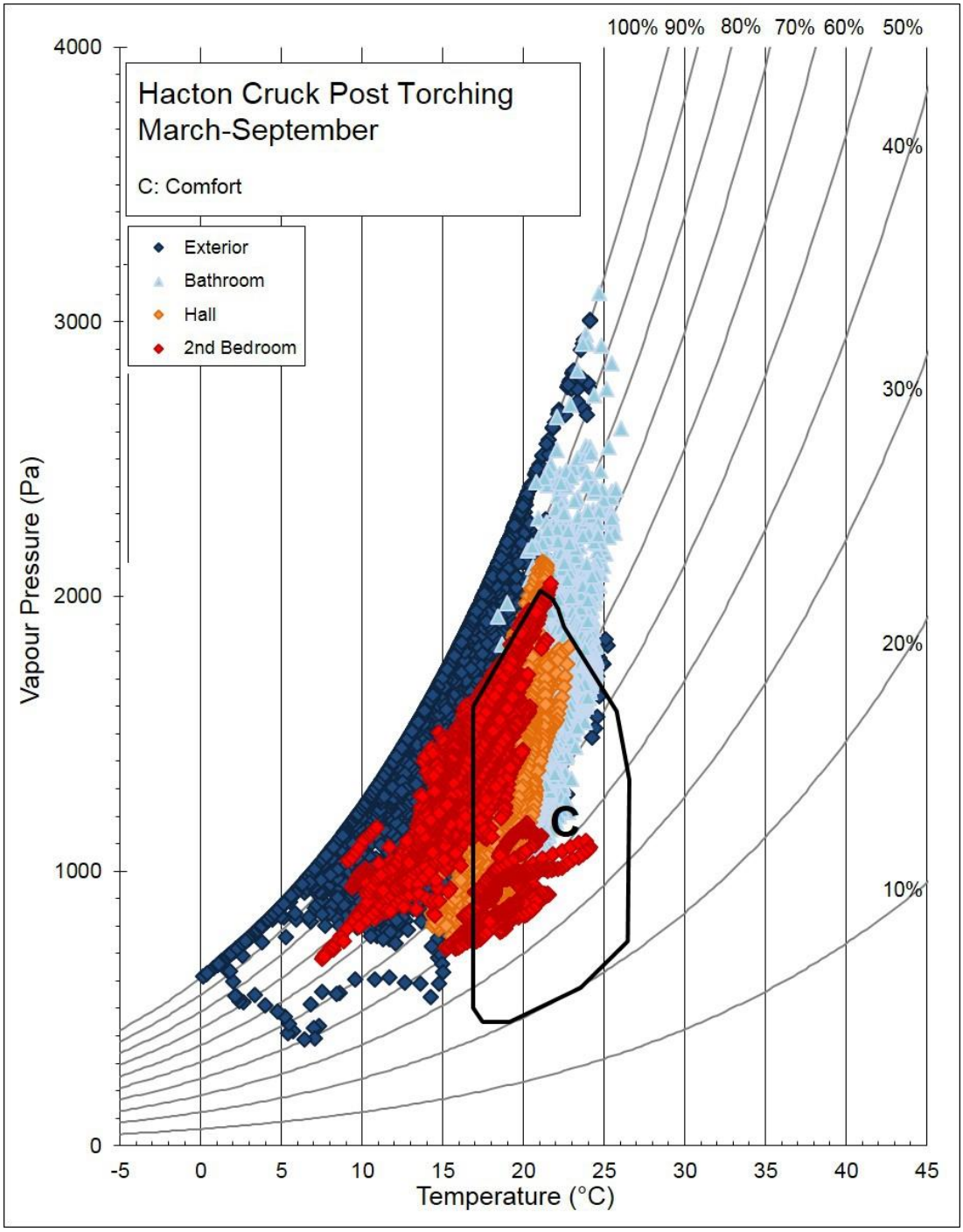

Figure 173. Hacton Cruck. Psychrometric chart according to Givoni showing hygrothermal comfort during occupied days July 2016 – September 2016 and March 2017 – July 2017 following torching of thatch ceiling. Source: (Author's own, 2017)

However, due to high relative humidity this achieves acceptable comfort conditions only 68% of the time pre-torching and 85% post-torching (Figure 171). The master bedroom is the coldest room in the house achieving comfort conditions only 15% of the time post-

torching. No data is presented for this room pre-torching due to interference from the adjacent hot water cupboard, as previously noted. The room that measurements would suggest is the second least comfortable, the ground floor second bedroom, achieves comfort conditions a mere 17% of the time pre-torching and 25% of the time post-torching, even though 62% of its external infill panels are insulated and 38% are repaired pre-existing lath and lime plaster. It should be noted that the effects of radiant temperature are not taken into account in these measurements.

Overall, on average across all monitoring positions, there can be seen to be a 15% increase in the time that hygrothermal comfort conditions (as defined by the GIvoni Bioclimatic chart) are met as a result of the improved airtightness achieved through the torching of the thatch ceiling.

Although the torching of the thatched ceiling has brought about an improvement in internal hygrothermal conditions, a review of the temperatures across the whole year July 2016-July 2017 (Figure 174) shows that overall during the winter months the house is still very cold, with only the bathroom regularly achieving a temperature of more than 17°C.

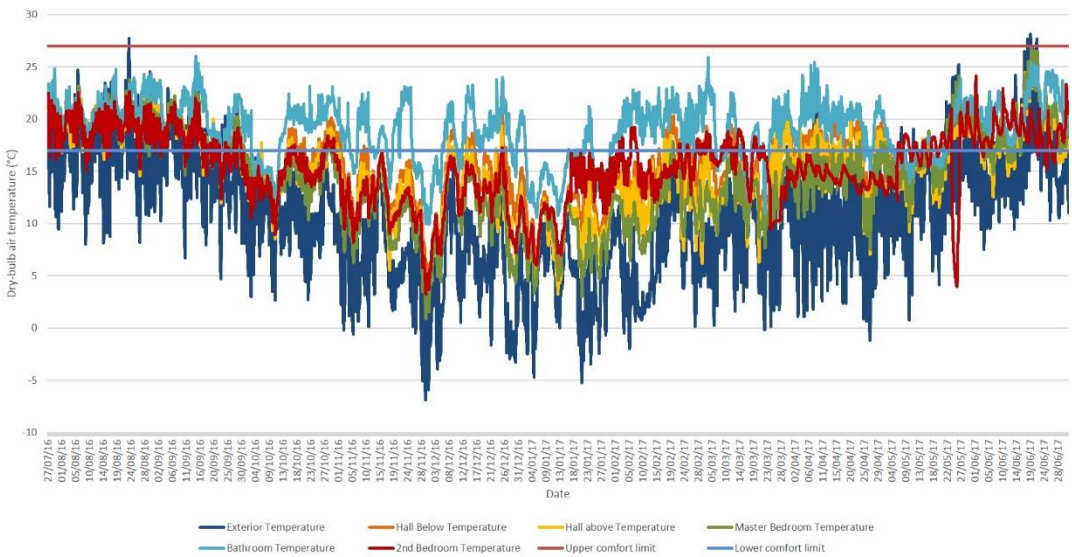

Figure 174. Hacton Cruck. Dry-bulb air temperatures as measured July 2016 – July 2017 following torching of thatch ceiling. Source: (Author's own, 2017)

In the most extreme situation when the external temperature drops to -6°C the temperatures in the master bedroom, gallery[51] and second bedroom are 1.2°C, 1.9°C and 3.6°C respectively. No one was staying that night, which in part might account for the lack of heat. However, a month later on the 30th December 2016 the house was occupied when the external temperature dropped to -3.3°C and the master bedroom dropped to 4.3°C, the gallery 6.3°C and the second bedroom 7.2°C. Indicating a need for traditional seasonal bed clothing such as blankets and coverlets.

9.2.5 Visitors' Perceptions and Comments

Empirical data can only give us an indication of the building's performance with most measurements being only a snapshot, both in time and of one specific parameter. In order to gain a greater understanding of the comfort perceived by occupants, it is necessary to obtain the opinion of the building users. In this respect, being a holiday rental property, the visitors' book provided a valuable resource, allowing an insight into guests' perceptions during their stay. Of the 173 guests who had written in the book, between the house opening in August 2011 and July 2017, 12% had commented on the house being cold and draughty and 9% had commented on it being warm or cosy (Figure 175).

[51] A box bed is also available on the gallery

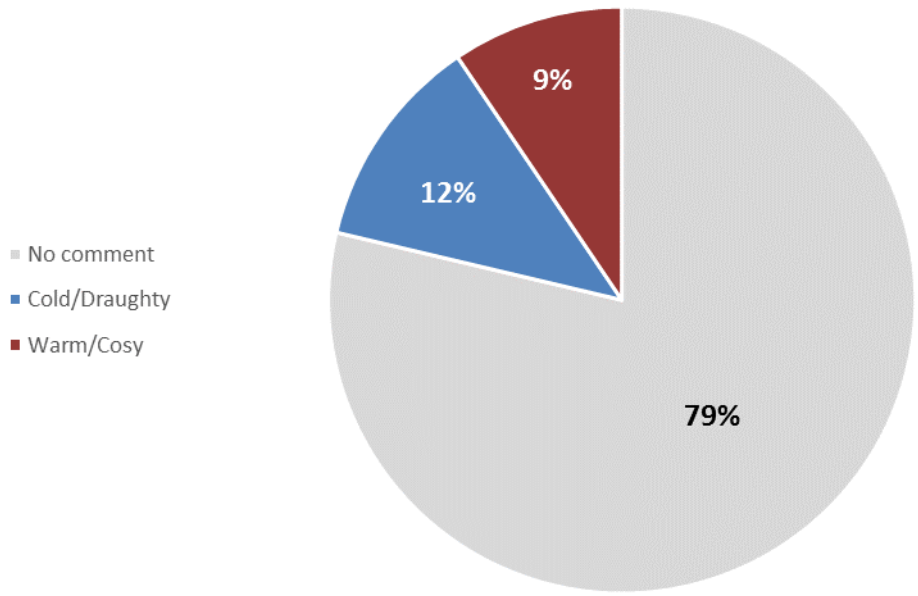

Figure 175. Hacton Cruck. Pie chart showing references to comfort by 135 guests in visitors' book August 2011-March 2016

The other 79% entries in the guest book made no mention of thermal comfort conditions within the house, commenting instead on their delight of staying in a 14th Century cruck hall and the quality of the restoration work that the owner and his architect had achieved. It is interesting to note that all of the comments related to the house being cold or draughty were written prior to the torching of the thatched ceiling. Some of the comments included such statements as "*The authentic indoor weather provided proper gusts of wind, rather than the mere draughts of other old homes…*" and "*…far less (chilly) than one might expect from a 500 year old mediaeval hall!"* It is also interesting to note that a number of comments remarked on how the second bedroom was the warmest, and how this was the bedroom of choice despite its smaller size. Its size is however probably one of the factors in its increased comfort, with its lower ceiling and reduced volume. In addition, direct contact with the radiant underfloor heating and reduced draughts are two other key features. The empirical data supports this by showing that the second bedroom does indeed achieve greater levels of hygrothermal comfort than the loftier master bedroom.

9.2.6 Conclusions

This study demonstrates just some of the complexities inherent in the retrofit of historic timber-frame buildings. Specific results show that the existing lath and lime plaster has a U-value of 2.5W/m2K, that the new wattle-and-daub has a U-value of 3.3W/m2K and a modern infill with multi-foil insulation has 0.7W/m2K, thereby allowing transmittance of only 28% of the heat transmitted by the historic lath and lime plaster panel. This clearly illustrates that the inclusion of modern insulation materials within replacement infill panels can significantly improve the thermal performance of these building elements. The question remains as to whether the introduction of these materials could have unintentional negative impacts on the surrounding historic fabric through an increase in panel moisture content and the creation of interstitial hygrothermal conditions favourable to fungal or insect attack. This aspect is explored in further detail in subsequent chapters.

At the same time both the thermography and pressure testing have highlighted the need for a whole-building approach when considering any energy retrofit, whether it be to contemporary or historical buildings. The simple act of torching the underside of the thatch roof was shown to double the airtightness of the building, an improvement that can be seen in the 15% improvement in internal hygrothermal comfort conditions. This is undeniably a step in the right direction, however, even at this reduced rate, these air changes greatly decrease any positive impact that the improved thermal transmittance of the walls might have on internal hygrothermal comfort conditions. It is therefore clear that a holistic approach must be adopted when considering the retrofit of these properties. Research and practice concerned with improving both the energy performance and internal comfort of historic buildings must therefore look at strategies for all aspects of the buildings performance and not only concentrate on individual elements.

Overall, 21st century expectations of hygrothermal comfort have not been achieved, however the building is not a permanent residence. The work by others at Hacton Cruck has saved a building, largely ignored in the 20th century, and enabled visitors to experience the pleasure of staying in a 14th century home. It is hoped that the research presented here and the owners continuing commitment to the conservation of the building, will allow the continuing enjoyment of this building, and others like it, for centuries to come.

9.3 The Oaks, Brockhampton

The first notification of the opportunity to monitor this residential let property was received on the 22nd June 2015, with the refurbishment work set to begin on the 1st July 2015. In order to undertake monitoring pre-retrofit the first set of measurements took place on the 30th June. This negated the possibility of undertaking in situ U-value measurements, this being outside of the heating season. As the retrofit was to focus on the windows and the roof, it was decided to concentrate on reviewing the airtightness of the building. The following monitoring was undertaken pre and post-retrofit:

- Pressure testing
- Thermography
- Timber moisture measuring

Out of respect to the occupant's personal situation at the time, in situ U-value measurements and hygrothermal monitoring were not undertaken post retrofit. A thermal comfort questionnaire was however completed.

9.3.1 Pressure Testing

9.3.1.1 Detailed Methodology

Pressure testing was carried out according to the methodology described in 9.1.2 on 30th July 2015 and again on 20th November 2015 following completion of the refurbishments but prior to the new tenant moving in.

9.3.1.2 Results and Analysis

Table 15 presents the results of the pressure testing undertaken on 30/06/2015 pre-retrofit[52] and on 20/11/2015 immediately following the completion of the work[53].

[52] (R^2) of the best fit line = 0.9846 showing a good degree of accuracy
[53] (R^2) of the best fit line = 0.9056, a lower but still acceptable level of accuracy.

Table 15 The Oaks, Brockhampton. Results of pressure testing pre and post-retrofit. (30/06/2015 & 20/11/2015)

	Air Permeability Index ($m^3/h/m^2$)	**Effective Leakage Area (m^2)**	**Air change Rate @50 Pa (/hr)**	**Air change rate unpressurised (/hr)**
Pre-Retrofit	17.8	4.71	16.5	0.83
Post-Retrofit	11.7	1.83	10.8	0.54
% post to pre	65.7	38.9	65.5	65.1

The results of the pressure testing post-retrofit show a reduction in the air permeability index and air change rate to 65.7% of that pre-retrofit (Table 15). At 11.7$m^3/h/m^2$ the air permeability index post-retrofit is approaching that required by Building Regulations for new-build constructions (HM Government, 2016c). It should however be noted that more stringent guidelines for low energy retrofit such as the Passivehaus® EnerPHit standard require air changes as low as 0.6 ac/h 50 Pascals (Feist, 2010 p.3), although without additional controlled ventilation there are concerns that this level of airtightness in historic buildings can lead to high levels of internal humidity.

As identified by the thermography the main areas of air leakage are the back door and loft hatch, in addition to some leakage again at the junction between some but not all panel infills and timber-frame. The infiltrations around doors and loft hatch could easily be addressed with draught stripping, whilst those at the junctions of frame to panel are more problematic.

9.3.2 Thermography

9.3.2.1 Detailed Methodology

The thermography for this case study was limited to internal images. Whilst the building was depressurised using the Minneapolis Blower Door. The thermography was undertaken pre-retrofit retrofit at 15:45 on 30/06/2015 using a FLIR i7 camera, and post-retrofit at 15:00 on 20/11/2015 with a FLIR B250. The conditions for both pre and post-retrofit measurements are shown in Table 16.

Table 16. Temperature difference for thermography at The Oaks, pre-retrofit 15:45 30/06/2015 and post-retrofit 15:00 20/11/2015

	External Temperature (°C)	Internal Temperature (°C)	Temperature difference (°C)
Pre-retrofit	28.8	22.3	6.5
Post Retrofit	11.2	8.9	2.3

Despite the lack of ideal conditions, the results still allow some clear conclusions to be drawn.

9.3.2.2 Results and Analysis

9.3.2.2.1 Pre-Retrofit

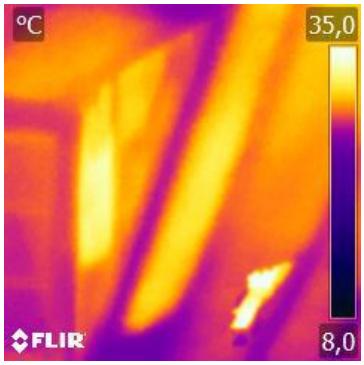

Figure 176. The Oaks. Dormer window cheek.

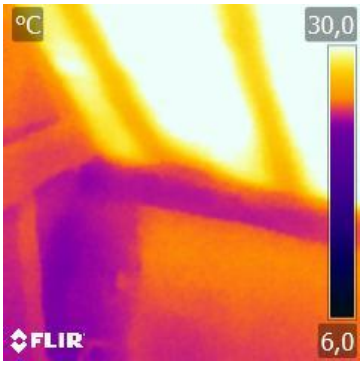

Figure 177. The Oaks. Uninsulated pitched roof to first floor bedroom

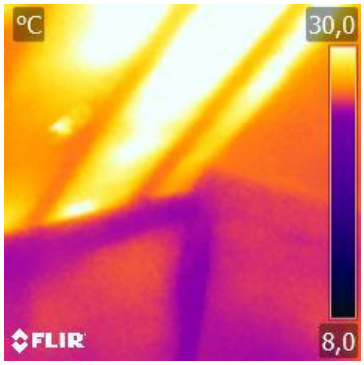

Figure 178. Uninsulated pitched roof to first floor bedroom

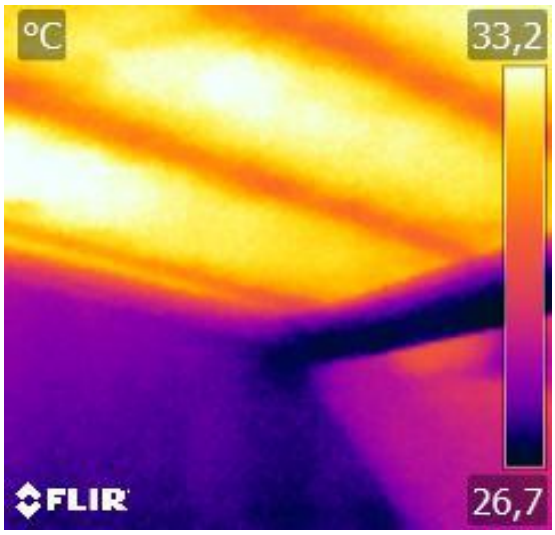

Figure 179. The Oaks. Uninsulated pitched roof and ceiling to roof void, first floor bedroom

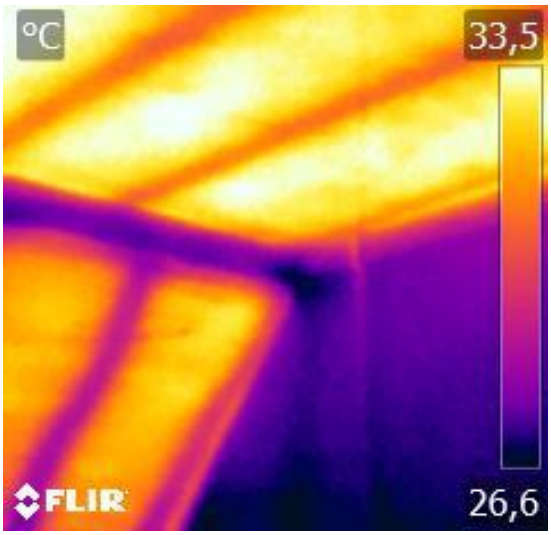

Figure 180. The Oaks. Uninsulated pitched roof and ceiling to roof void, first floor bedroom

These thermographic images, Figure 176-Figure 180 clearly show the ingress of heat through the poorly insulated roof, with internal surface temperatures reaching 35°C. The rafters can be distinguished as elements with a lower thermal transmitance.

9.3.2.2.2 Post-retrofit

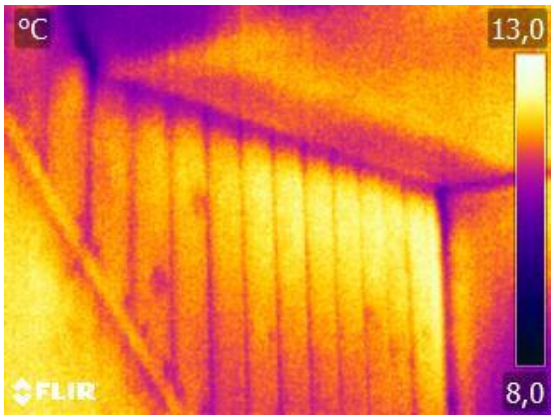

Figure 181. The Oaks. Insulated dormer window cheek.

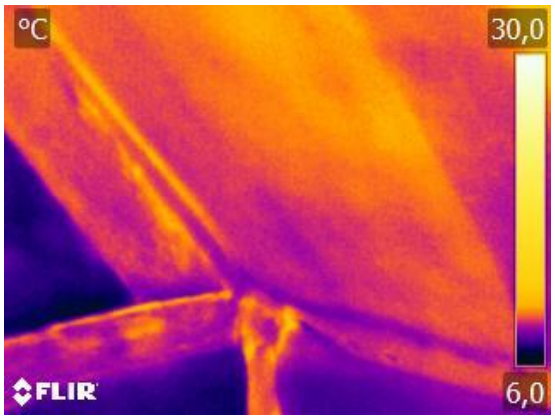

Figure 182 Insulated pitched roof to first floor bedroom

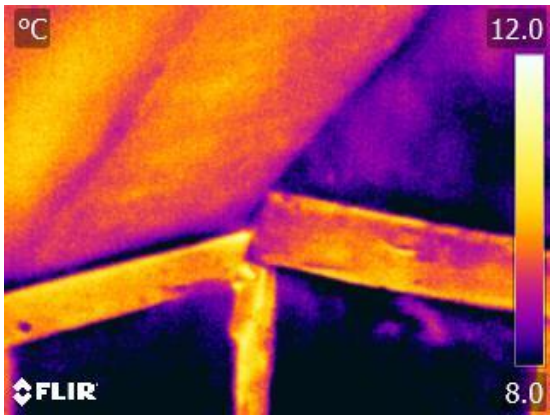

Figure 183. The Oaks. Insulated pitched roof and uninsulated walls.

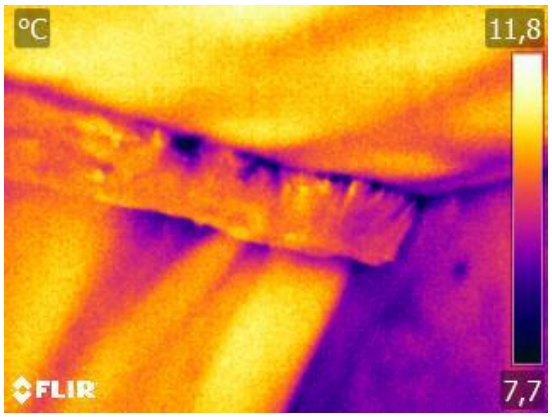

Figure 184 The Oaks. Insulated pitched roof and ceiling to roof void, first floor bedroom

Whilst taken under very different climatic conditions, Figure 182-Figure 184 show an reduction in the heat transfer through the pitched roof, dormer cheeks and ceiling of the first floor. A clear distinction is seen between the now insulated roof, the timber-frame and uninsulated panel infill. Some thermal-bridging by the rafters can be detected, as can cold air infiltration around the exposed timber beam (Figure 184)

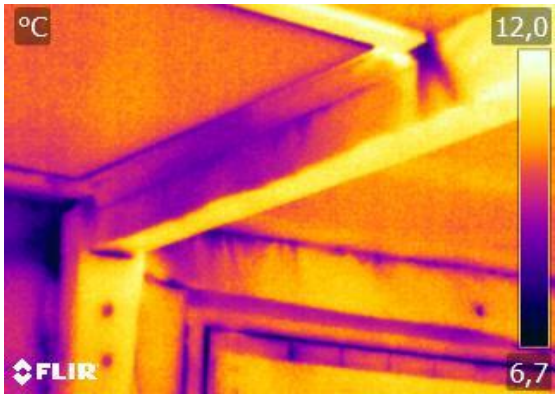

Figure 185. The Oaks. Loft hatch to void above living room and back door, showing infiltrations.

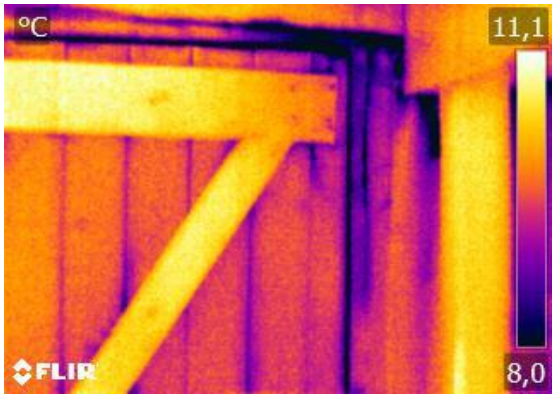

Figure 186 The Oaks. Back door showing infiltrations

Figure 185 and Figure 186, taken during depressurisation, identify cold air infiltration through and around the back door, and around the unsealed loft hatch. These are two areas where simple weather-stripping could easily reduce air infiltration.

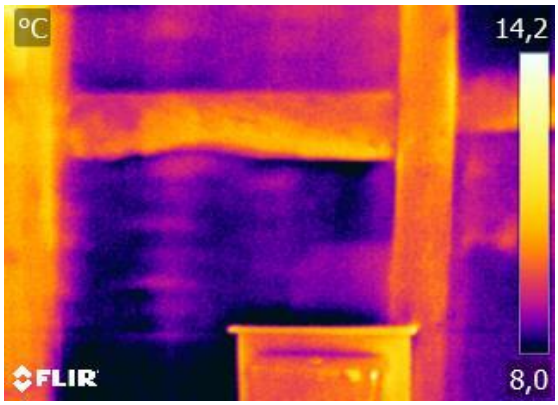

Figure 187. The Oaks. Suggested wattle or lath infill in former parlour, now bathroom.

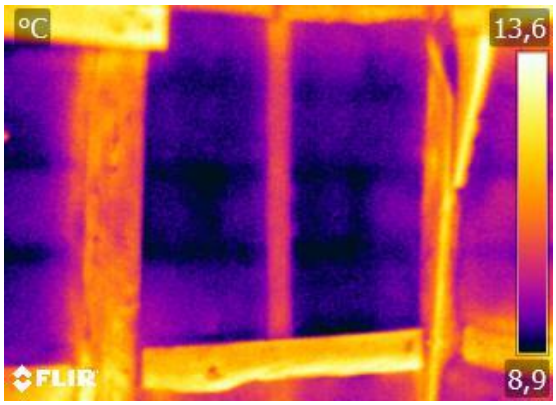

Figure 188 The Oaks. Clear indication of concrete block infill in living room

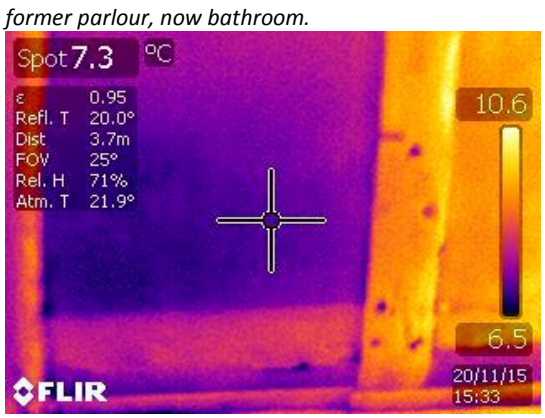

Figure 189. Two panels in first floor bedroom wall, showing differing thermal performance.

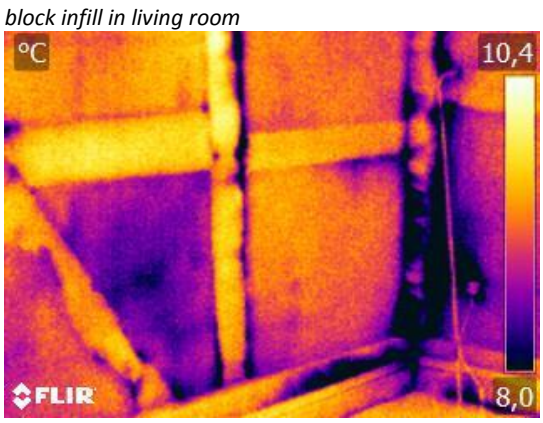

Figure 190 Infill panels in living room, west corner, showing differing thermal performance.

In addition to thermal performance, the thermograph also revealed further information regarding the cottage's construction. In Figure 187, a pattern suggesting wattling or lathwork can be seen in the panel infill behind the newly installed toilet cistern, in what was previously the parlour. Figure 188 shows the infill panels to the living room to have been replaced at some point during the 20th century with concrete blockwork, with the mortar joints clearly visible. If further energy retrofit work was to be considered, the replacement of these panels could be considered without the loss of historic fabric. Finally, Figure 189 and Figure 190 show clear differences in thermal performance of adjacent panels both in the first floor bedroom (Figure 189) and the living room southwest wall (Figure 190). This most probably suggests differing panel infill constructions and highlights further areas for investigation.

9.3.3 Occupants' perception of thermal comfort

9.3.3.1 Detailed Methodology

The simple questionnaire described in section 9.1.4 and presented in appendix F was used with the one occupant to gain an insight into their perception of the internal thermal comfort. The questionnaire took place on the morning of 28/07/2017 in the kitchen with the sun shining outside.

9.3.3.2 Results and Analysis

A copy of the completed questionnaire can be found in appendix F. In summary, the occupant felt comfortable at the time of answering, whilst standing wearing jeans and long sleeve top, with a dry-bulb temperature of 23.7°C and a relative humidity of 52.2%. They found the house cold in winter. This they counteract by wearing thick jumpers. They describe the kitchen as the coldest room of the house, with the bathroom being OK and the sitting room being warm once the log burner was lit. They commented on how the heat

from the log burner did not reach the rest of the house due to the sitting room being single storey and separated from the rest of the house by the thick stone chimney. Historically this would have been continually heated from both sides by open fires in both the living room and kitchen. Currently the flue of the log burner imparts little heat to this large thermal mass. In summer the downstairs rooms were reported to be comfortable or pleasantly cool; however, the upstairs room can get too hot, with the main bedroom, above the kitchen, being the worst.

The heating is a modern central heating system fuelled by liquefied petroleum gas (LPG), which the occupant noted was expensive. This expense was not felt to be a limiting factor in the use of the heating with it being used when necessary from September to March, on a thermostat set to 21°C from 6am-10pm, and 15°C at night or when unoccupied. However, it was noted that the heating struggled to achieve a temperature of 19°C, this being blamed on the insufficient number of radiators. In the living room, the one radiator was felt to make little difference and the log burner is used every day in winter 1pm-10pm.

With regards to ventilation habits, windows are opened on a regular basis in both winter and summer, although in summer flies and bats can be problematic.

Even though the occupant found the house cold in winter and hot upstairs in summer they were happy living there and accepted that these were part and parcel of choosing to living in an old house in the countryside, something they wouldn't change.

9.3.4 Timber frame surface moisture content

9.3.4.1 Detailed Methodology

At The Oaks a two pin, Testo 606-2 resistance moisture meter was used to measure the surface moisture content in the historic timber-frame. Measurements were taken in the living room and parlour (later converted to bathroom) both immediately prior to retrofit

and immediately after. Subsequent readings were then taken 12 months and 20 months post-retrofit. The timbers in the semi-basement cellar were only tested post-retrofit, as access was not possible before the retrofit began. The precise dates and climatic conditions are presented in Table 17. Measurement locations are as indicated in Figure 191 and Figure 192.

Table 17. Dates of measurement of timber surface moisture content and hygrothermal conditions of air within each room.

Date	Pre or post-retrofit	Barometric pressure (hPa)†	Living room			Parlour/Bathroom		
			Temp (°C)	RH (%)	AH (kg/m³)	Temp (°C)	RH (%)	AH (kg/m³)
30/06/2015	Pre	1019.35	22.8	57.6	**0.012**	23.7	52.5	**0.011**
20/11/2015	Post	1007.04	7.6	62.0	**0.005**	8.9	64.2	**0.006**
18/11/2016	Post	994.79	12.0	52.0	**0.005**	17.3	51.0	**0.008**
28/07/2017	Post	1006.12	24.3	51.0	**0.011**	23.6	59.2	**0.013**

† Source of barometric pressure www.wunderground.com
AH- Absolute Humidity

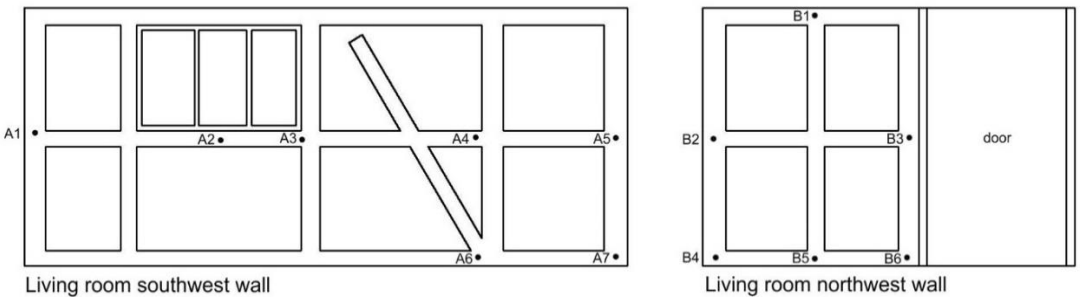

Figure 191 The Oaks, living room walls showing location of timber surface moisture content testing. Source: (Author's own, 2015)

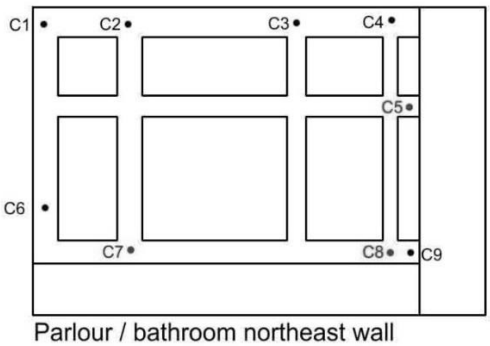

Figure 192 The Oaks, parlour/bathroom wall showing location of timber moisture content testing. Source: (Author's own, 2015)

9.3.4.2 Results and Analysis

As can be seen from the climatic conditions on the days measurements took place there is a large difference in absolute humidity between summer and autumn due to seasonal variations (Table 17). As such, the readings can only be compared for each season individually. Whilst absolute moisture levels in the living room remain constant within each season, those for the parlour/bathroom show a slight increase.

A comparison between summer 2015 (pre-retrofit) and summer 2017 (20 months post-retrofit) are shown in Figure 193, with a comparison between autumn 2015 (immediately post-retrofit) and autumn 2016 (12 months post-retrofit) shown in Figure 194. The threshold of 20% moisture content is highlighted in both graphs as this is the minimum moisture content needed for theoretical fungal growth (McCaig and Ridout, 2012 p.200).

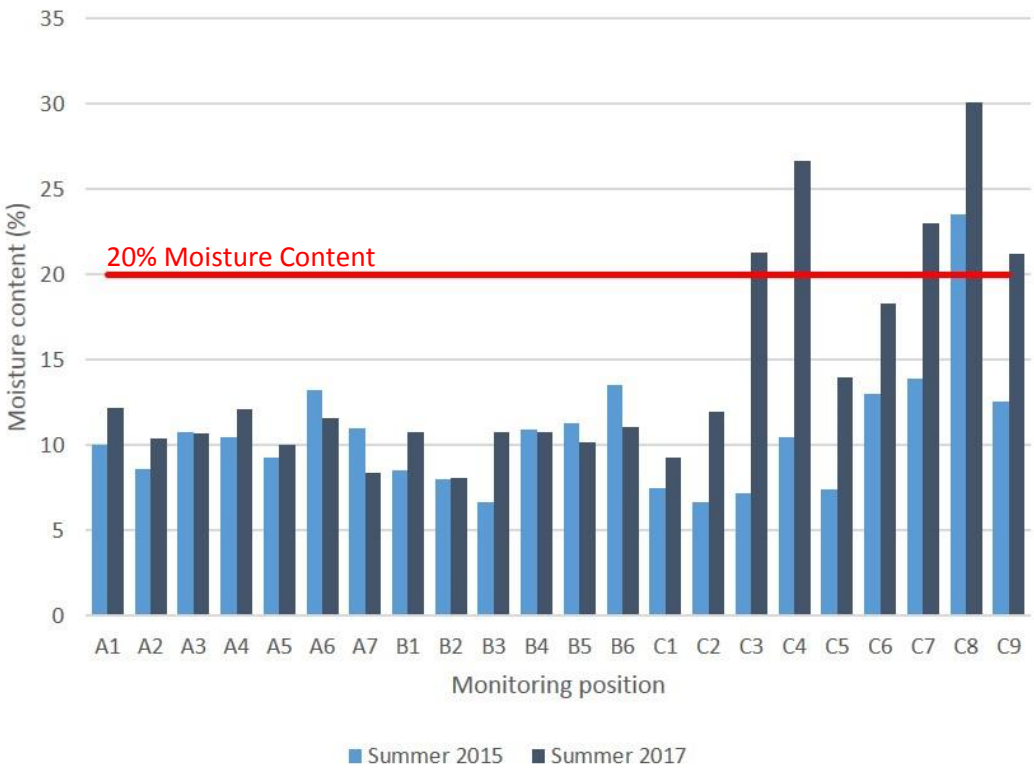

Figure 193. Surface moisture content of timber measured 30/06/2015 pre-retrofit and 28/07/2017 twenty months post-retrofit. Source: (Author's own, 2017)

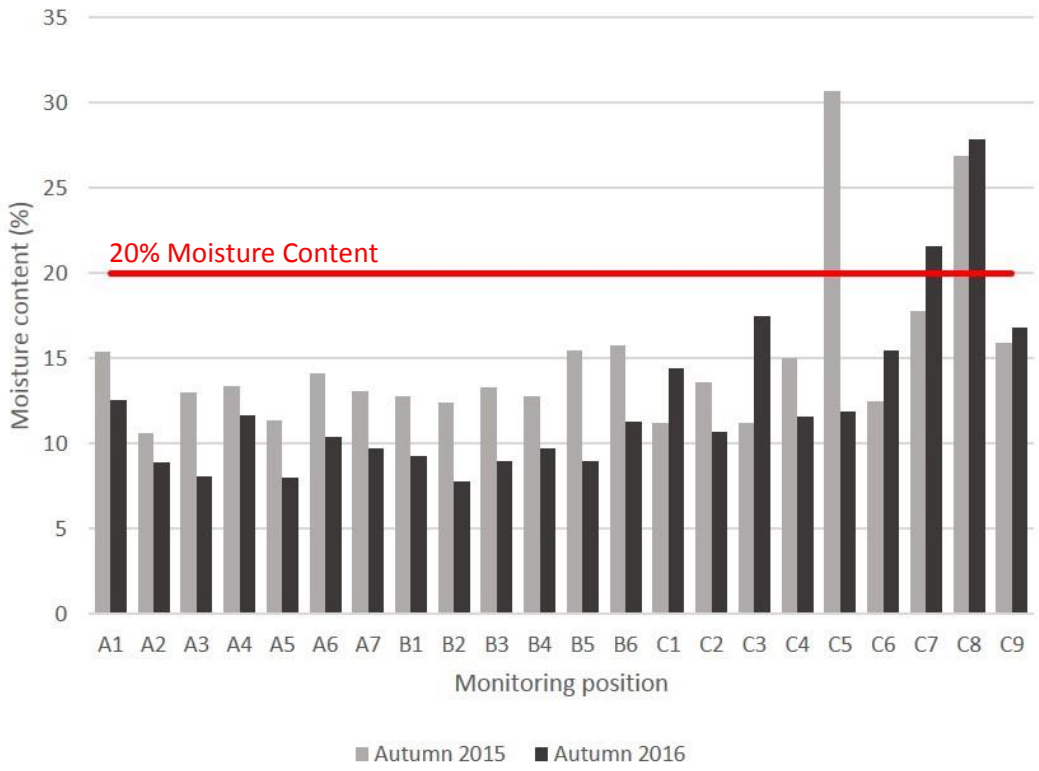

Figure 194. Surface moisture content of timber measured 20/11/2015 immediately post-retrofit and 18/11/2016 twelve months post-retrofit. Source: (Author's own, 2017)

The graph comparing summer readings (Figure 193) allows the best comparison pre to post retrofit. There can be seen that for the series of monitoring groups A and B, both in the living room, there is some fluctuation between pre-and post-retrofit with some points showing a slight increase and some a slight decrease in moisture content. This is however not the case in the parlour/bathroom (group C) where there is an increase in moisture content at all monitoring positions, with five positions now exceeding the 20% threshold and a further position (C6) approaching this. Overall, in the bathroom there is an 8% average increase in moisture content. This increase may be due to the change of use of this room from parlour to bathroom and the increased humidity that this will have caused, although it should be noted that position C8 was already over the 20% threshold pre-retrofit. As such, the problem may be due to external water penetration at the junction between the sill beam and stone plinth wall, as much as the internal factors.

With the autumn measurements (Figure 194) there can be seen to be a reduction in moisture content in the living room (series A & B) from immediately following the retrofit to after one year of occupation. However, in the bathroom two thirds of the monitoring positions see a rise in moisture content, with an average 3% increase for these positions.

In order to investigate further, more detailed moisture surveys with increased monitoring positions were undertaken on 18/11/2016 and 28/07/2017 for all external walls of the bathroom and living room. The results of those undertaken for the bathroom on the 28/07/2017 are presented in Figure 195 and Figure 196. The results of all measurements can be seen in appendix E.

For the bathroom, the moisture content was found to be highest in the sill beams, with specific problems in the sill beam of the north-east wall (Figure 195). However, moisture contents higher than 20% were also recorded in other individual locations and in the top right-hand corner of the north-east wall. Given that the thermography had identified the presence of wattlework in this wall there is additional reason for concern. If action is not taken then potentially historic fabric could be lost.

9.4	9.3	12	15.7	19.4	20.35	21.3	26.7
8.75		9.5				11	
8.1		12.1				8.3	
9.92		20.8				11.9	
11.73	18.3	11.5	12.25	13	12	11	14
8.8		8.6				12	
9.95		16.2				20.9	
11.1		26.4				27.5	
17.85	24.6	23	31.1	30.4	34.8	30.1	21.2

Figure 195. Surface moisture content (%) of timbers of north-east wall of bathroom, The Oaks. As measured 28/07/2017. Source: (Author's own, 2017)

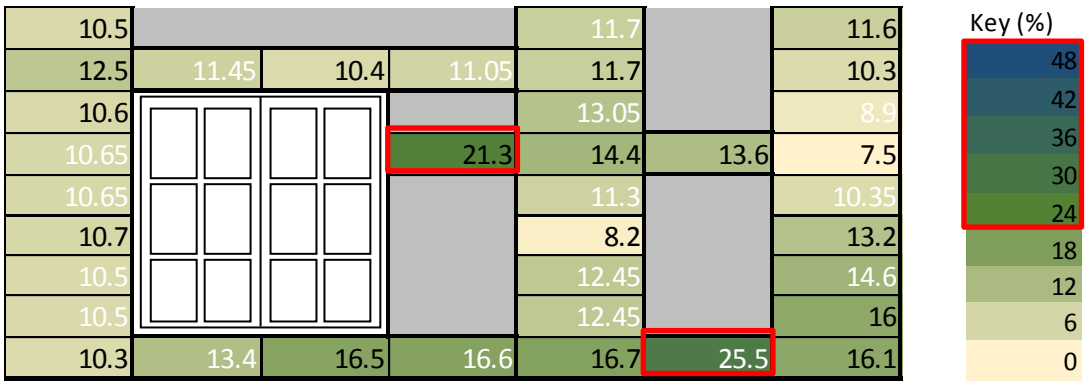

Figure 196. Surface moisture content (%) of timbers of south-east wall of bathroom, The Oaks. As measured 28/07/2017. Source: (Author's own, 2017)

In addition to the habitable rooms, surface moisture content was also measured in the timbers of the semi-basement cellar. As previously mentioned no access was available prior to the retrofit and so measurements were only undertaken post retrofit. The monitoring positions are indicated in Figure 197.

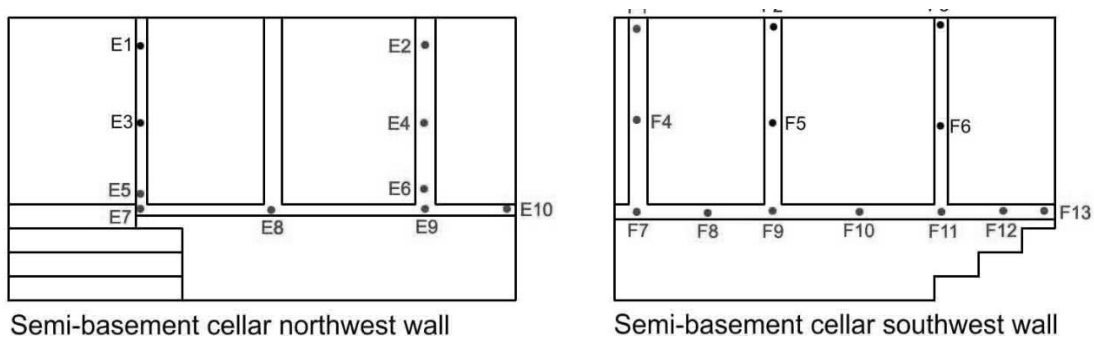

Figure 197 The Oaks, semi-basement cellar walls showing location of timber moisture content testing. Source: (Author's own)

The results of the surface moisture content measurements of the cellar timbers on the 20/11/2015, 18/11/2016 and 28/07/2017 are presented in Figure 198. Complete surface moisture surveys for both walls with timber framing are presented in Figure 199, Figure 200 and in appendix E.

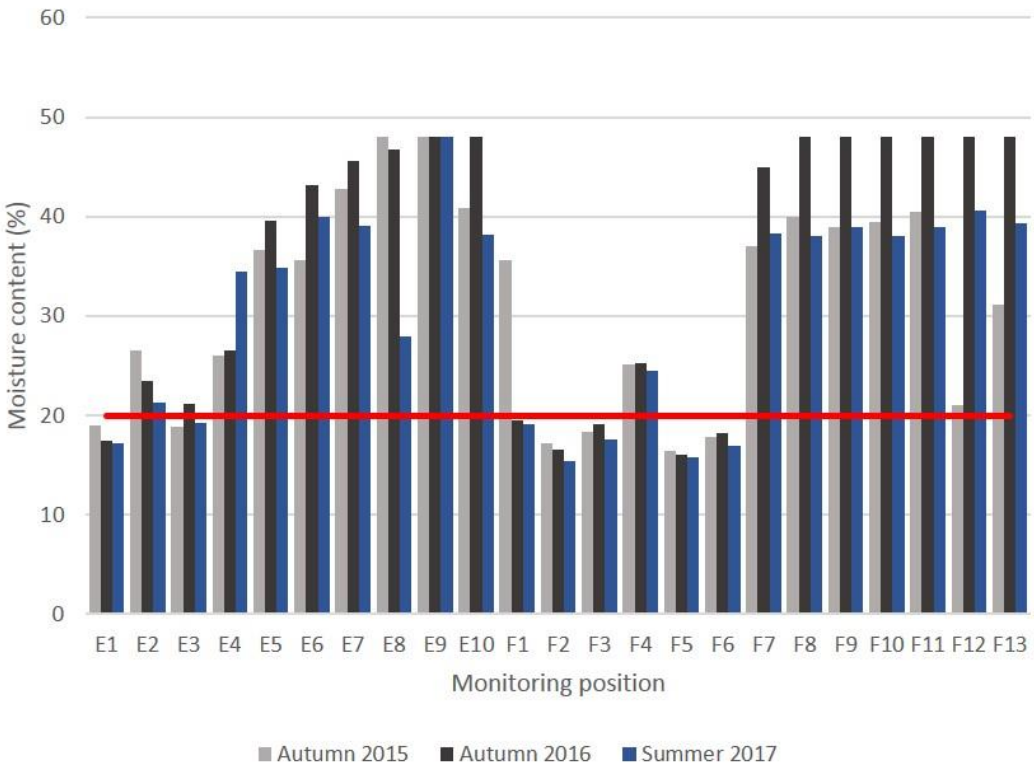

Figure 198. Surface moisture content of semi-basement cellar timbers measured 20/11/2015 immediately post-retrofit and 18/11/2016 twelve months post-retrofit and 28/07/2017 eighteen months post-retrofit. Source: (Author's own, 2017)

	19.5		16.6		19.1		
	25.3		16		18.2		
	32.9		30.3		39.6		
45	45	48	48	48	48	48	48

Figure 199. Surface moisture content (%) of timbers of south-west wall of cellar, The Oaks. As measured 18/11/2016. Source: (Author's own, 2016)

17.5				23.4		
21.2				26.5		
39.6				43.1		
45.6	46.1	46.8	48	48	47.4	48

Figure 200. Surface moisture content (%) of timbers of north-west wall of cellar, The Oaks. As measured 18/11/2016. Source: (Author's own, 2016)

The moisture readings recorded in the semi-basement cellar post-retrofit are high, with 72% of all readings being greater than 20% moisture content. In the case of eleven readings, all within the sill beams, the readings were off the top end of the meters scale (>47.9%). Again, there was a noticeable concentration of moisture content at the lower

level of the wall (Figure 199 and Figure 200). Although no readings were taken pre-retrofit, there was some concern that the moisture was the result of the new concrete screed, laid as part of the refurbishment works. Condensation was noted on the inside of the closed window. The estate manager was informed of the readings, advised to ensure maximum ventilation to the area and to monitor the moisture content of these timbers. The subsequent measurements taken a year after the retrofit in November 2016 show a further increase, especially at the base of the southwest wall (F7-F13 Figure 198). The tenant informed the author that they believed that there had been a problem with water ingress. The source of the water was believed to be runoff from the rear roof and the lack of horizontal sill boards forming a flashing, which had recently been installed (Figure 201).

Figure 201. Newly replaced horizontal sill boards to north-west façade of The Oaks. Source: (Author's own, 2016)

Those readings taken eight months later, in July 2017, do show a reduction in the surface moisture content, although it does remain critically high. Continuing monitoring will be required to see if this drying continues or if further remedial work such as land drains may

be required. It is now not believed that the moisture in the cellar is a result of the energy retrofit of the dwelling.

9.3.5 Conclusions

Although more limited in both the scope of the monitoring and the extent of the retrofit, this case study shows how simple measures such as secondary glazing can improve the performance of the building without intervention to the historic timber-frame and infill panels. Further improvements could be achieved by weather-stripping the doors and loft hatch. The exact impact of the improvement on airtightness on the internal hygrothermal comfort has not be measured but will be simulated in following chapters. The increase in timber moisture content, especially in the bathroom, may or may not be related to the increased airtightness, although the change of use of the parlour to bathroom, with no additional controlled ventilation is an obvious contributing factor. The thermography has identified that some infill panels are modern concrete block. This opens up the potential for future replacement of these with replacement infill panels with enhanced thermal performance. Future research should be undertaken to identify the infill of each panel on a panel-by-panel basis.

9.4 The Old Mayor's Parlour and No.25 Church Street, Hereford

At this gallery and commercial premises, where the principal retrofit actions were the architect led replacement of the panel infill to the east façade and the use of multi-foil insulation behind tile hanging to the west, the following monitoring was undertaken:

- in situ U-value monitoring
- pressure testing
- thermography
- hygrothermal monitoring

9.4.1 In situ U-value monitoring

9.4.1.1 Detailed Methodology

The in situ U-value monitoring was of two panel infills, one in the Old Mayor's Parlour (M1) and the other in the first floor office of no.25 (M2, Figure 202).

Figure 202 Old Mayor's Parlour and No. 25 Church Street, location of in situ U-value measurement locations M1 & M2. Source: (Base drawing courtesy of Jacqueline Demaus Architect).

9.4.1.1.1 Instrumentation

In this instance, the output of the Huxeflux HFP01 heat flow meter plates (Figure 203) was connected directly to an Eltek® Squirrel® data logger with the voltage recorded at 5-minute intervals. The internal ambient dry bulb air temperature (˚C) directly behind each heat flow plate and the corresponding external ambient dry bulb air temperatures (˚C) were measured with a thermistor also wired directly back to the Squirrel® datalogger, with readings at the frequency as the voltage. The external temperature thermistor was supported by string in tension between the perimeter timber-frame and was protected from direct solar radiation by a ventilated, plastic and foil cover (Figure 204).

Figure 203. OMP Heat flux plate and internal temperature thermistor. Source: (Author's own, 2016)

Figure 204 OMP Shielded external temperature sensor. Source: (Author's own, 2016)

9.4.1.1.2 Time and duration of monitoring

The in situ U-value monitoring was undertaken between 18th February and 10th March 2016, with a measurement period of 21 consecutive days.

9.4.1.2 Results and Analysis

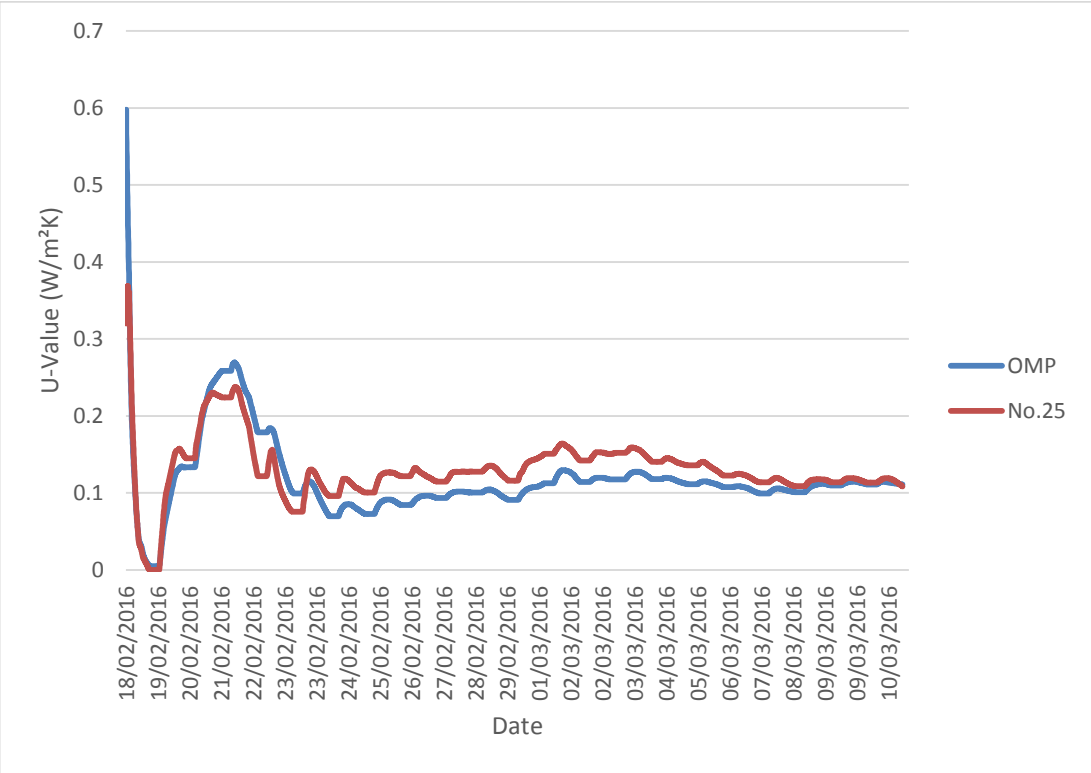

Figure 205. Old Mayor's Parlour and No.25 Church Street. Cumulative average of measured U-value, corrected to omit direct solar radiation. 18th February – 11th March 2016

Table 18 Old Mayor's Parlour and No.25 Church Street. Comparison of average measured U-value and values calculated according to BS EN ISO 6946:2007

	Measured U-value (W/m²K)	Standard deviation (W/m²K)	Calculated U-value (W/m²K)
Old Mayor's Parlour Historic England detail + Polyisocyanurate internal lining	0.11	±0.04	0.13
No 25 Church Street Historic England detail + Mineral wool internal lining	0.11	±0.03	0.17

Only readings taken from one hour after the façade had passed into shade until sunrise were used for these calculations. Even so, the readings are fairly erratic, as can be seen in Figure 205. This is most probably due to the lack of heating within the internal spaces and so minimal heat transfer through the wall. The measurements in the Old Mayor's Parlour reached and maintained a difference of no more than ±5% three days before the termination of the study. However, those in no.25 did not, although a difference of ±10% was achieved in the last 4 days. Although not within the ±5% stated by the BS, the average

measured U-value over these days corresponds closely with the U-values calculated according to BS EN ISO 6946:2007 as presented in Table 18, when the standard deviation is considered. It is to be expected that the measured and calculated U-values are similar as, unlike measurements of historic or non-conventional constructions, these infill panels are of standard layers of know materials, with known dimensions and properties measured by their manufacturers. It should be noted that these U-values are well within the limiting fabric parameters as defined by the Building Regulations for new-build construction (HM Government, 2016c).

9.4.2 Pressure Testing

9.4.2.1 Detailed Methodology

Pressure testing was completed on 11th March 2016 following the previously described methodology. Due to the compartmentalised configuration of the property, only pressure testing of the Old Mayor's Parlour gallery space, located on the first floor, was undertaken. The Minneapolis® blower door was inserted in the doorway between the semi-external staircase and the gallery. The tube measuring external air pressure was extended down and out onto the street. Although the gallery is a separate property from the café below, it cannot be assumed that the dividing floor has been designed to act as an air barrier. Additional leakage through this element must therefore be considered when reviewing the results.

9.4.2.2 Results and Analysis

Based on the readings measured[54] the calculated air permeability index and air change rates are:

Air Permeability Index	17.6 $m^3/h/m^2$
Air change rate @50 Pa	22.5 /hr
Air change rate unpressurised	1.12 /hr

Whilst not achieving the 10 $m^3/h/m^2$ air permeability index required by building regulations for new-build (HM Government, 2016c), the property is far more airtight than the first case study Hacton Cruck. The internal lining is probably fundamental in achieving this and further highlights the risk of exposing timbers both internally and externally. The weakest areas are most probably the windows and the floor separating the room from the café below.

9.4.3 Thermography

9.4.3.1 Detailed Methodology

Thermography was undertaken on 11/03/2016, at 06:00 for the external and 06:30 for the internal. A FLIR® B250 thermal imaging camera was used for both. The building was pressurised with a Minneapolis® blower door for the external images and depressurised for the internal. The recommended temperature differences of >10°C were achieved as presented in Table 19

Table 19. Temperature difference for thermography at The Old Mayor's Parlour, 11/03/2016

	External Temperature (°C)	Internal Temperature (°C)	Temperature difference (°C)
External Thermography	2.4	20.4	18
Internal Thermography	0.4	22.9	22.5

[54] (R^2) of the best-fit line = 0.9781 showing a good degree of accuracy.

9.4.3.2 Results and Analysis

Figure 206. External thermography of east façade. Internal temperature 20.4°C. External temperature 2.4°C. 06:00, 11/03/2016

Figure 206 shows that the new infill panels are performing better than the surrounding timber-frame. The weak points of the façade are the windows and some joints between the timbers of the frame, especially around the first floor window.

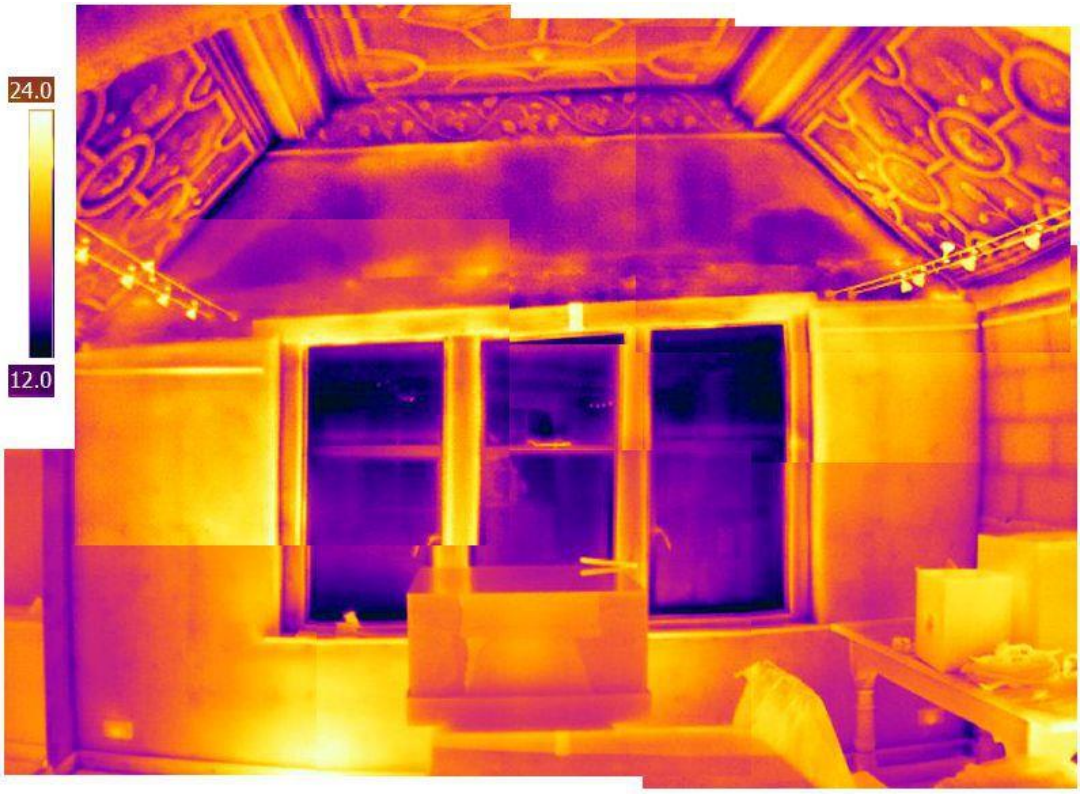

Figure 207. Internal thermography of east façade. Internal temperature 22.9°C. External temperature 0.4°C. 06:30, 11/03/2016

Figure 207 shows the efficacy of the internal lining, with no noticeable cold bridging or temperature difference across the surface. It can however been seen that the upper portion of the wall with no internal lining is cooler, with marked cold spots in the corners and recesses of the historic plasterwork. This image raises some concern over the decision not to internally line the upper portion or increase roof insulation. The decision was taken to minimise intrusion and damage to the historic fabric, but leaves a question as to whether this might, over time, lead to increased concentration of condensation and accelerated decay? This issue is explored further in the analysis of the hygrothermal monitoring below.

9.4.4 Hygrothermal monitoring

9.4.4.1 Detailed Methodology

The initial hygrothermal monitoring measured the internal temperature and relative humidity in two locations within the Old Mayor's Parlour, one to the east end and one to the west. In no. 25 Church Street a further two locations were monitored, one within the WC and the other in the office, both of which are located on the first floor to the east of the property. TinyTag® Ultra 2 TGU-4500 sensors were used for the monitoring between 18th February and 10th March 2016. Following this period Maxim Hygrochron® iButton DS1923 hygrothermal sensors were installed due to their smaller size and discrete design. These were left in place until July 2017 with the intention of obtaining at least one calendar year of measurements. Unfortunately, the capacity of the sensors memory was not as large as anticipated and logging ceased on 03/06/2016 having recorded only three months of data.

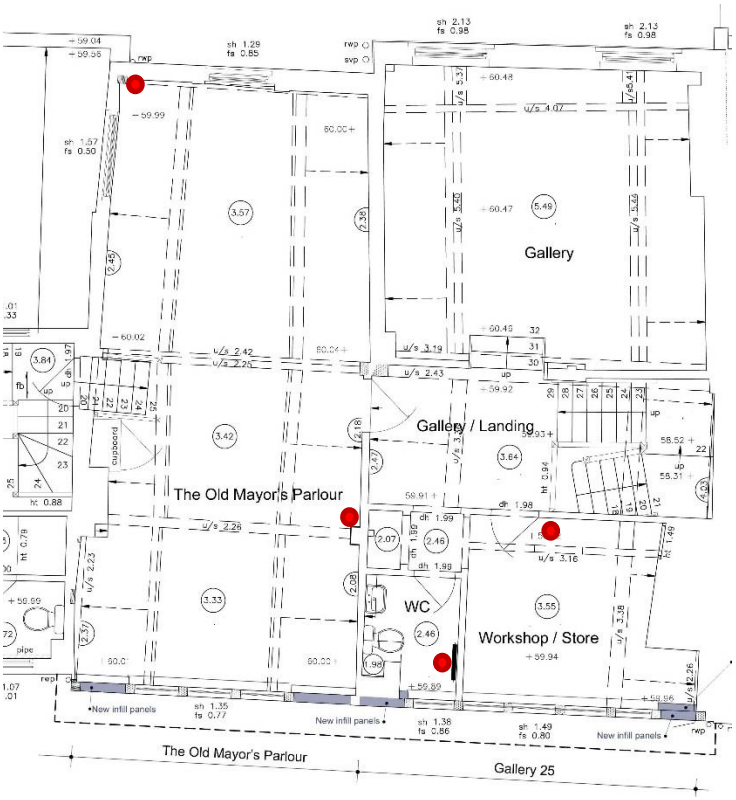

Figure 208. Old Mayor's Parlour and No.25 church Street, first floor plan showing location of hygrothermal sensors. Source: (Based on Jacqueline Demaus Architect, 2013

9.4.4.2 Results and Analysis

Prior to commencing the initial monitoring, it was known that the Old Mayor's Parlour (OMP) would be unoccupied during the first measurement period and as such unheated. It was however expected that the office and WC of No. 25 Church Street, both of which were in daily use, would have some degree of heating. It is therefore surprising to see from the results of the initial monitoring that neither of these spaces were heated, with temperatures in the WC closely following those in the parlour at around 10°C (Figure 209).

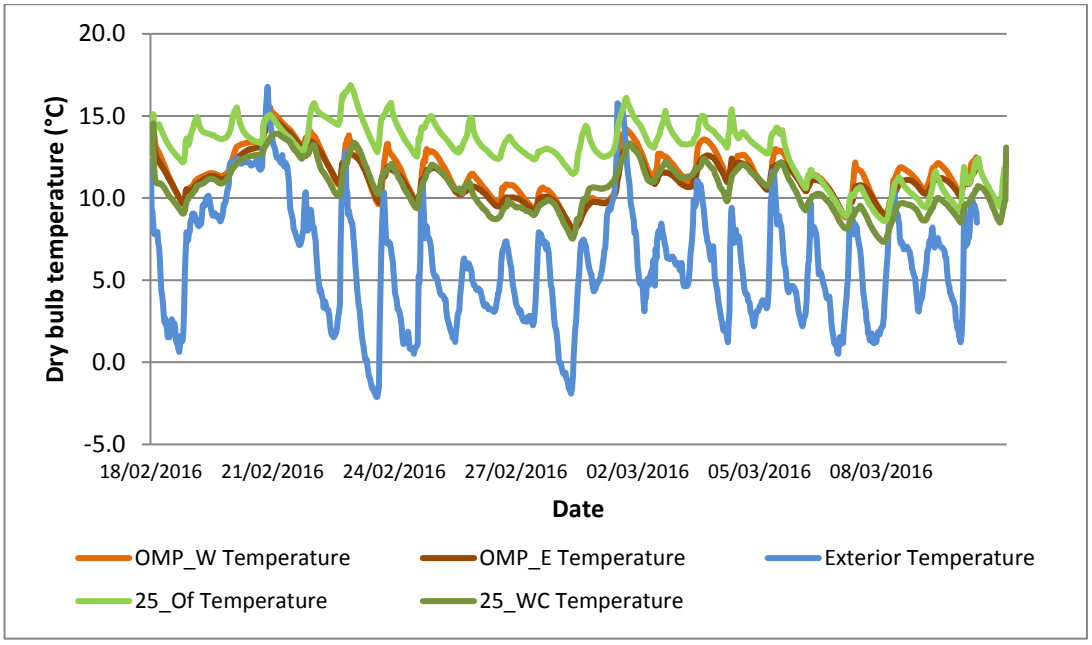

Figure 209 Dry bulb temperature as measured at the Old Mayor's Parlour and no.25 Church Street, 18/02-10/03/2016. (Author's own, 2016)

Temperatures in the office are a little higher, occasionally exceeding 15°C, probably due to heat rising from the shop below, but fail to achieve levels of comfort (Figure 211). Whilst the author has encountered similar situations in a developing country or fuel poor households, it is perhaps unexpected in a commercial premises in Hereford. The results for The Old Mayor's Parlour (Figure 210) also show that comfort conditions were not achieved during office hours. For both properties, although the lack of heating may reduce energy

demand and associated costs, it may create unintended consequences such as increased condensation and accelerated deterioration of interior finishes and building fabric.

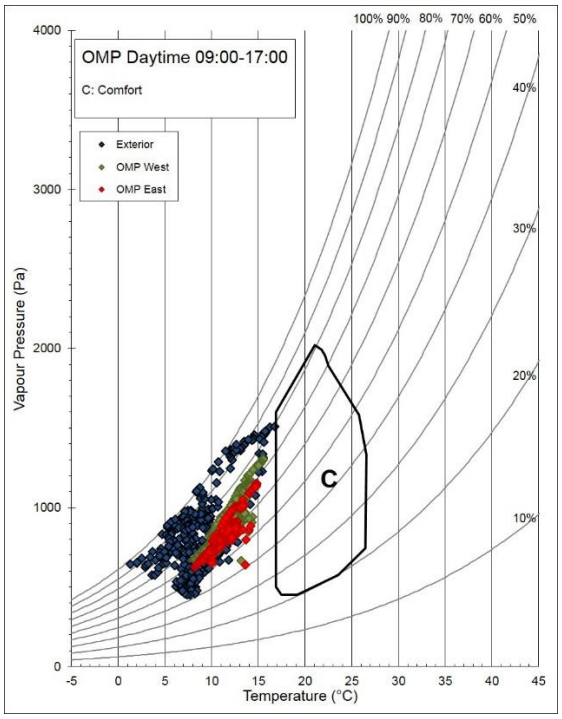

Figure 210 Psychrometric chart according to Givoni showing daytime (09:00-17:00) hygrothermal measurements in The Old Mayor's Parlour, as recorded 18/02-10/03/2016. Source: (Author's own, 2016)

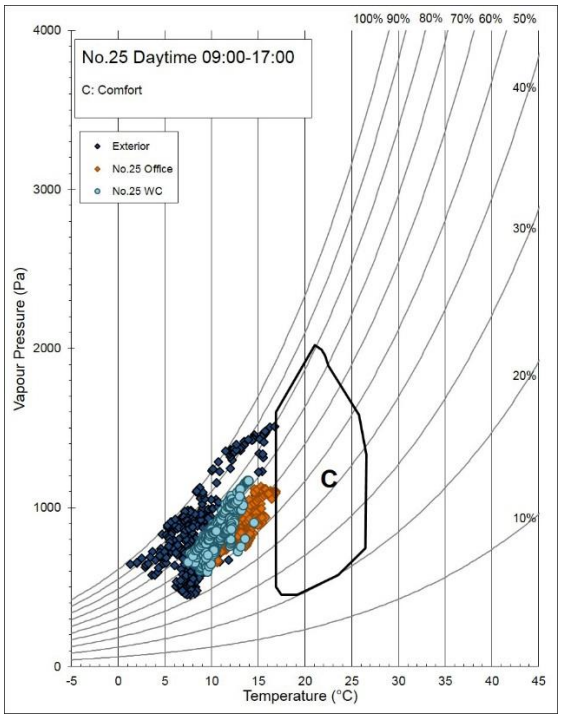

Figure 211. Psychrometric chart according to Givoni showing daytime (09:00-17:00) hygrothermal measurements in No.25 Church Street, as recorded 18/02-10/03/2016. Source: (Author's own, 2016)

The second stage of monitoring from 10th March until the 4th June 2016 showed that once in use, the temperatures in The Old Mayor's parlour did begin to exceed 17°C for parts of the working day (Figure 212). However, the office of No.25 did not begin to enter the thermal zone until the external temperatures rose in early May.

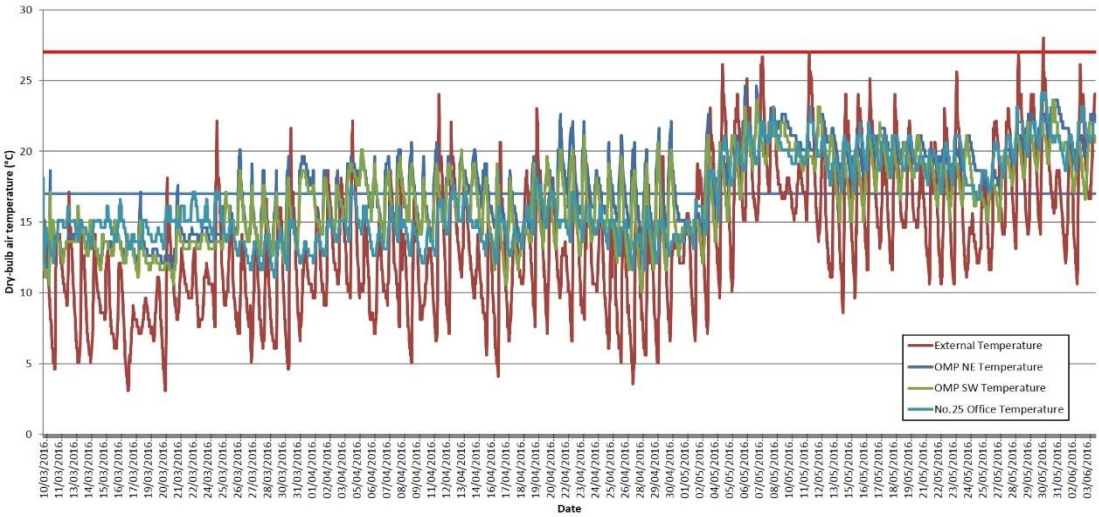

Figure 212. Dry-bulb air temperatures as measured in The Old Mayor's Parlour and No.25 Church Street 10/03/2016 to 04/06/2016. Source: (Author's own, 2017).

Over the full four and a half months of monitoring, during opening hours (09:00-17:00), hygrothermal comfort was achieved 50% of the time in the east end of The Old Mayor's Parlour, 55% of the time at the west end but only 28% of the time in no.25. The difference between the east and west end of The Old Mayor's Parlour may be due to the door to the semi-external staircase being located towards the east, although the electric heater is also located at this end of the room.

As noted from the results of the thermography, the lack of insulation to the roof raised some concern over the possible condensation that may occur on the cold surface of the 17th century decorative plaster ceiling. This condensation would be most likely to occur when high vapour pressure occurs, coupled with a large diurnal temperature variation. Analysing the hygrothermal data measured in The Old Mayor's Parlour it can be seen that the highest vapour pressure recorded was 1557Pa (Figure 213), with this occurring at 15:30 on 12/05/2016 at a dry-bulb temperature of 23°C.

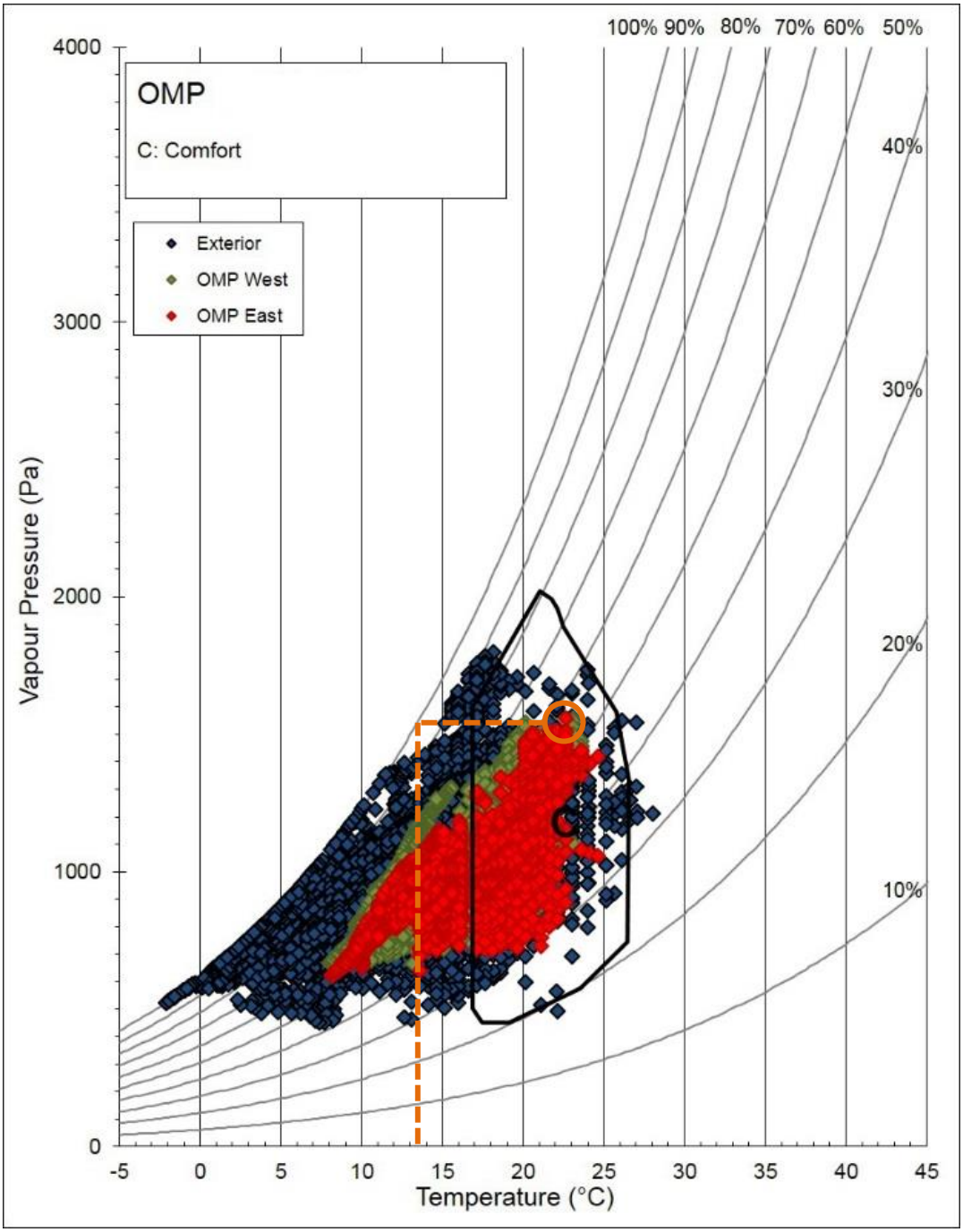

Figure 213. Psychrometric chart according to Givoni showing all hygrothermal measurements in The Old Mayor's Parlour, as recorded 18/02-04/06/2016. Highest vapour pressure highlighted with calculation of dew point. Source: (Author's own, 2017)

Tracing this vapour pressure across on the psychrometric chart it can be seen that condensation would occur at a dew point temperature of 13.5°C. Within the next 24 hours, the minimum internal dry-bulb temperature recorded was 18.6°C and the minimum external temperature 11.1°C. As such, it is possible that the internal surface temperature of

the ceiling could have dropped, in places, below the dew point temperature and condensation may have occurred. Equally, on the day with the largest diurnal temperature oscillation, the 28/04/2016, a maximum vapour pressure of 913Pa was recorded at a temperature of 17°C. The internal dry-bulb temperature then dropped to 11.6°C with a minimum external dry-bulb temperature of 5.6°C. Given that the dew point temperature for the maximum vapour pressure measured (913Pa) would be 5.7°C, there again exists a small possibility that conditions for condensation may have occurred.

9.4.5 Conclusions

In order to verify if condensation is occurring, further detailed monitoring of surface temperatures and hygrothermal conditions would be required. This additional monitoring has not been undertaken as part of the research for this thesis but could form an area for future investigation. The results presented here do however highlight the potential for situations to arise where the thermal improvement of only one part of an external envelope may increase the risk of condensation on another. Owners or agents often target areas that are easy or cheaply retrofitted, however the risks of treating elements in isolation require significant analysis. It is therefore critical that this is considered when proposing retrofit strategies.

9.5 Nos. 25-27 Church Street, Saffron Walden, Essex

At this privately owned residence, where no energy retrofit actions have taken place, the following monitoring was undertaken:

- in situ U-value monitoring
- pressure testing
- thermography
- hygrothermal monitoring.

Given the historic value of the pargetted north façade, the monitoring was focused on this element. As no exposed timber frame is present as part of this façade no timber moisture measurements were undertaken.

9.5.1 In situ U-value monitoring

9.5.1.1 Detailed Methodology

The in situ U-value monitoring was of two locations on the north (street) façade of the eastern cross-wing (Figure 214 & Figure 215).

Figure 214. North façade of 27 Church Street showing in situ U-value monitoring positions. Source: (Author's own, 2017)

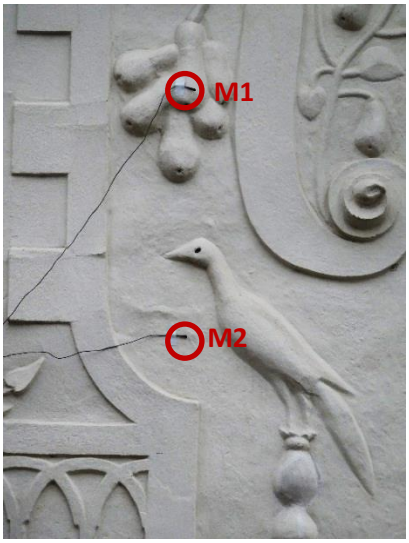

Figure 215. Detail. Source: (Author's own, 2017)

The two locations are both midway between vertical studs but have differing thicknesses of pargetting. The first monitoring location (M1) is located over a bunch of fruit, whilst the second (M2) is within a clear area of the background. The thermography undertaken and presented in section 9.5.3.2 appeared to indicate that neither location coincided with a timber-frame member.

9.5.1.1.1 Instrumentation

The same general methodology for in situ U-value monitoring as previously described was employed, with the same specific equipment as detailed for the Old Mayor's Parlour (paragraph 9.4.1.1.1). The internal set-up is shown in Figure 216 and Figure 217. The external temperature thermistors as shown in Figure 215 were held in place with adhesive tape. Due to the northern orientation of the façade, no protection from direct solar radiation was installed.

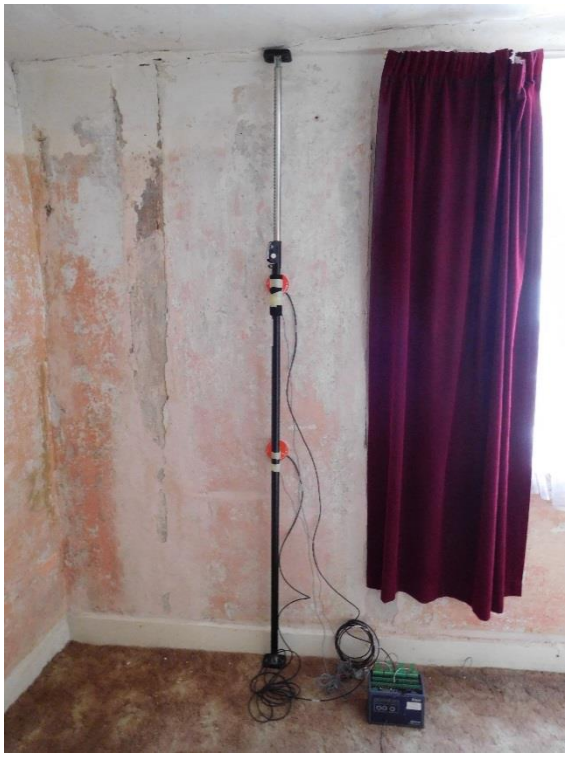

Figure 216. Heat flux plates, internal thermocouples and data loggers, no.27 Church Street.

Figure 217. Detail. Source: (Author's own, 2017)

9.5.1.1.2 Time and duration of monitoring

The in situ U-value monitoring was undertaken between 12th March 2017 and 2st April 2017, with a measurement period of 21 consecutive days. Unfortunately, it was discovered on the 2nd April that the upper heat flux plate (M1), measuring the thicker pargetting had slipped. As such, readings for monitoring position M1 were only obtained for five consecutive days from the 12th-17th March 2017.

9.5.1.2 Results and Analysis

The results of the in situ U-value monitoring for the wall of 27 Church Street are shown in Figure 218. For monitoring position M2 a difference of ±5% was achieved and maintained for 1 week before the end of the monitoring period. The average U-value measured over this period was 0.64W/m²K, with a standard deviation of 0.04W/m²K. As previously noted, due to an unknown event, the readings for monitoring position M1 were limited to five consecutive days. Figure 218 shows that during these five days no steady state was achieved. However, the final cumulative average U-value measured for monitoring position M1 was 0.85 W/m²K.

Figure 218. 27 Church Street, Saffron Walden. Daily average measured U-value, corrected to omit direct solar radiation 12th March – 1st April 2017. Source: (Author's own, 2017)

The measured U-value for monitoring position M2 is unexpectedly good, outperforming the new infill panels with multi-foil insulation at Hacton Cruck. The pargetting is most likely highly influential in this result, acting as both an external insulating render, and sealing the joints between panel and timber-frame, thereby reducing infiltration and the associated edge effect.

It is interesting to note that during the five days of concurrent monitoring the daily average measured U-value for position M1 was between 0.04 and 0.4W/m^{2}K higher than that for position M2. It had previously been assumed that the increased thickness of pargeting would improve (decrease) the thermal transmittance of the wall. The measured results would appear to contradict this, suggesting that in fact was not the case. One hypothesis for this that the three dimensional moulding of the pargetting, in this case fruit, increases the external surface area and as such increases the heat flux through this area. However, simulation with THERM® 7.5 two dimensional heat-flow simulation software through a cross section[55] of the wall does not show this to be the case (Figure 219). Whilst the tips of the moulded pargetting fruit are colder, the simulation shows less heat flux in this location.

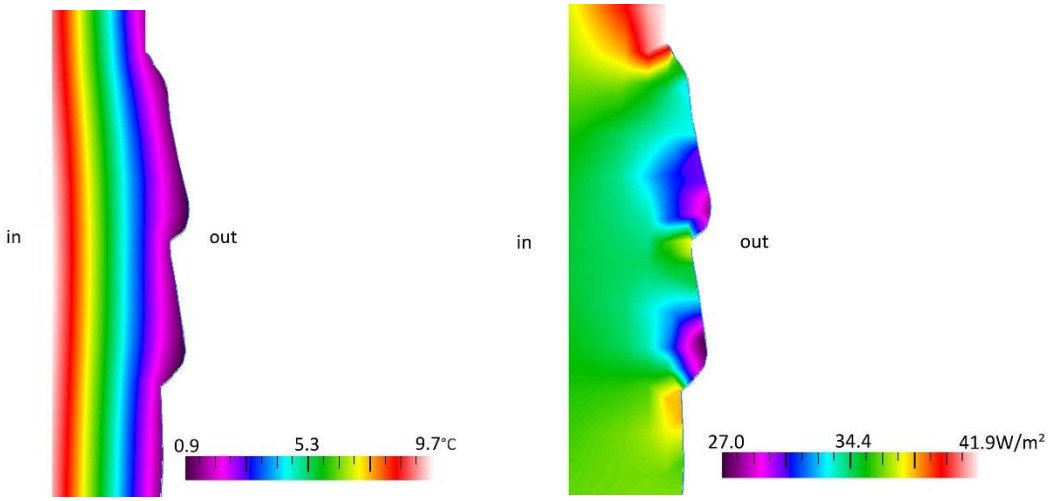

Figure 219. Simulation with THERM 7.5 software of section through wall at location of moulded fruit showing temperature distribution (left) and heat flux magnitude (right). Source: (Author's own, 2017)

[55] The dimensions of the section were derived from a laser scan of both the exterior and interior of the monitoring position.

It should be noted that THERM® 7.5 calculates in only two dimensions and does not take into account the influence of external air movement. There are also anomalies in the heat flux both directly above and below the fruit. These may be further complicated if modelled in three dimensions. As such, it is still possible that the hypothesis of increased surface area could hold, however this has yet to be proven. Further research is required. The following results of the thermography could also suggest another hypothesis.

9.5.2 Pressure Testing

Pressure testing was completed on 12th March 2017 following the previously described general methodology. All fireplaces, broken windows and both back doors were sealed with plastic sheet and adhesive tape, as was a hole cut in a bedroom ceiling of no 27 and the space around a cable passing through the upstairs partition separating the two cottages. Holes in the broken lath and plaster ceilings of no 25 were not sealed due to concern over further damage to historic fabric. The Minneapolis® Blower Door was mounted in the front doorway of no 27. For the first pressure test, the newly opened interconnecting ground floor doorway between no 25 and no 27 was sealed to allow the depressurisation of only no 27 and enable direct comparison with an earlier pressure test undertaken on 12th January 2012 by Diane Hubbard of ArchiMetrics (Hubbard, 2012). Between this previous test and that presented here, modern internal wall and floor finishes have been removed, along with draughtproofing from certain windows and doors. Following the pressure testing of just no.27, the doorway was unsealed and both properties were depressurised. The building metrics used in the calculations are shown in Table 20.

Table 20. Building dimensions used in calculations

Property	Building Dimension	Calculated by author	Calculated by D.Hubbard (Hubbard, 2012)
No.27	Internal floor area (m^2)	55	61
	Internal surface area of building envelope (m^2)	178	201
	Habitable building volume (m^3)	130	146
Nos. 27 & 25	Internal floor area (m^2)	134	-
	Internal surface area of building envelope (m^2)	314	-
	Habitable building volume (m^3)	325	-

9.5.2.1 Results and Analysis

The initial depressurization of just no.27 was undertaken with the blanking plate on the fan and a maximum building pressure of 37 Pa was achieved[56]. Depressurization was then repeated with the blanking plate removed. A maximum building pressure of 58 Pa was achieved; however, the lower fan pressures were more difficult to read accurately due to the precision of the pressure gauges[57].

Following the removal of the seal to the interconnecting doorway, the depressurization of both cottages together with the blanking plate proved hard to achieve. With the blanking plate removed, depressurization was achieved, however with only a maximum building pressure of 15 Pa. The R^2 of the best-fit line was 0.995 showing a very good fit with a low degree of error in extrapolation of these results. The results for the three pressure tests are presented in Table 21 along with those previously measured by ArchiMetrics (Hubbard, 2012).

[56] (R^2) of the best-fit line = 0.9937 showing an almost perfect fit
[57] (R^2) of the best-fit line = 0.9899 showing a good fit.

Table 21. Results from pressure testing of nos. 25-27 Church Street, Saffron Walden

	Air Permeability Index ($m^3/h/m^2$)	Effective Leakage Area (m^2)	Air change Rate @50 Pa (/hr)	Air change rate unpressurised (/hr)
No.27-2012†	7.3	-	10	-
No. 27-2017 BP	14.9	2.03	20.4	1.02
No. 27-2017 NBP	14.2	1.36	18.8	0.94
Nos.25&27-2017 NBP	58.6	13.12	56.6	2.83

† (Hubbard, 2012)
BP- With blanking plate
NBP- without blanking plate

The results would appear to suggest that the removal of the 20th century internal finishes from walls and floors had led to an approximate doubling of the air permeability index and air change rate, that is to say a halving of the airtightness of the building. It should however be noted that potentially the sealing up of the interconnecting doorway was not as airtight as the previous lath and plaster wall. What is clear is that the combined building has a very high air change rate. This is not surprising given the openings to both ceiling and roof voids and cellar that are currently uncontrolled with no.25. It would be interesting, following completion of the conservation of this property, to undertake further testing.

9.5.3 Thermography

9.5.3.1 Detailed Methodology

Due to particular interest in the performance of the pargetted north façade of the cross-wings, the thermographic survey concentrated on these two areas both internally and externally. The building was unpressurised. The thermography was undertaken on 12/03/2017 starting at 6:30am. A FLIR® B250 thermal imaging camera was used for both. Electric heaters were used to augment the internal temperature. The temperature differences are as shown in Table 22. For the eastern cross-wing the ideal 10°C difference for unpressured thermography (Hart, 1991 p.17-18) was achieved, whereas for the western wing the difference was only 5.5°C, however this is still deemed to be acceptable (Young, 2015 p.23).

Table 22. Temperature difference for thermography at nos.25&27 Church Street, Saffron Walden, 12/03/2017

	External Temperature (°C)	Internal Temperature (°C)	Temperature difference (°C)
Eastern cross-wing	10.5	22	11.5
Western cross-wing	10.5	16	5.5

9.5.3.2 Thermography

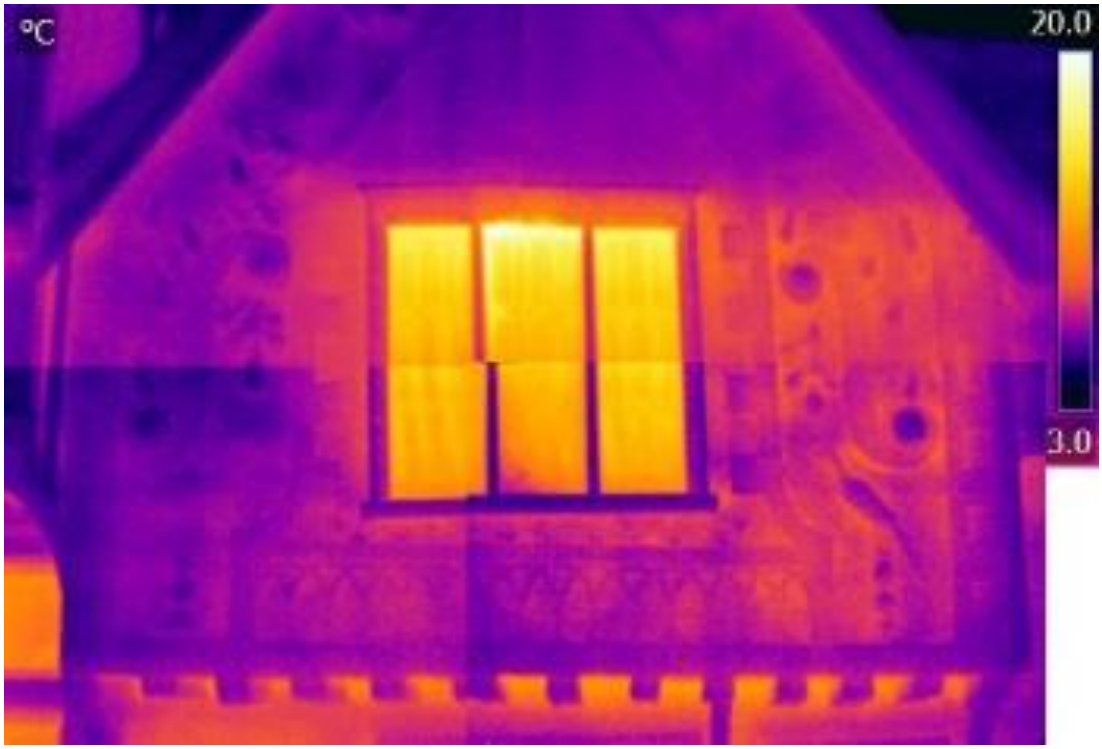

Figure 220. External thermography of the north façade of eastern cross-wing, no.27 Church Street. Source: (Author's own, 2017)

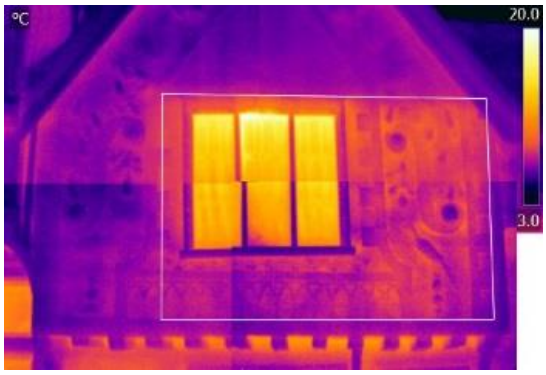

Figure 221. Annotation highlighting extent of room behind.

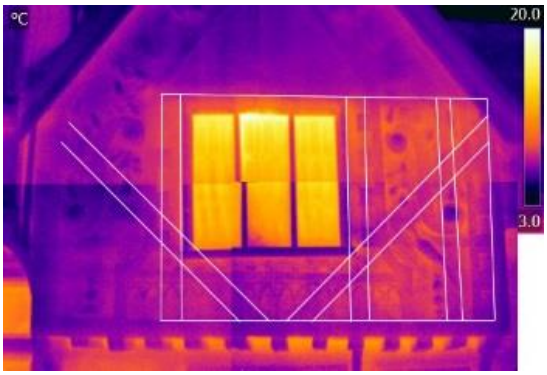

Figure 222. Annotation showing possible timber locations

Figure 220, Figure 221 and Figure 222 show the external thermography of the north façade of the eastern cross-wing. The extent of the front bedroom is clearly visible, as highlighted

in Figure 221. It is interesting to note that a very large proportion of the room has been encroached upon by the construction of the chimneybreast, taking up most of the wall to the left of the window. The location of the timbers can also be seen as highlighted in Figure 222, including the presence of two diagonal down braces. Recent research sent to the owner by an unnamed master's student has also suggested that it is likely that the building has these diagonal braces. The research also suggests that the apex of the gables may have arched bracing; however, these are not detectable in the thermography, perhaps due to the lack of temperature difference between the loft space and the exterior. The presence of these diagonal timbers, unknown at the time of installation of the in situ U-value monitoring sensors, could suggest another hypothesis for the increased U-value at monitoring position M1. As shown in Figure 223 the location of monitoring position M1 is closer to the timber and as such will have a great effect from the edge condition than that of M2, this would increase the thermal transmittance at this point, thereby explaining the increased U-value measured. In addition, subsequent investigation with a stud detector by the house owner has raised the possibility of a vertical stud being present behind both positions. The results of the stud detection were not however conclusive and are not clearly supported by the thermography. Further measurements are therefore recommended to confirm the U-value of the infill panels on this building.

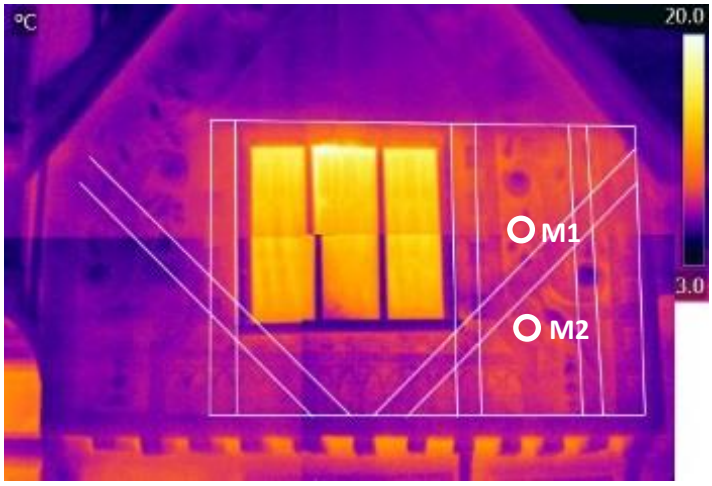

Figure 223. Thermography of 25 Church Street with annotation showing location of timber members and in situ monitoring positions M1 and M2. Source: (Author's own, 2017)

A complete view of the whole north elevation of the eastern cross-wing (no.27) (Figure 224) appears to show that the pargetted upper façade is allowing less thermal transmittance than the lower brick underbuilding of the ground floor. Given the unequal heating of the two corresponding internal spaces there may be some degree of error in this conclusion, however, the internal temperature of the ground floor room was substantially lower at 13°C compared to the 22°C of the upper bedroom. Therefore, it could perhaps be presumed that if both spaces were at an equal temperature the difference in the thermal performance of the two materials would be even more apparent. The greatest thermal weaknesses of the envelope are however undoubtedly the single glazed windows and the protruding floor of the jetty. The effect of the varying thickness of pargetting is also apparent.

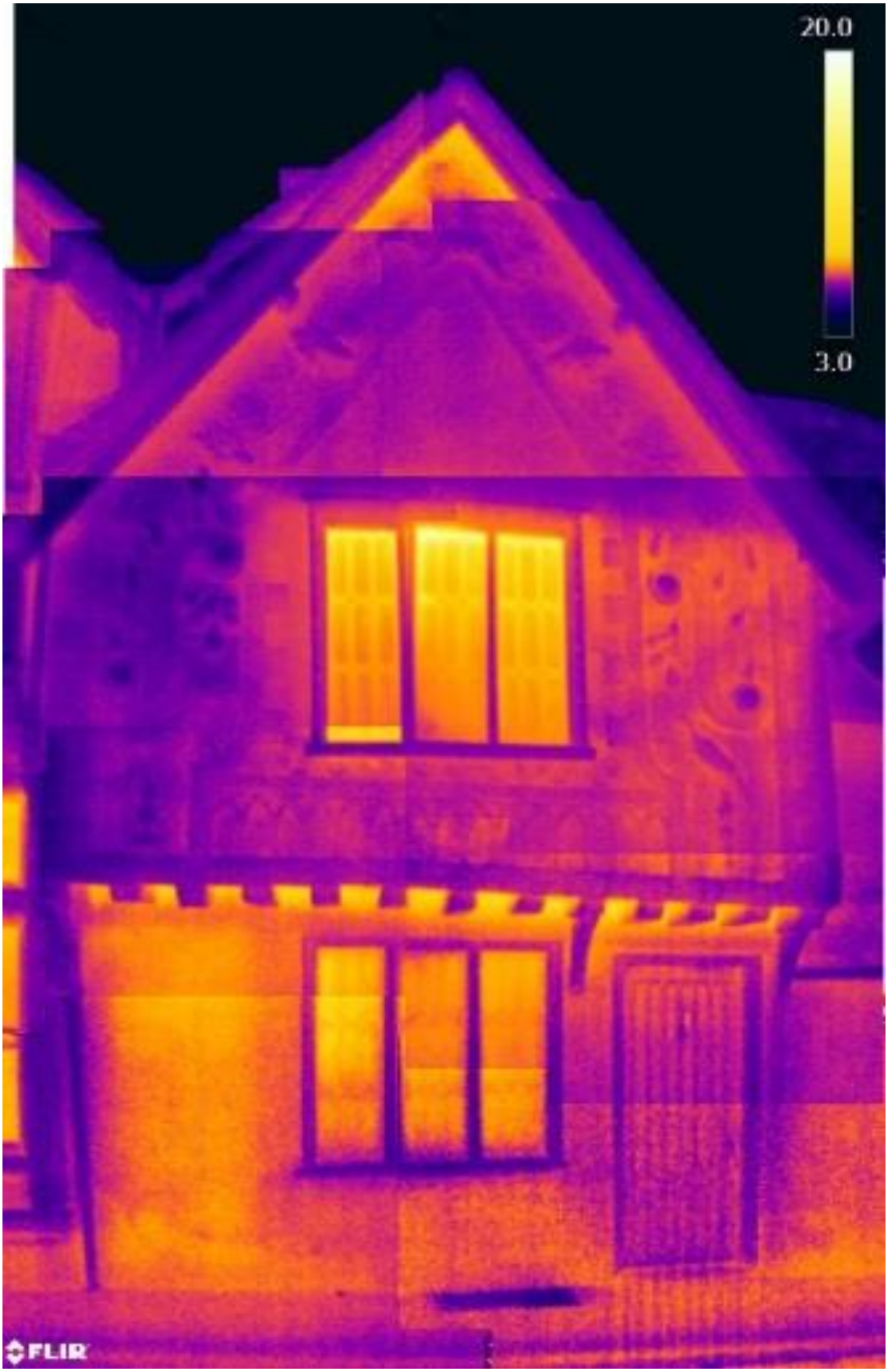

Figure 224. External thermography of north façade of eastern cross-wing, no.27 Church Street. Source: (Author's own, 2017)

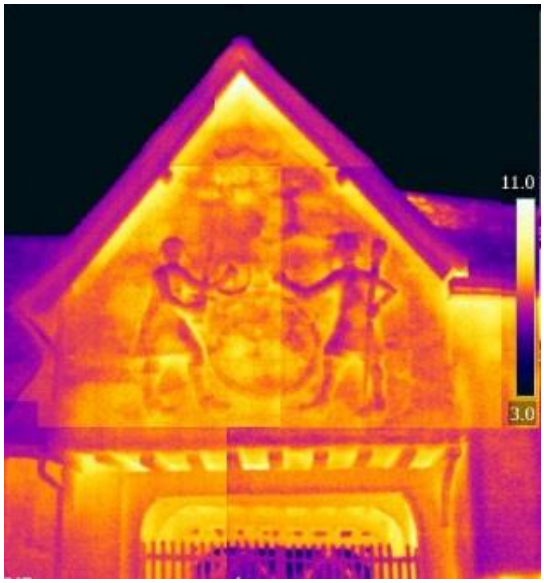

Figure 225. External thermography of north façade of western cross-wing, no.27 Church St.

Figure 226. Annotation highlighting possible timber locations. Source: (Author's own, 2017)

The external thermography of the west cross-wing also clearly shows the differing thermal performance of the various thicknesses of pargetting (Figure 224 and Figure 225). On this wing, the location of the timber structural members is less evident than that of the eastern cross-wing. It is however still possible to locate the tie-beam and the left-hand end of a rail, these are highlighted in Figure 225. The poor thermal performance of the floor over the carriageway is also evident.

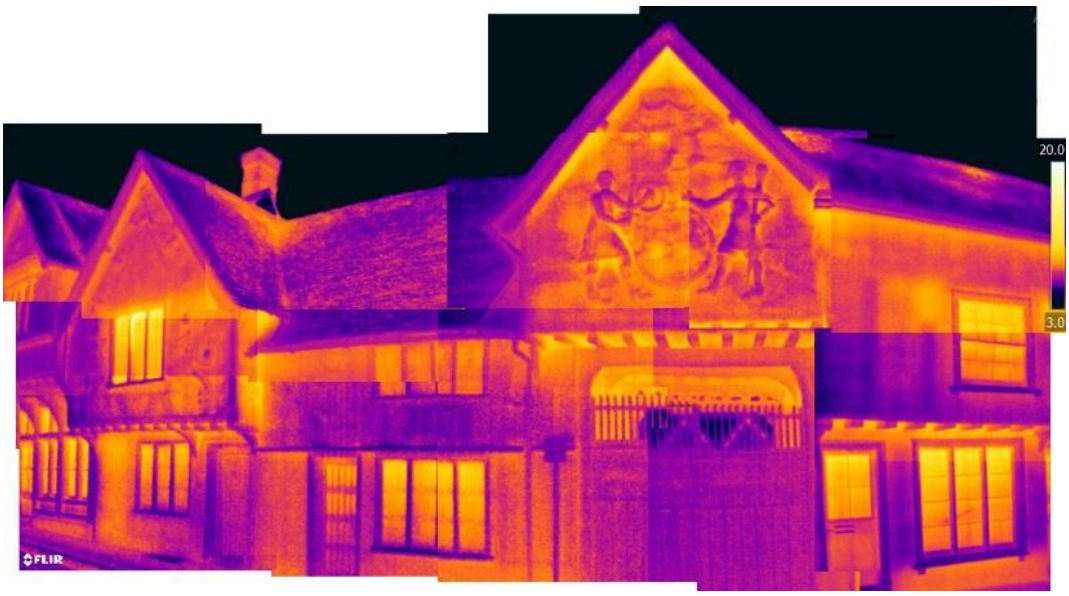

Figure 227. Overall external thermograph of north façade of nos. 25-27 Church Street. Source: (Author's own, 2017)

The high thermal transmitance of the jettied floors and the single glazed windows is also demonstrated in Figure 227. It should be noted that the unjettied front bedroom (former upper-hall) of no.25 was unheated during the monitoring, hence the lesser heat loss through the central section of first floor wall between the two cross-wings.

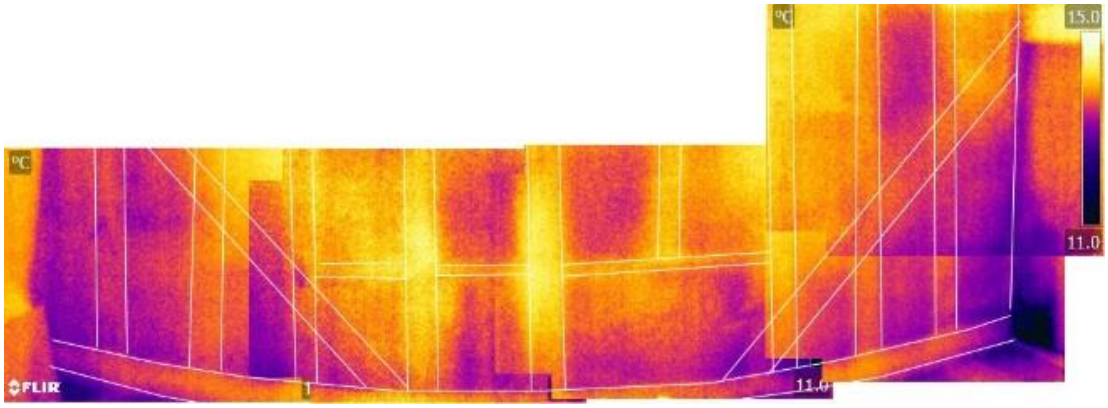

Figure 228. Internal thermography of north façade of western cross-wing, no.25 Church Street showing base of lower wall, annotated with possible timber locations. Source: (Author's own, 2017).

Internal thermography of the western cross-wing shows more clearly than the external the possible location of the timber-frame. In addition to again suggesting diagonal down bracing, as seen externally on the eastern cross-wing, it also shows the location of a windowsill that predates the pargetting. This can also be seen in further images of the same wall in Figure 229 and Figure 230.

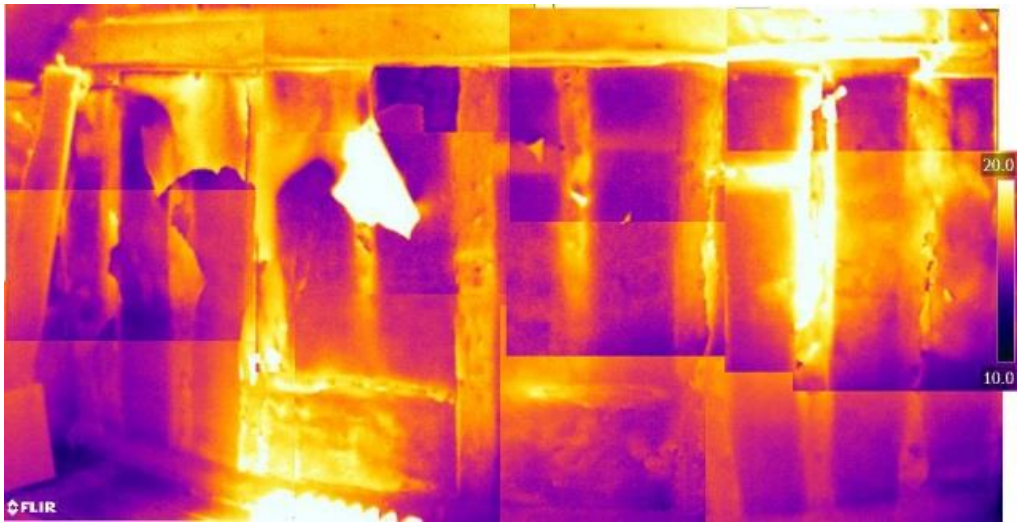

Figure 229. Internal thermography of north façade of western cross-wing, no.25 Church Street showing lower wall. Source: (Author's own, 2017).

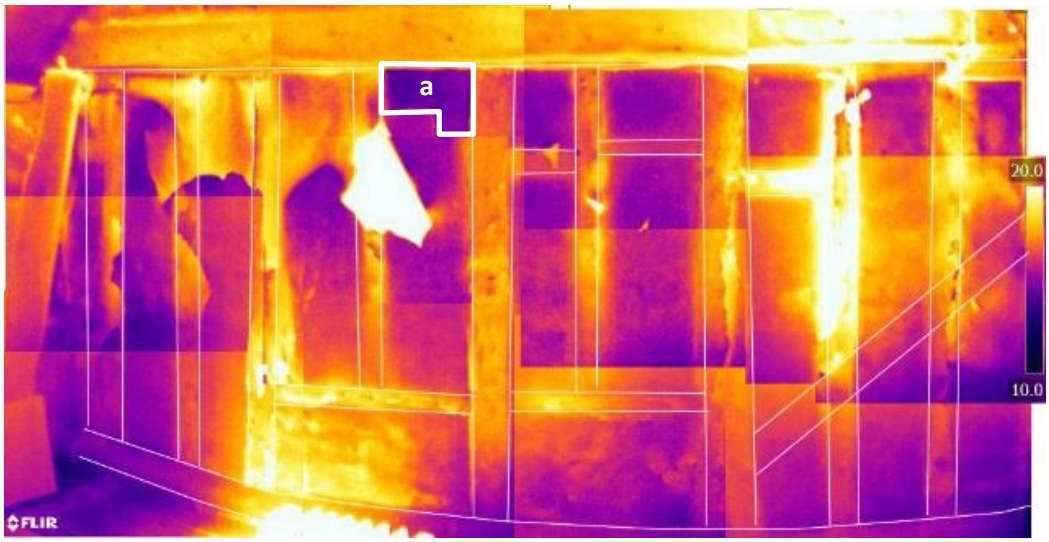

Figure 230. Internal thermography of north façade of western cross-wing, no.25 Church Street showing lower wall, annotated with possible timber locations, and exposed brick nogging (a). Source: (Author's own, 2017).

These also clearly show that infill panels have a higher thermal transmittance than the surrounding timber-frame. In one location ((a) on Figure 230) the lime plaster has been removed and a patch of brick nogging exposed. It is however interesting to note that the mortar joints of the brick nogging are not discernible through the plaster as previously seen with the concrete blockwork at The Oaks (Figure 188) and The Old Mayors Parlour (Figure 207). It is thought that the brick nogging is confined to the infill of the original window. There would appear to be some degree of higher thermal transmittance through these panels compared to the surrounding wattle and daub.

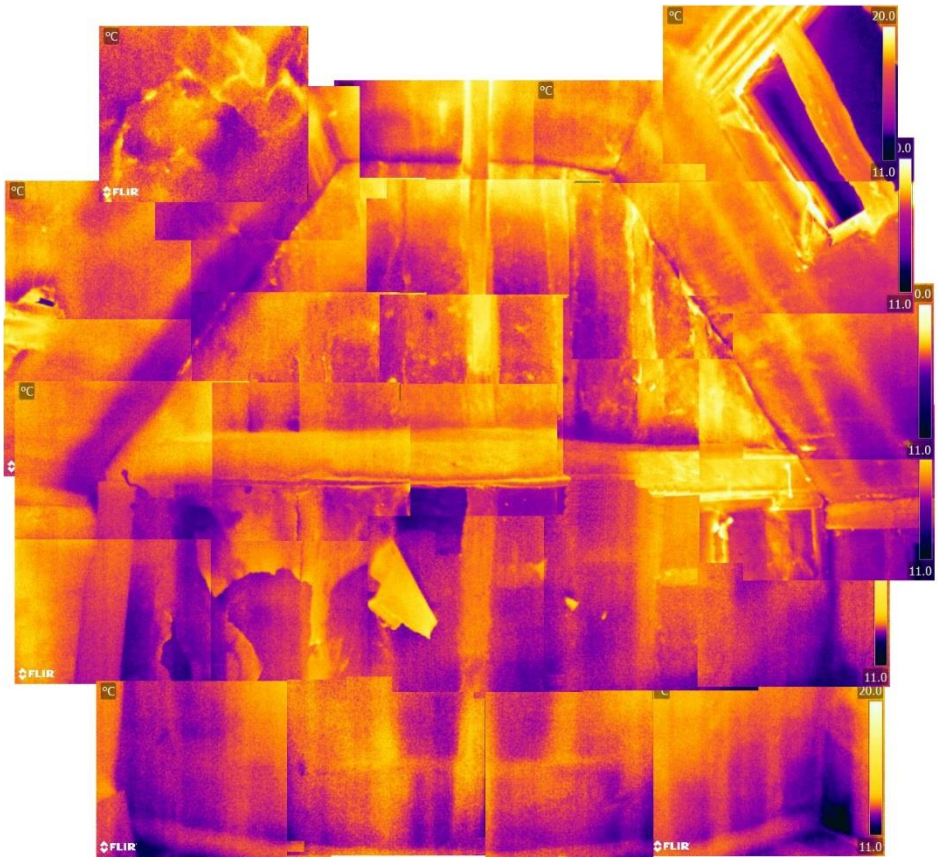

Figure 231. Internal thermography of complete north wall of western cross-wing, no.25 Church Street. Source: (Author's own, 2017)

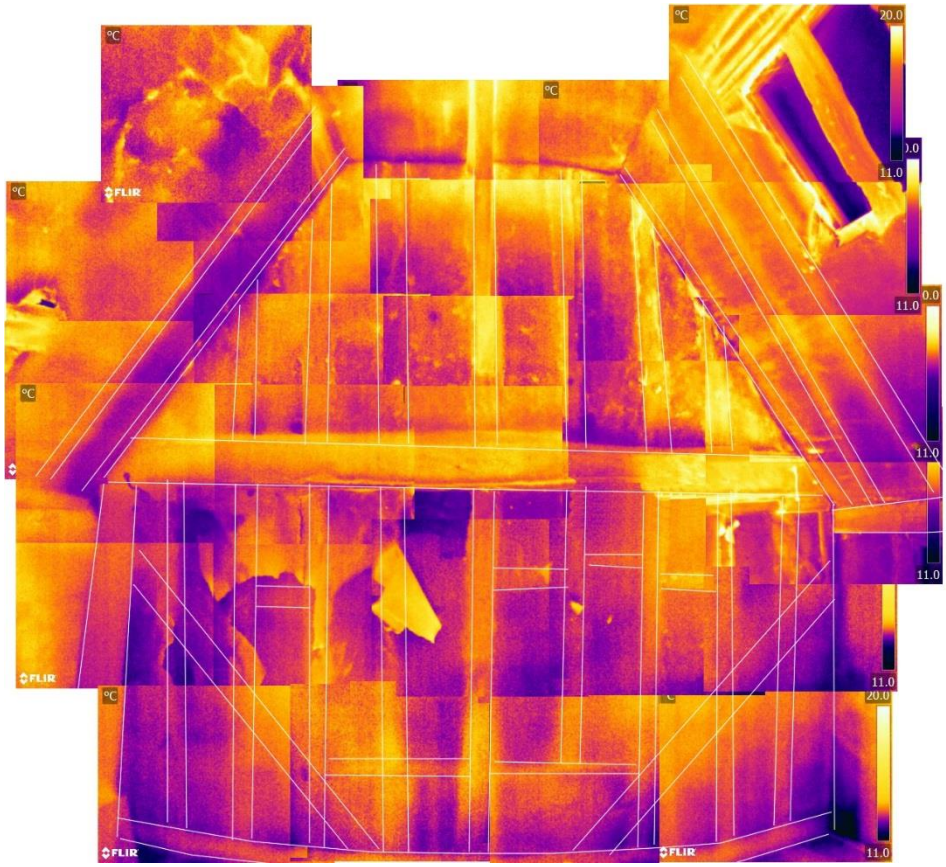

Figure 232. Annotated internal thermography of north wall of western cross-wing, showing timber framing. (Author's own, 2017)

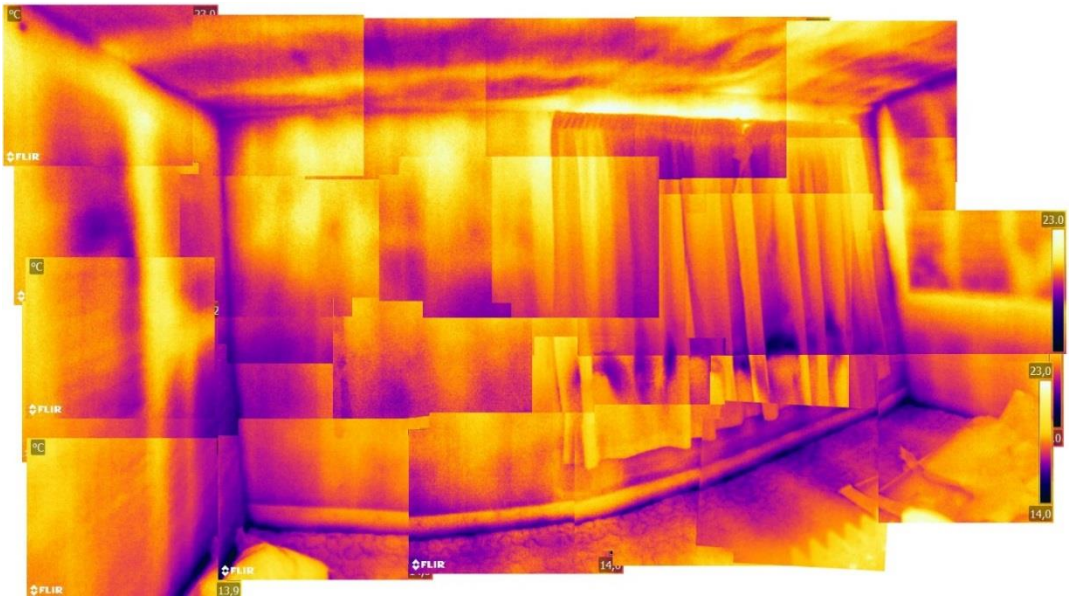

Figure 233. Internal thermography of north wall of eastern cross-wing, no.27 Church Street. Source: (Author's own, 2017)

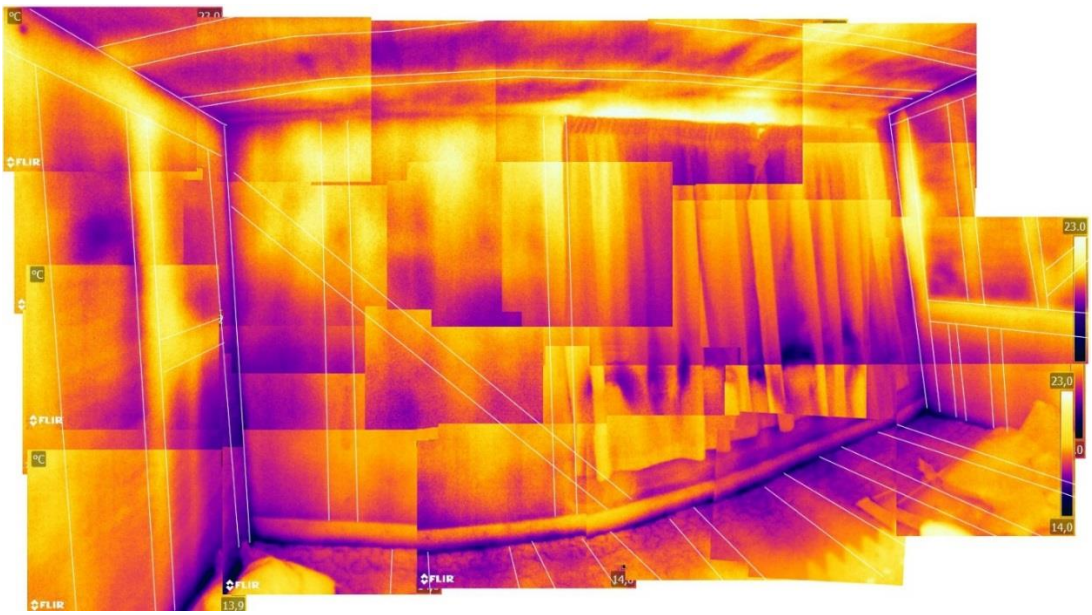

Figure 234 Internal thermography of north wall of eastern cross-wing, no.27 Church Street. Annotated to show possible location of timber framing. Source: (Author's own, 2017)

Despite the higher internal temperature, the internal thermography of the eastern cross-wing in no.27 does not give such clear results as that of the western cross-wing. Whilst the timber-frame can be clearly seen in the internal walls, the ceiling and the floor, the internal plaster makes it difficult to read the timbers in the external north wall. Together with the information gathered from the external thermography it is however possible to just about make out the timber-frame as highlighted in Figure 234.

9.5.4 Hygrothermal monitoring

9.5.4.1 Detailed Methodology

The owner has had Lascar® EasyLog® EL-USB-2 hygrothermal sensors installed in the locations shown in red in Figure 235 since March 2010. These sensors have a similar accuracy to the TinyTag but as with the iButton used at The Old Mayor's Parlour the resolution is reduced (0.5°C and 0.5%RH). In addition to these, TinyTag® Ultra 2 TGU-4500 sensors were installed in the locations shown in blue in Figure 235. Measurements were taken at half hour intervals from 11th March – 16th August 2017.

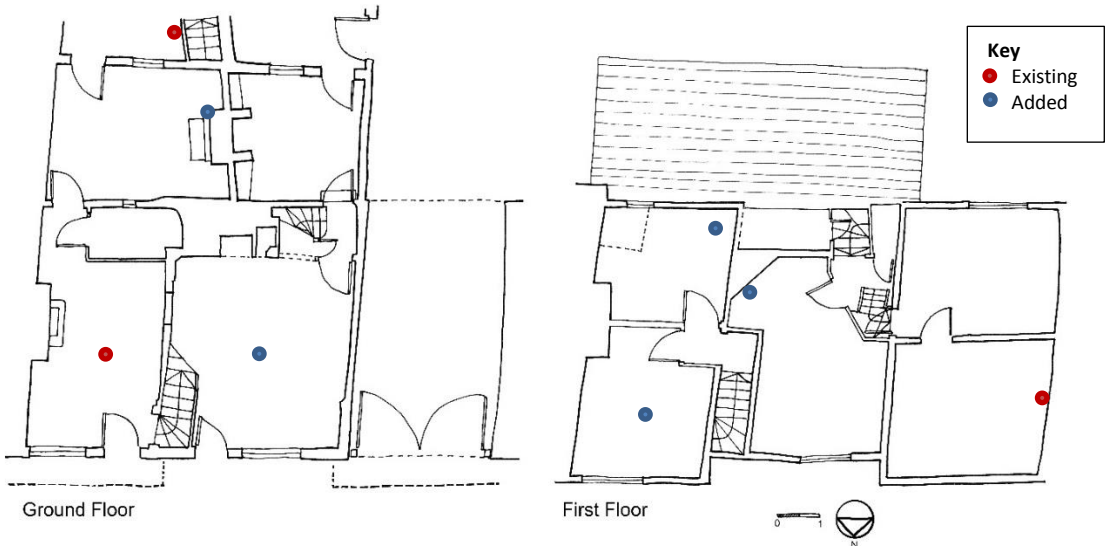

Figure 235. Plans of nos.25 & 27 Church Street showing location of hygrothermal sensors. Source: (author's 2017 own based on plans by (Kent, 2015))

9.5.4.2 Results and Analysis

The results show that only the front bedrooms of no.27 & no.25 achieved any hygrothermal comfort during March (Figure 236). This was due to the electric heating in both rooms to reduce the risk of frost damage to the 17th century pargetting. The heating was maintained for longer in the front bedroom of no.27 to enable the in situ U-value monitoring. As the house is currently uninhabited, no space heating is provided in the rest of the house and hygrothermal comfort is only achieved in mid-May once external ambient conditions have also reached comfort conditions.

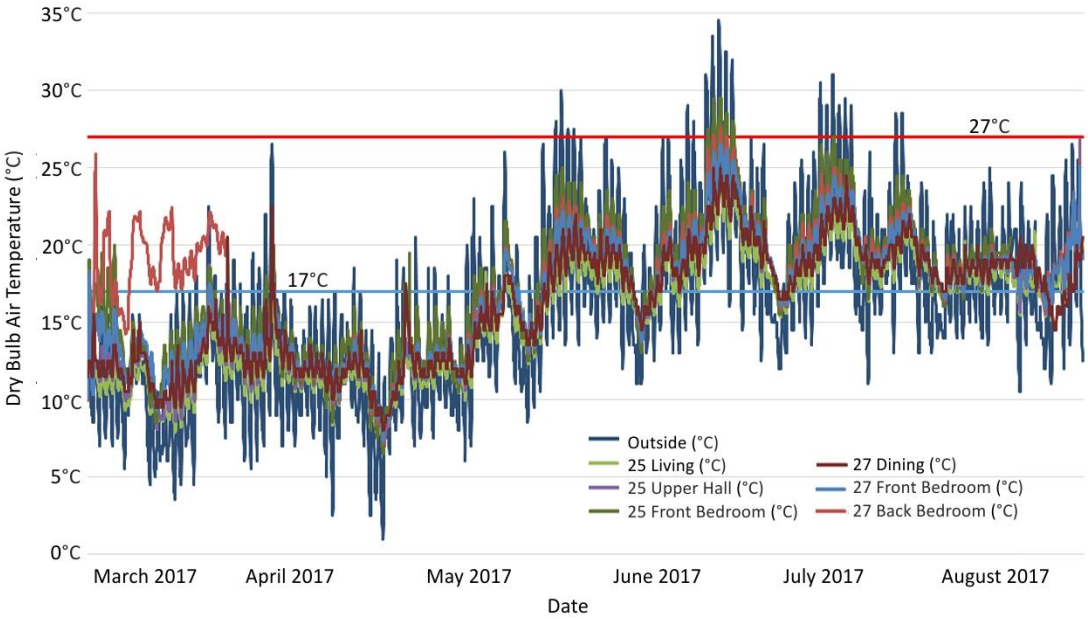

Figure 236. Dry bulb air temperatures for nos.25 & 27 Church Street, Saffron Walden as recorded 11/03-16/08/2017. Source: (Author's own, 2017)

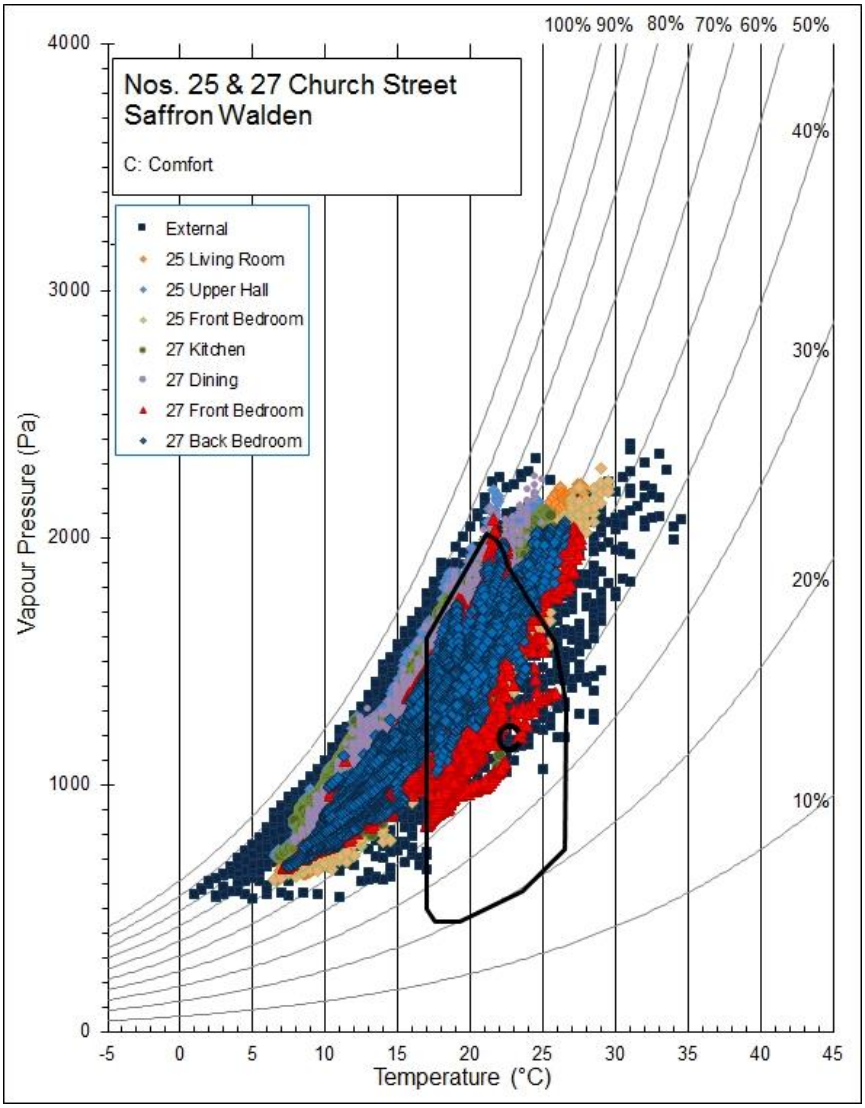

Figure 237. Psychrometric chart according to Givoni showing (09:00-17:00) hygrothermal measurements at Nos. 25 & 27 Church Street, Saffron Walden as recorded 11/03-16/08/2017. Source: (Author's own, 2017)

Overall, the results show that whilst hygrothermal comfort conditions are achieved for all rooms for some of the time (Figure 237 and Figure 238), there are also times when these not met (Figure 239), with conditions falling both above and below. With the heating of the front bedroom of no.27, comfort conditions are achieved 55% of the time, unlike the living room of no.25 where they are met for only 19% (Figure 238). When looking at the reasons for hygrothermal comfort conditions not being met, it can be seen that it is principally due to temperatures below 17°C (Figure 239), although in the ground floor rooms excessive relative humidity is a greater problem.

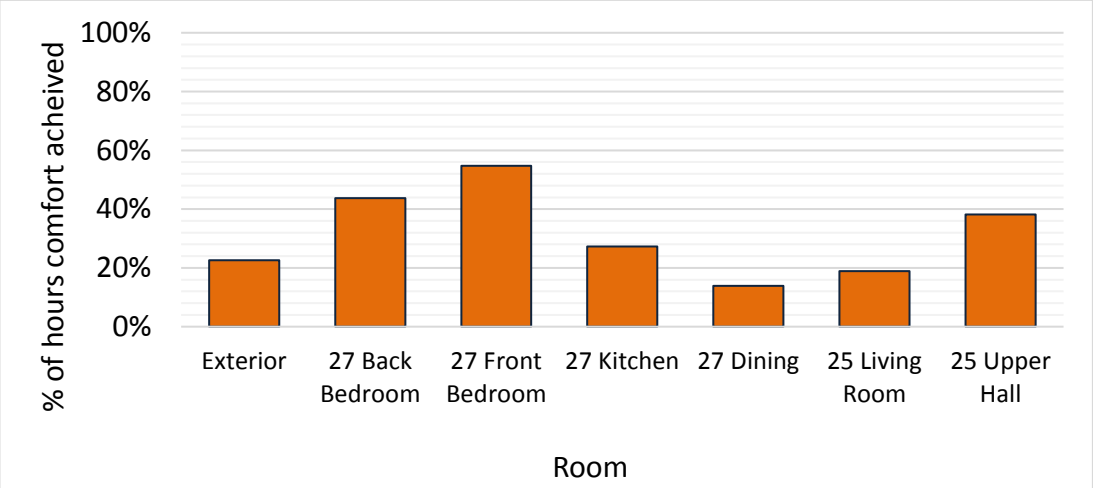

Figure 238. Percentage of time that hygrothermal comfort as defined by Givoni is achieved at Nos. 25 & 27 Church Street, Saffron Walden as recorded 11/03-16/08/2017. Source: (Author's own, 2017)

Figure 239. Percentage of time that hygrothermal comfort as defined by Givoni is not achieved due to low temperatures, high temperatures and high relative humidity at Nos. 25 & 27 Church Street, Saffron Walden as recorded 11/03-16/08/2017. Source: (Author's own, 2017)

The excessive relative humidity on the ground floor rooms is most probably due to the open connection to the subterranean cellar of both properties. As the conservation work proceeds this issue should be resolved with the installation of an airtight door to the cellar.

9.5.5 Conclusions

The monitoring at this un-retrofitted property has highlighted areas for improvement but has also shown that at times the historic fabric can perform better than expected. The measured u-values indicate that the pargetted wall is performing better than the panels with multi-foil insulation at Hacton Cruck. The pargetting is most likely highly influential in this result, acting as both an external insulating render, and sealing the joints between panel and timber-frame, thereby reducing infiltration and the associated edge effect. Although inconclusive, the in situ U-value measurement for the thicker pargetting may suggest that the modelling of the exterior surface has a negative impact due to the increased surface area. This is an area for further research and in no way diminishes the cultural value of this historic feature.

The pressure testing showed that currently the property is not very airtight and that the work so far undertaken by the owner to remove 20th century finishes has made it even less so. If the property is to be an inhabitable dwelling, this is an area that will require careful consideration. The thermography showed the windows and exposed floors also to be areas of thermal weakness.

The hygrothermal monitoring shows that in its current unoccupied state, few rooms in the house achieve comfort levels. This is to be expected and the measurements in the front bedroom of no.27 show that with heating, comfort can be achieved. The high levels of relative humidity, especially on the ground floor are thought to be attributable to the open connection to the cellar. However, further monitoring is recommended as the conservation of this building progresses.

9.6 Old Stokes Farm, Battisford, Suffolk

At this private residential property, where the principal retrofit actions in the past have been the replacement of panel infill with PIR thermal insulation, and the application of cement render, the following monitoring was undertaken.

- in situ U-value measurement
- pressure testing,
- thermography
- hygrothermal monitoring
- thermal comfort questionnaires
- interstitial hygrothermal monitoring
- Timber surface moisture measurements

9.6.1 In situ U-value monitoring

9.6.1.1 Detailed Methodology

Given that all infill panels have been retrofitted with an equal thickness of rigid polyisocyanurate (PIR) thermal insulation, in situ U-value monitoring was undertaken in only one location. A location on the North façade was selected to minimise the influence of direct solar radiation. The wall of the study was chosen due to ongoing building work in the kitchen and the continual heating of the study. The monitoring equipment was installed midway between two vertical studs (Figure 241)

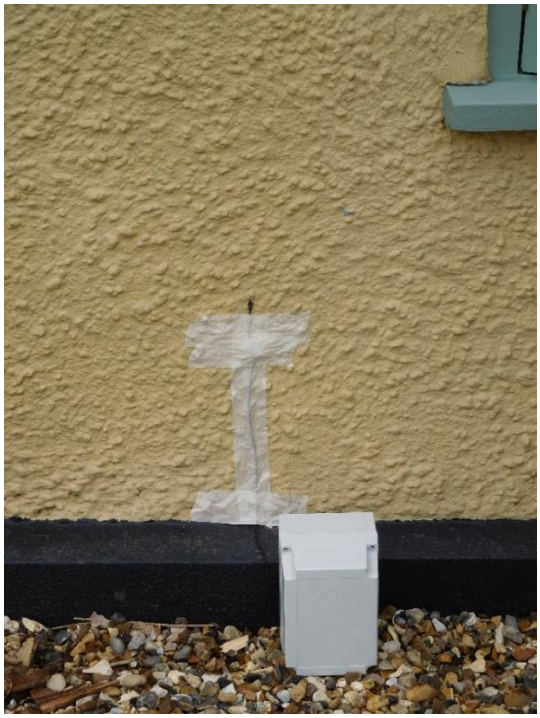

Figure 240. External thermistor, Old Stokes Farm

Figure 241. Internal thermistor and heat flux plate

9.6.1.1.1 Instrumentation

The same general methodology for in situ U-value monitoring as previously described was employed, with the same specific equipment as detailed for Hacton Cruck (paragraph 9.2.1.1.1). The external thermistor was held in place with adhesive tape (Figure 240) and internally with an extendable building prop and plastic clip (Figure 241).

9.6.1.1.2 Time and duration of monitoring

The in situ U-value monitoring was undertaken between 11th March 2017 and 3rd April 2017, with a measurement period of 23 consecutive days.

9.6.1.2 Results and Analysis

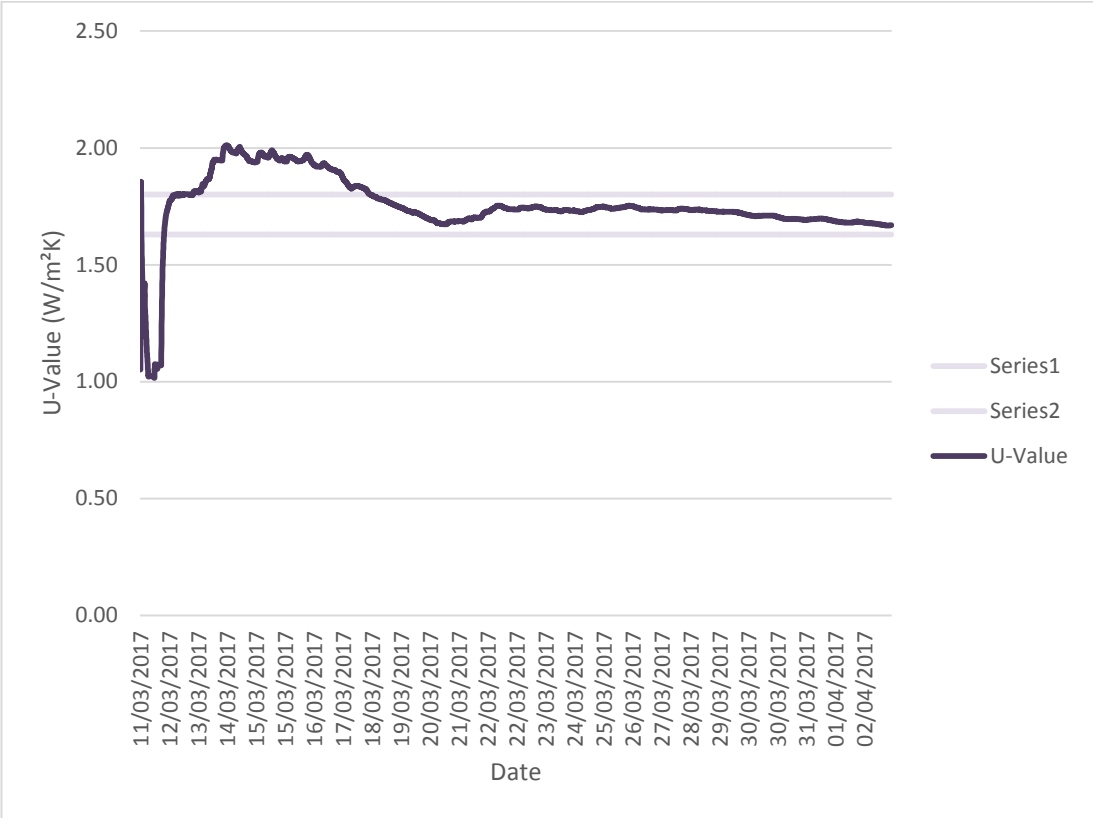

Figure 242. Old Stokes Farm, Battisford. Daily average measured U-value, corrected to omit direct solar radiation 12th March – 1st April 2017. Source: (Author's own, 2017)

The results of the in situ U-value measurements for Old Stokes Farm (Figure 242) show that the ±5% variation as specified by BS ISO 9869-1:2014 (British Standards Institution, 2014) is achieved and maintained for over 15 days before the termination of the monitoring. During this time, the average value is 1.72 W/m^{2}K, with a standard deviation of 0.10 W/m^{2}K. Neither of these values are close to the supposed calculated design U-value of the infill of 0.340W/m^{2}K. This large discrepancy can in part be attributed to the edge effect of the timber-frame creating a cold bridge at the perimeter of the panel. However even when this bridging is taken into account a U-value of 0.921 W/m^{2}K is still calculated. The additional difference between measured and calculated U-value is most probably a result of the poor detail design and installation of the insulation. Both the rigid polyisocyanurate insulation and the gypsum plasterboard are ill suited to the irregularities of the timber-frame. In some

areas where the walls were opened up, the polyisocyanurate panels were effectively freestanding within the timber-frame with a clear gap around the edges. As such, air can freely move around the panel transferring heat by both convection and air movement. To compound this problem, there is no mechanical connection between the face of the insulation and the back of the cement render. A ventilated cavity is thereby formed. This highlights the need for replacement infill panel details to acknowledge that timber-frames have a complex three-dimensional geometry, where joints are rarely at 90° and timbers are not straight. Infill materials must be capable of adapting to these geometries without relying on careful craftsmanship and ideally should form a seal between frame and insulation.

9.6.2 Pressure Testing

9.6.2.1 Detailed Methodology

Pressure testing was undertaken on 11th March 2017 using the same Minneapolis® Blower Door previously described.

9.6.2.2 Results and Analysis

The results of the pressure testing indicate that air permeability index and air change rates for Old Stokes Farm are[58]:

Air permeability index	19.0 $m^3/h/m^2$
Air change rate @50 Pa	18 ac/hr
Air change rate unpressurised	0.9 ac/hr

With an effective leakage area of 9.43m^2.

[58] (R^2) of the best-fit line = 0.9871 showing a good fit

It should be noted that during the testing some work was being undertaken in the western section of the house, including the insertion of new plasterboard partitions, which were not taped or skimmed, and contained holes awaiting the fitting of services. As such, it is possible that the airtightness of the house is better than the test results suggest.

9.6.3 Thermography

9.6.3.1 Detailed Methodology

Thermography was undertaken of the whole house on 11th March 2017 starting at 9:00am using the FLIR B250. The building was unpressurised. The internal and external temperatures were as presented in Table 23 showing that the ideal temperature difference of 10°C as stated by Hart (Hart, 1991 p.17-18) is achieved only in the study, however all other rooms, except for the 2nd bedroom, achieve the 5°C difference as recommended by Young (Young, 2015 p.23). It should be noted that the 16th century wing containing the kitchen, upstairs bathroom and 3rd bedroom was undergoing building work at the time and as such was not as well heated as the rest of the house.

Table 23. Temperature difference for thermography at Old Stokes Farm, 09:00, 11/03/2017

	External Temperature (°C)	Internal Temperature (°C)	Temperature difference (°C)
Study	9.2	19.3	10.1
Drawing Room	9.2	17.4	8.2
Master Bedroom	9.2	15.5	6.3
Guest Bedroom	9.2	12.2	3

9.6.3.2 Results and Analysis

Figure 243 shows, through the cement render, the square framing of the original 16th century wing on the right, in comparison with the close-studding of the 17th century addition to the left. In both cases, the thermography would suggest that the modern insulation infill has a lower thermal transmittance than the timber-frame, which is acting as a cold bridge.

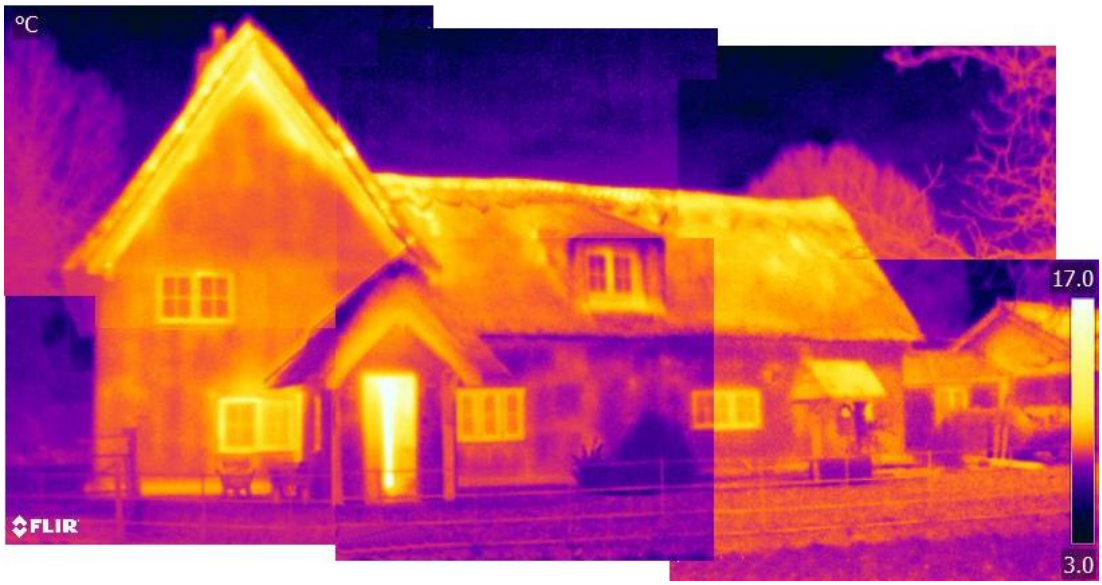

Figure 243. External thermography of north façade of Old Stokes Farm, Battisford, Suffolk. Source: (Author's own, 2017)

The overall difference in heat loss between the two wings is mostly likely due to the 16th century wing not being fully heated at the time of the thermography (see section 9.6.2). The poor thermal performance of the thatched roof is also notable, as it is in Figure 244.

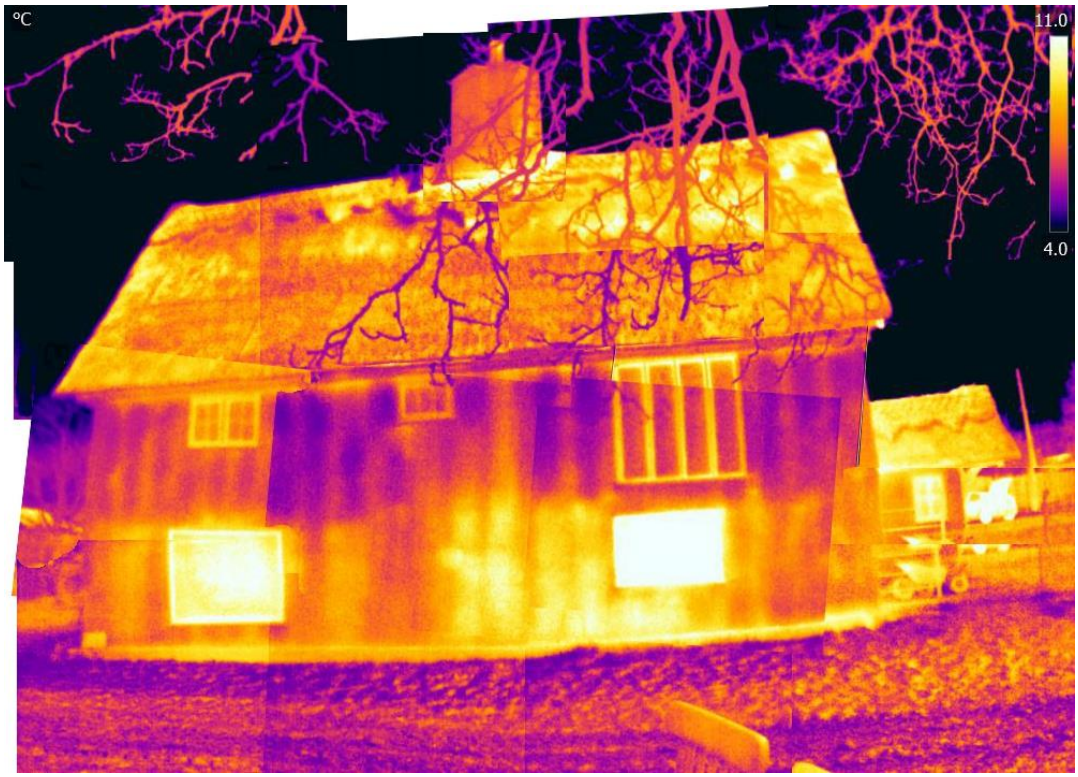

Figure 244. External thermography of east façade of Old Stokes Farm, Battisford, Suffolk. Source: (Author's own, 2017)

Figure 244 also clearly shows the higher internal temperatures of the ground floor and especially the study where a 10°C temperature difference was achieved. The single glazed windows of both the study and master bedroom are clearly the weakest thermal element of the envelope fabric of this façade. The concrete encased brick plinth is also shown to be a thermal bridge.

Figure 245 showing the south façade does not really identify much; however, Figure 246 clearly shows the difference between the insulated infill of most of the west façade of the lower 16th century wing, in comparison with the uninsulated infill above the ceiling level, with the triangular apex glowing orange. The image again demonstrates the poor thermal performance of the thatched roof, as shown in the previous images.

Figure 245. External thermography of south façade of Old Stokes Farm, Battisford, Suffolk. Source: (Author's own, 2017)

Figure 246. External thermography of west and south façades of Old Stokes Farm, Battisford, Suffolk. Source: (Author's own, 2017)

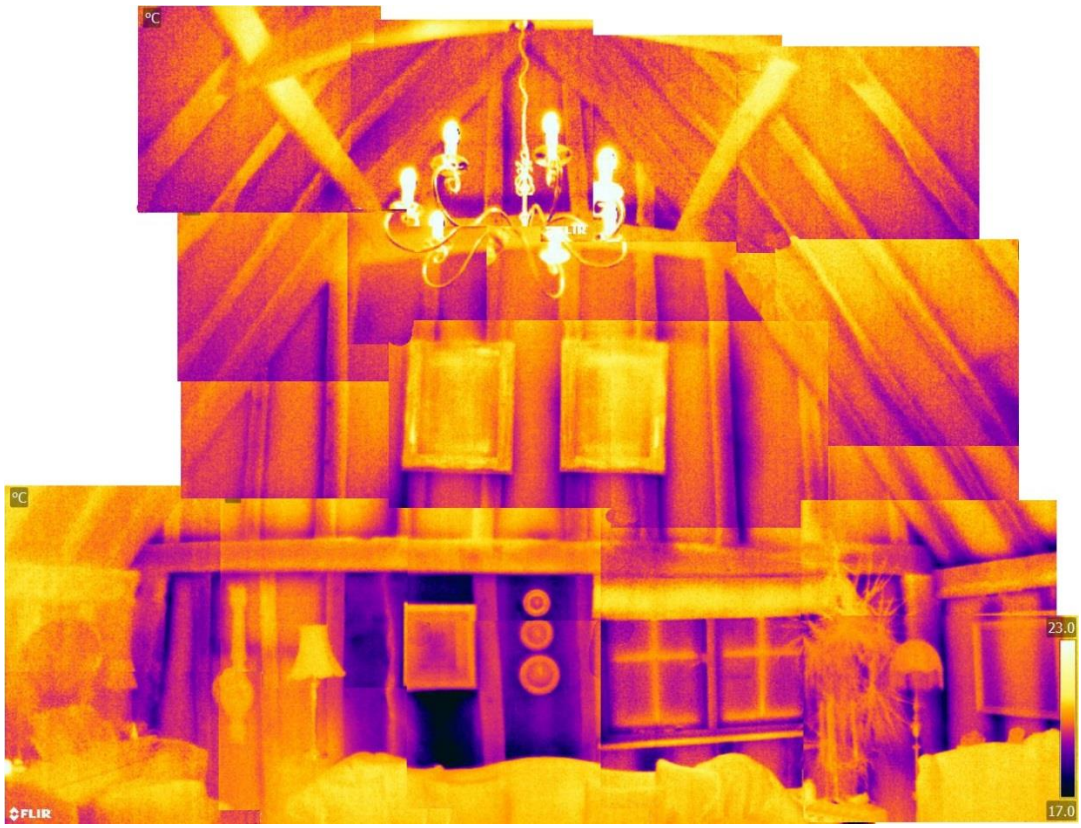

Figure 247. Interior thermography of north wall of drawing room of Old Stokes Farm, Battisford, Suffolk. Source: (Author's own, 2017)

From the inside of the property, the internal thermography, Figure 247 highlights the weakness of the junction between the modern polyisocyanurate thermal insulation and the timber-frame. This detail has no mechanical bond, such as a sealant or taping, between the two materials and as such, thermal transfer through air movement is occurring. The low

radiant surface temperature of the infill panel to the bottom centre left of the image is however unexplained and requires further exploration.

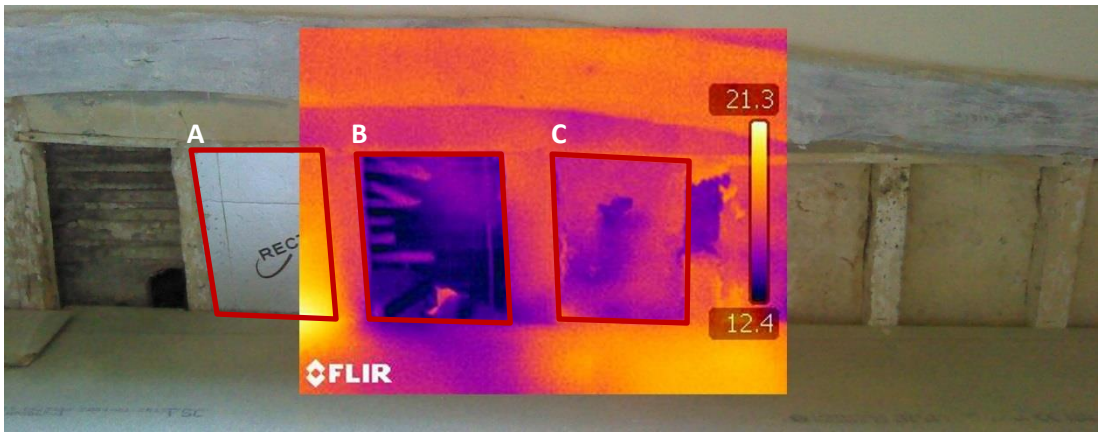

Figure 248. Internal thermography of west wall of 3rd bedroom, showing difference between rigid polyisocyanurate thermal insulation (A), open panel (B) and original lath and plaster (C). Source: (Author's own, 2017)

Finally, Figure 248 shows the difference in thermal performance of the modern polyisocyanurate thermal insulation (A), a traditional lath and plaster panel (C). In between there is an open panel (B) without any infill demonstrating the high thermal transmitance of the cement render seen beyond.

9.6.4 Timber Surface Moisture Content

9.6.4.1 Detailed Methodology

Surface moisture content measurements were taken using a Testo® 606-2 resistance moisture meter for the north wall of the study and the east wall of the ground floor master bedroom on 02/08/2016 and 11/03/2017.

9.6.4.2 Results and Analysis

There follows the results of surface moisture content of the timber-frame of two walls at Old Stokes farm. The first wall is an east-facing wall located in the ground floor master bedroom (Figure 249 & Figure 250), and the second is a north-facing wall in the ground floor study (Figure 251 & Figure 252). The measurements were taken on the 2nd August

2016 and the 11th March 2017. The results are shown applied schematically to simplified elevations of the walls.

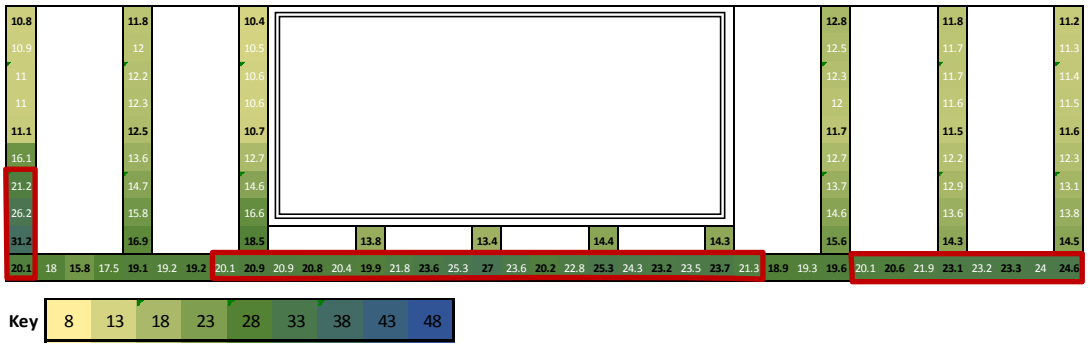

Figure 249. Elevation of ground floor bedroom east wall, Old Stokes Farm, showing measurements of surface moisture content (%) of timber-frame. 02/08/2016 (not to scale). Source: (Author's own, 2017)

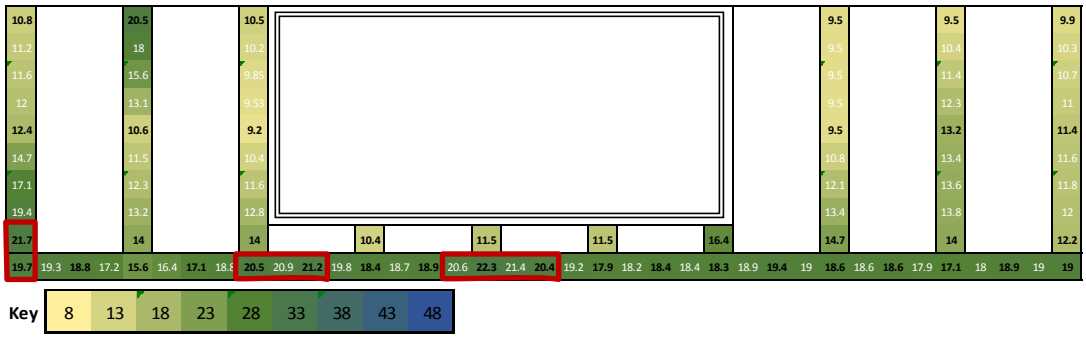

Figure 250. Elevation of ground floor bedroom east wall, Old Stokes Farm, showing measurements of surface moisture content (%) of timber-frame. 11/03/2017 (not to scale). Source: (Author's own, 2017)

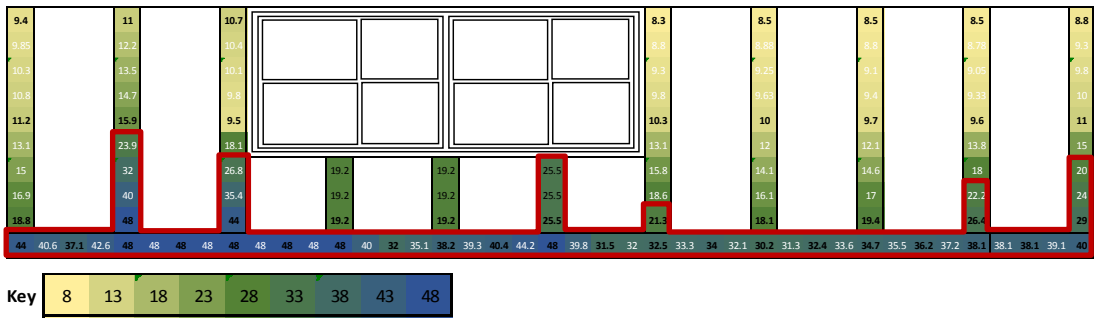

Figure 251. Elevation of ground floor study north wall, Old Stokes Farm, showing measurements of surface moisture content (%) of timber-frame. 2nd August 2016 (not to scale). Source: (Author's own, 2017)

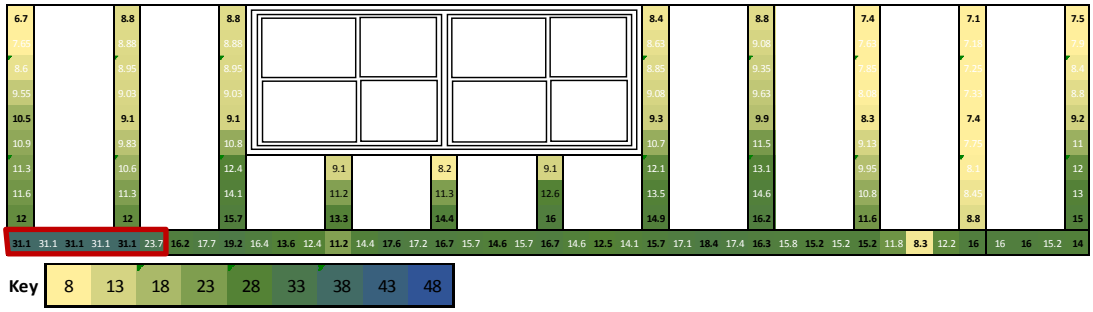

Figure 252. Elevation of ground floor study north wall, Old Stokes Farm, showing measurements of surface moisture content (%) of timber-frame. 11th March 2017 (not to scale). Source: (Author's own, 2017)

These show a clear problem with high moisture content in the sill beam of both walls due to them being encased in cement rendered brick externally and resin coated internally. There is however a clear indication of drying of the timbers of both walls between the summer and winter measurements, with the exception of the head of the second stud from the left in the east wall of the bedroom where an increase in moisture is observed.

9.6.5 Hygrothermal Monitoring

9.6.5.1 Interstitial Hygrothermal Monitoring and Hygrothermal Monitoring of Habitable Spaces

9.6.5.1.1 Detailed Methodology

For this case study, it was possible to install hygrothermal sensors within the thickness of the wall. Omnisense® GE Hygrotrac™ S-4 Wireless Dual Channel wireless sensors were used connected to electrical resistance sensors for measuring timber moisture content, and Hygrosticks™ measuring temperature (°C) and relative humidity (%). Each S4 sensor transmitted data at 30 minute intervals to an Omnisense® GE Hygrotrac™ Gateway connected to the internet. The system allowed remote data acquisition; however, a subscription charge of US$20 per month was required to access data. The sensors were installed in the locations indicated in Figure 253, Figure 254 and detailed in Table 24. The sensors included dry bulb temperature and relative humidity measurements of the air in all locations, surface moisture content of sill beams in locations B & D and measurements of interstitial conditions inside walls in locations C, E & F.

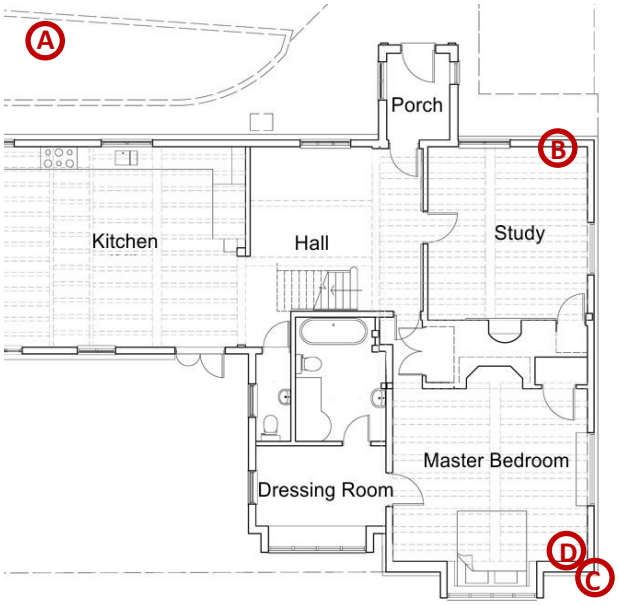

Figure 253 Plan of Ground Floor Old Stokes Farm showing location of hygrothermal sensors

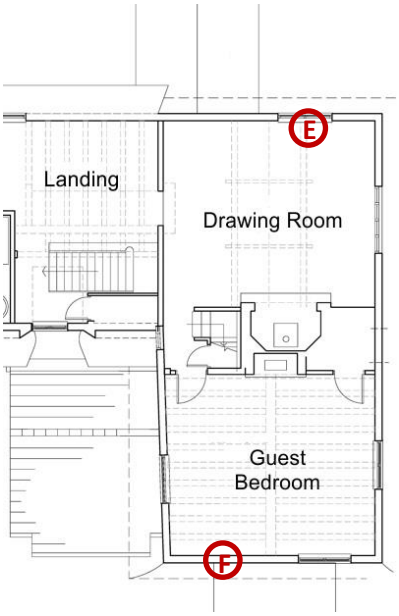

Figure 254 First Floor of Old Stokes Farm showing location of hygrothermal sensors

Table 24. Location of hygrothermal monitoring at Old Stokes Farm 01/08/2016-07/08/2017

Room	Location			Parameter	Units
External	A		Under roof of well-head	Temp	°C
				RH	%
Study	B		Face of sill beam in NE corner	WMC	%
				Room Temp	°C
				Room RH	%
Master Bedroom	C		Inside brick plinth attached to sill beam in south- east corner. Accessed from outside	WMC	%
				Interstitial Temp	°C
				Interstitial RH	%
	D		Face of sill beam midway along east wall	WMC	%
				Room Temp	°C
				Room RH	%
Drawing Room	E	i	Inside of infill panel in centre of north wall (Figure 255)	Interstitial Temp	°C
				Interstitial RH	%
		ii	Left hand side frame of infill panel on north wall, adjacent to external concrete render	WMC	%
		iii	Left hand side frame of infill panel on north wall, adjacent to internal gypsum plasterboard lining	WMC	%
		iv	Right hand side of infill panel on north wall, adjacent to external concrete render	WMC	%
		v	Adjacent to base of infill panel but inside room	Room Temp	°C
				Room RH	%
2nd Bedroom	F	i	Inside infill panel in southwest corner (Figure 256)	Interstitial Temp	°C
				Interstitial RH	%
		ii	Right hand side of frame of infill panel in southwest corner, adjacent to external concrete render	WMC	%
		iii	Right hand side of frame of infill panel in southwest corner, adjacent to internal gypsum plasterboard lining	WMC	%
		iv	Adjacent to base of infill panel but inside room	Room Temp	°C
				Room RH	%

WMC-Wood Moisture Content
RH- Relative Humidity

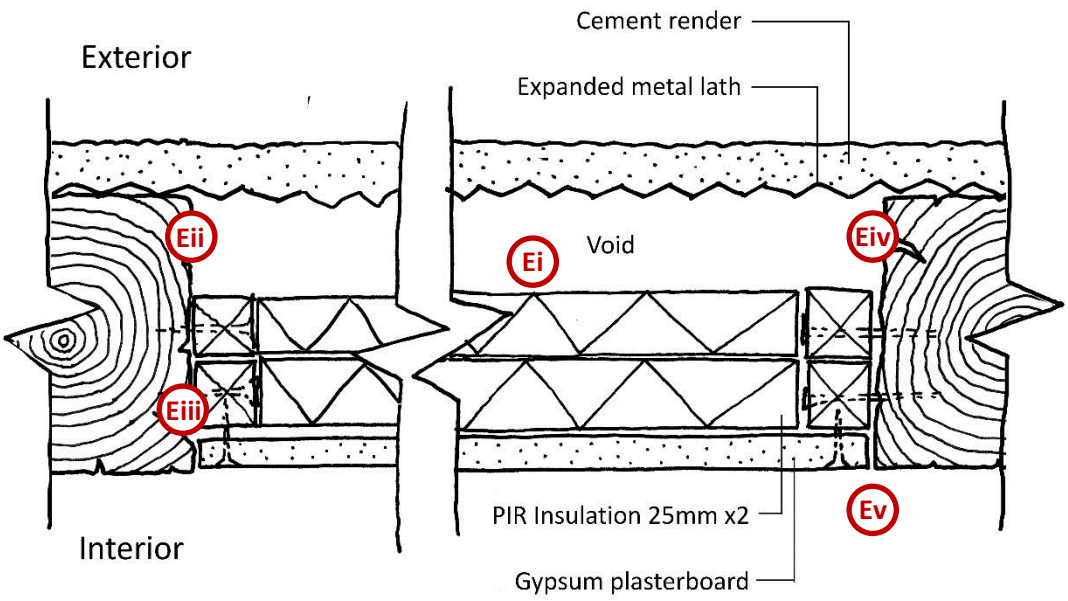

Figure 255. Monitoring positions within panel in Drawing Room (location E) refer to Table 24 Source: (Author's own, 2017)

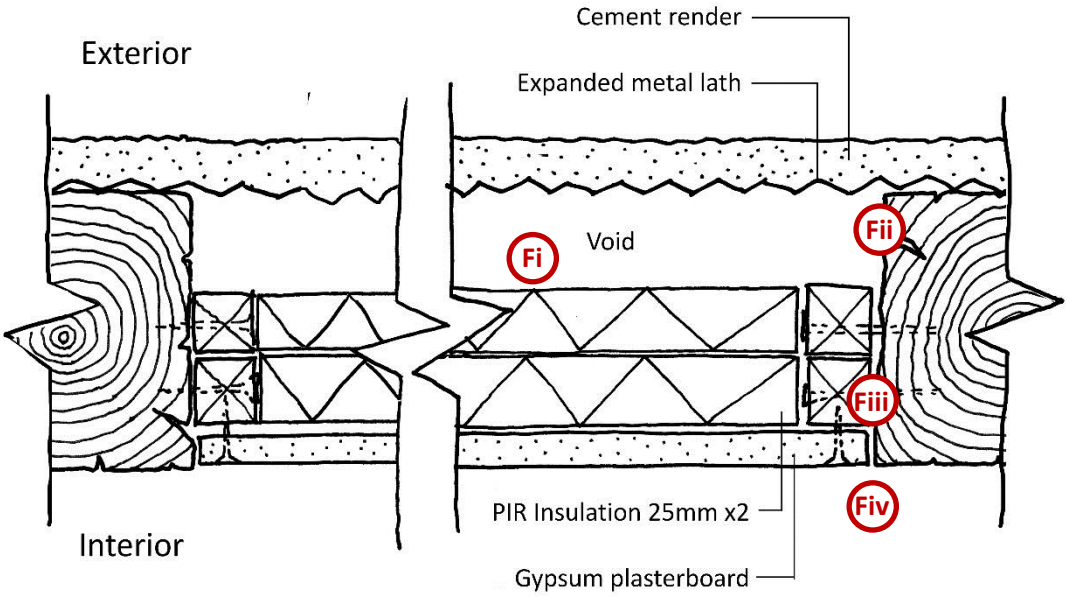

Figure 256. Monitoring positions within panel in 2nd Bedroom (location F) refer to Table 24. Source: (Author's own, 2017)

The monitoring was undertaken over a twelve-month period from 02/08/2016 to 07/08/2017. Unfortunately, the wireless relay for sensor positions Ei, Eiii and Ev ceased functioning on 05/11/2016 and was not replaced until 11/03/2016.

9.6.5.1.2 Results and Analysis

9.6.5.1.2.1 Interstitial moisture

The high moisture content of the sill beams is also evident in the results of the surface and interstitial timber moisture content measurements are shown in Figure 257, where the surface moisture content of the sill beam in the ground floor master bedroom remains constantly above 20% both inside the room (D) and within the wall (C). The sill beam of the study (B) can be seen to begin at over 20% until early October before drying to below 15% in February. The moisture content then begins to rise again reaching 20% once more in late June (Figure 257). Initially the drying was thought to be attributable to the clearing of a draining ditch; however, the later rise would suggest the effect might be seasonal.

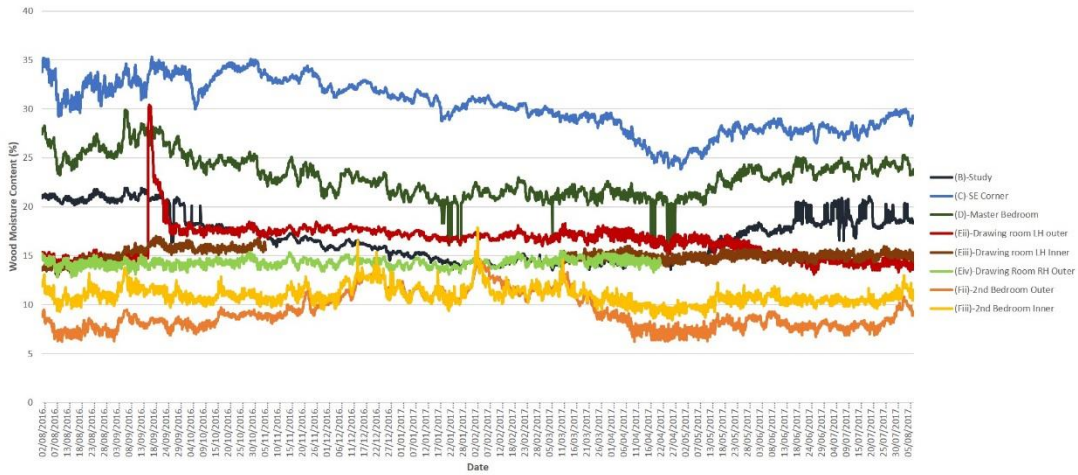

Figure 257. Moisture content of timber frame as measured 02/08/2016 to 07/08/2017. Source: (Author's own, 2017)

Within the north-facing wall of the drawing room, a prominent spike in moisture content can be seen in the left hand outer edge of the frame (Eii, Figure 257). This sudden increase in moisture content is due to heavy wind-driven rain coming from the north, part of the post-heatwave storms that affected much of the East, South and Southeast of England on the 16/09/2016 (BBC, 2016). Cracks in the cement render have allowed penetrating damp to double the timber moisture content at this point, from 15% to over 30% in just under 5

hours. It can be seen that within 8 days the moisture content had drop back below 20% however, it then took a further 9 months for the trapped moisture to dry out and the timber to return to below 15%. This clearly highlights the problems of the use of an impervious brittle external render such as cement. Had the render been vapour permeable the timber may well have still become soaked, however drying should have occurred more rapidly. Similar, less dramatic, wetting can also be seen in the south facing wall of the second bedroom during the winter months (Figure 257).

Looking at the hygrothermal conditions created both within the walls and on the surface of the sill beams within the rooms, it can be seen that many of the monitoring locations are experiencing conditions favourable to biological attack (Figure 258 and Figure 258).

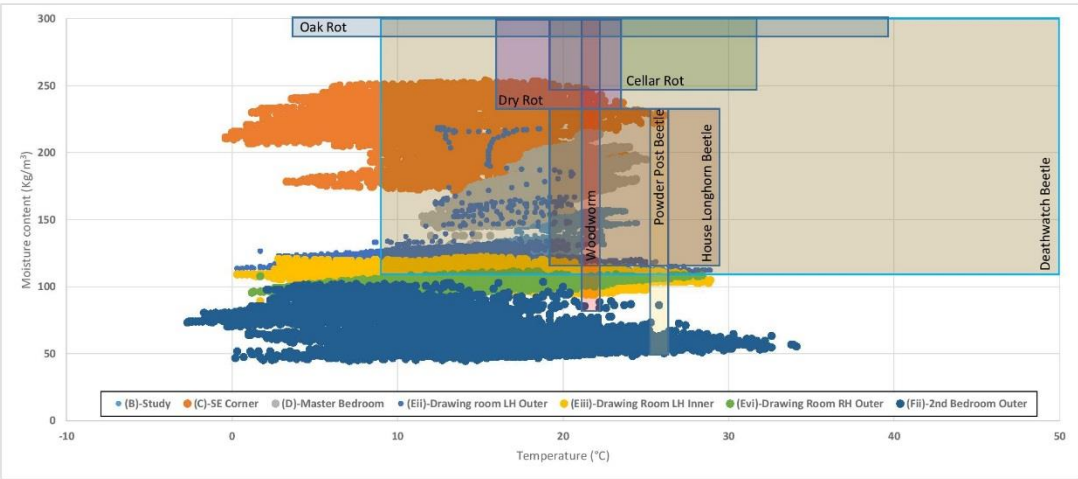

Figure 258. Hygrothermal conditions at monitoring positions with conditions favourable to biological attack overlaid. Source: (Author's own 2017, with conditions favourable to biological attack based on (McCaig and Ridout, 2012))

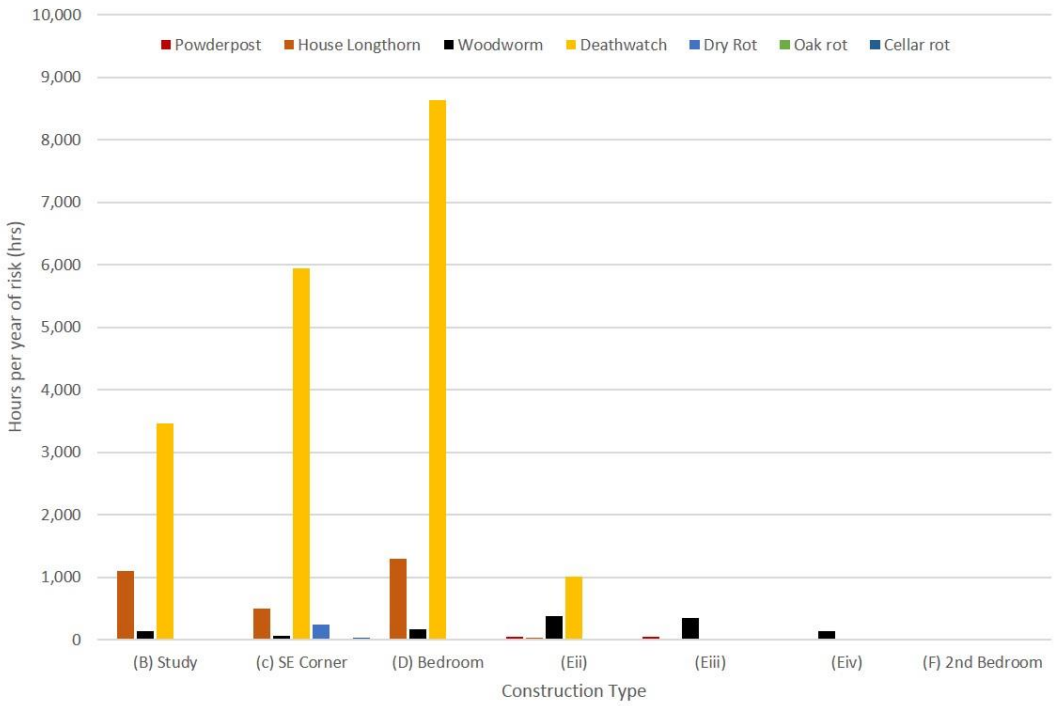

Figure 259. Risk of insect infestation and fungal decay at each monitoring position, Old Stokes Farm. Source: (Author's own, 2017 based on parameters (McCaig and Ridout, 2012)).

The most frequent risk is from deathwatch beetle with the SE corner of the master bedroom, both inside the room (D) and within the wall (C), being the worst affected. In the case of monitoring position D inside the master bedroom the sill beam is open to the threat of deathwatch beetle 99% of the time. This location is also at threat from house longhorn beetle more than 1000 hours per year. Within the same wall, at monitoring position C, there also exists 249 hours when conditions are favourable for dry rot and 35 hours favourable to cellar rot. This potential for fungal decay further increases the risk of insect attack as both deathwatch and house longhorn will only inhabit wood that has already been damaged by decay. Overall the results show that the combination of cement render and non-vapour permeable insulation and internal finishes have created conditions that are leading to the potential destruction and collapse of this historic property.

9.6.5.1.2.2 Hygrothermal Monitoring of Habitable Spaces

The results for Old Stokes Farm (Figure 260 to Figure 263) shows that hygrothermal comfort was only achieved 38% of the time in Master Bedroom, 26% in the Study and just 4% in the Guest Bedroom (Figure 261).

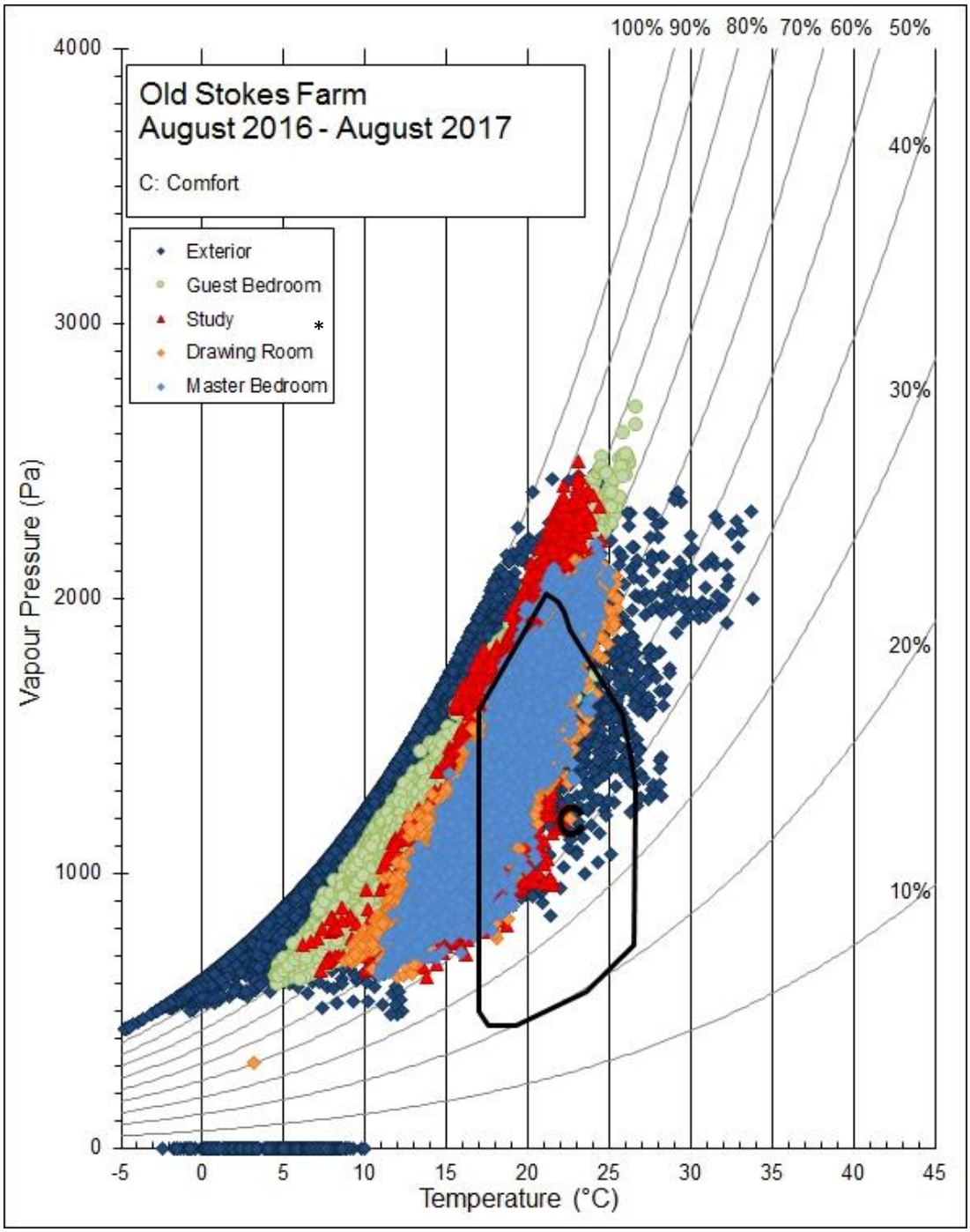

*Figure 260. Psychrometric chart according to Givoni showing hygrothermal measurements at Old Stokes Farm, as recorded 02/08/2016-07/08/2017. *Note that no data was recorded in the Drawing Room 05/11/2016-11/03/2017.Source: (Author's own, 2017)*

In the Drawing Room hygrothermal comfort was achieved 50% of the time, although it should be noted that no measurements were taken in this location over the winter months (02/11/2016-11/03/2017).

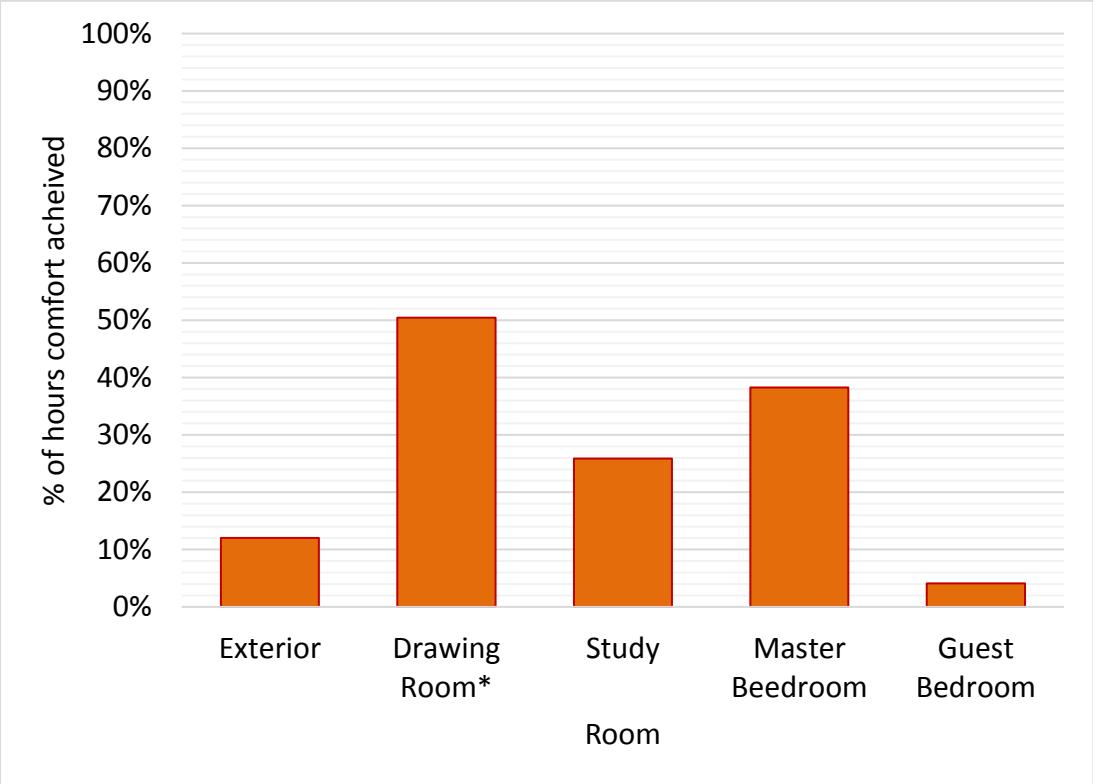

*Figure 261. Percentage of hours where hygrothermal comfort is achieved. 02/08/2016-07/08/2017. *Note that no data was recorded in the Drawing Room 05/11/2016-11/03/2017. Source: (Author's own, 2017)*

Figure 260 shows that the conditions extended well below the minimum thermal threshold in all rooms and that overall the relative humidity was high, exceeding comfort conditions at the higher temperatures. When the temperatures (Figure 262) and relative humidity (Figure 263) are reviewed according to date, it can be seen over that over the winter months the temperatures rarely exceed 17°C (Figure 262), whilst over the summer and autumn high humidity is the problem.

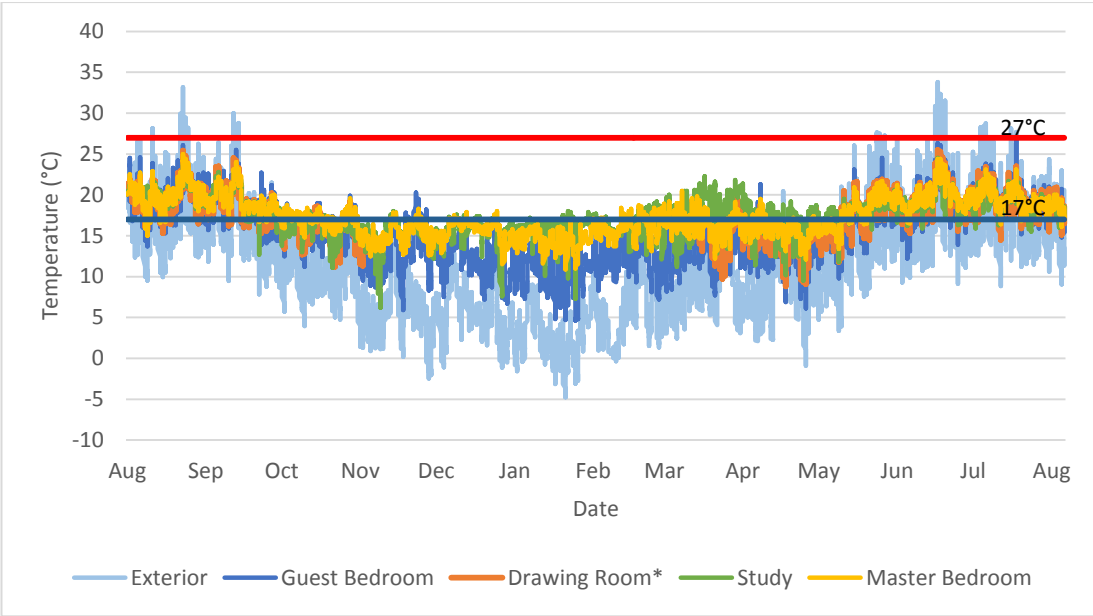

*Figure 262. Dry bulb air temperatures (°C) as measured at Old Stokes Farm, 02/08/2016-07/08/2017. *Note that no data was recorded in the Drawing Room 05/11/2016-11/03/2017. Source: (Author's own, 2017)*

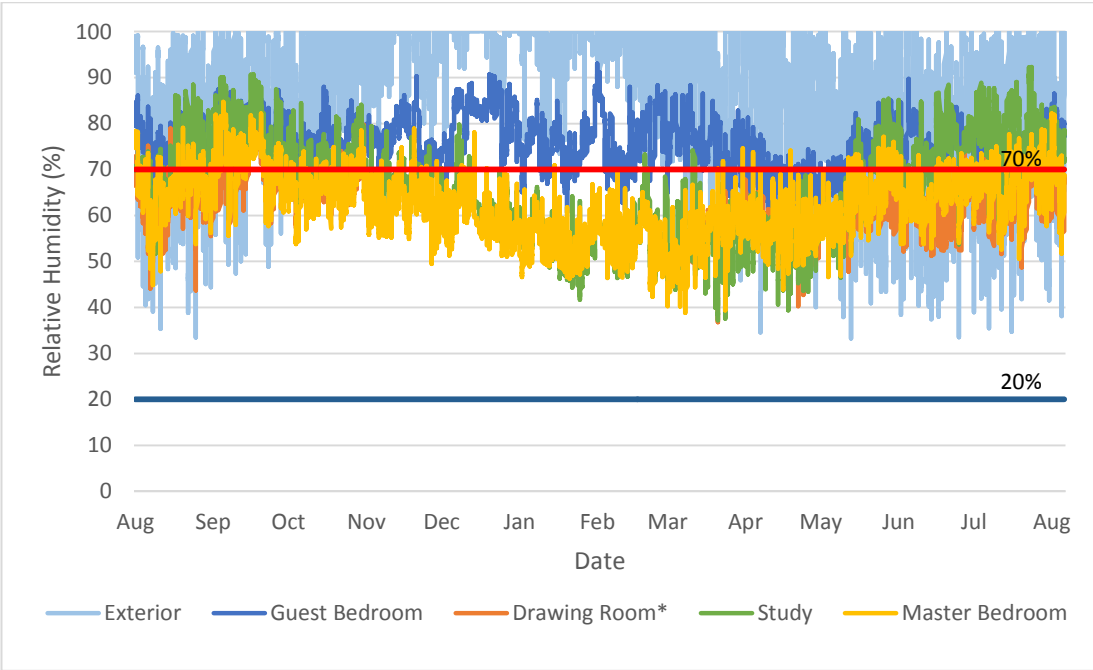

*Figure 263. Relative Humidity (%) as measured at Old Stokes Farm, 02/08/2016-07/08/2017. *Note that no data was recorded in the Drawing Room 05/11/2016-11/03/2017. Source: (Author's own, 2017)*

9.6.6 Occupants' perception of thermal comfort

9.6.6.1 Detailed Methodology

At Old Stokes Farm, it was also possible to conduct a questionnaire with the occupants with regard to their perception of thermal comfort within the house. The questionnaire took place on the 11/03/2017 with the sun shining. A copy of the completed questionnaires can be found in appendix F.

9.6.6.2 Results and Analysis

In summary, both occupants found the ground floor of the house to be comfortable in winter but slightly warm in summer due to the underfloor heating and thermal mass of the ground floor. The converse was true with the upper floors, with both finding them comfortable in summer but slightly cool in the case of the male occupant and cold in the case of the female. The difference in subjective thermal perceptions and preferences between the two occupants was evident from both reporting to feel comfortable during the interviews, despite the male occupant being outside in a t-shirt and trousers with a dry bulb temperature of 14.8°C and the female occupant reclining inside in a fleece, t-shirt and jeans at a temperature of 18.8°C. It was also notable in the female's study being kept slightly warm and the male's study on the top floor being slightly cool.

It is interesting to note that these perceptions do not appear to corroborate the hygrothermal monitoring. This is possibly due to the fact that the hygrothermal monitoring measured only air temperature and thermal comfort may have been achieved by radiation from the underfloor heating. It may also indicate that to some degree the occupants are willing to accept lower comfort criteria in order to allow them to realise their ambition to live in a historic timber-frame building in a rural location. Whilst at The Oaks this was explicitly said, here this is only conjecture and would require further investigation.

With regards to heating and ventilation habits, the ground source heat pump was used almost continually throughout the year, except June and July, providing underfloor heating to the ground floor only. In addition, the log burner in the first floor drawing room was used every night throughout the year. Although the use of the log burner appeared to be at least in part a custom rather than being driven by thermal requirements. Electric convection heaters provide heating for the guest rooms. The windows to the master bedroom were always open and a window in the study was often opened. The rest of the windows were regularly opened especially in summer, with their use being governed principally by the need for fresh air, rather than as a means of regulating temperature.

9.6.7 Conclusions

The monitoring at Old Stokes Farm has shown the damage that can be done by energy retrofitting without the correct guidance. The measured U-value is well below that expected, most probably due to the poor detailing and excessive air movement around the insulation panels. This is confirmed by the thermography.

The timber moisture measurements and the interstitial hygrothermal measurements show that the historic timbers are saturated in many places due to the sealing of the building with cement render externally and resin internally, trapping penetrating moisture entering through cracks in the walls and rising from the ground. However, there does not appear to be evidence of the insulation adding to moisture problems, although this may be due to its poor performance.

The hygrothermal comfort monitoring suggests that comfort conditions are achieved infrequently. This is however at odds with the occupants perceptions. This inconsistency may be due comfort being provided by radiation which was not monitored or to lower comfort expectations. It is however clear that the radiant heating, both floor and wood burner, do little to raise the air temperature.

9.7 Summary and comparison of findings

9.7.1 In situ U-values

Table 25 Summary of measured and calculated U-values of walls at Hacton Cruck, The Old Mayor's Parlour and no.25 Church Street

	Measured U-value (W/m²K)	Calculated U-value (W/m²K)	Difference Measured to calculated (%)
Hacton Cruck Original Lime Plaster	2.21	2.40	-8.6
Hacton Cruck New Wattle and Daub	2.88	2.99	-3.8
Hacton Cruck Multi-foil insulation	0.66	0.41	37.9
Old Mayor's Parlour Historic England detail + Polyisocyanurate internal lining	0.11	0.13	-18.2
No 25 Church Street, Hereford Historic England detail + Mineral wool internal lining	0.11	0.17	-54.5
No 27 Church Street, Saffron Walden Pargeted with presumed wattle and daub infill	0.64	1.79	-179.7
Old Stokes Farm Rigid polyisocyanurate (PIR) Insulation	1.72	0.92	46.5

The measured in situ U-values presented in Table 25 illustrated that in general, the modern replacement infill panels have lower U-values than both the existing lath and plaster and those replaced with traditional (wattle and daub) construction. However, the pargeted wattle and daub in Saffron Walden performs better than both the multi-foil insulation at Hacton Cruck and the unsuccessful detail using PIR insulation at Old Stokes Farm. Potentially this may point to the use of external insulating render, such as hemp/lime or cork/lime being potential retrofit solutions. This is an area for further research.

It is important that existing historic fabric be retained where possible and as advocated by SPAB, where more than 50% of existing fabric remains repair or part renewal should be undertaken (Reid, 1989 p.6). However, where complete renewal of the panel infill is required due to extensive damage, decay and consequential repair of surrounding timbers or the removal of inappropriate modern materials then these modern details can

potentially improve the performance of the building envelope. The efficacy of such measures will be simulated in the next chapter, with the possibility of producing inadvertent negative impacts examined in the chapters that follow. It should be noted that these U-values are only for the infill panel and do not take into account the different thermal properties of the surrounding timber-frame.

9.7.2 Thermography

Figure 264. Hacton Cruck thermography north elevation 25/03/2015

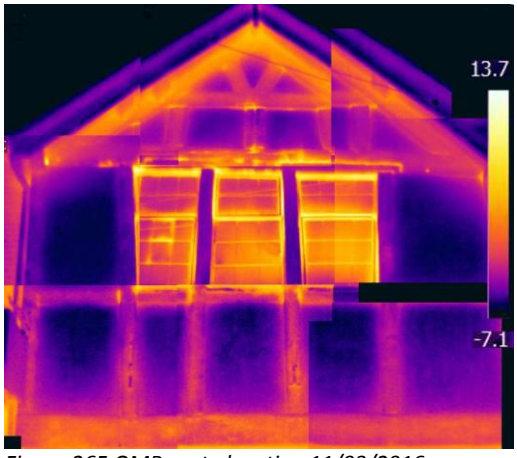

Figure 265 OMP east elevation 11/03/2016

The thermography at Hacton Cruck (Figure 264) and the Old Mayor's Parlour (OMP) (Figure 265) demonstrates the change in thermal performance of infill panels, from being the worst performing wall element at Hacton Cruck, to being better than the surrounding timber-frame at OMP. The results from Hacton Cruck, The Oaks and Old Stokes Farm highlight the importance of the roof and the need for a whole-building, holistic approach to low carbon retrofit, and images from all properties identified large surface temperature differences between adjacent materials, which could lead to concentrated condensation and mould growth. The lack of adequate seals around doors and windows was a common feature, potentially simple to remedy, however the increased air infiltration at the junctions between infill panel and timber-frame, underlines this as a critical and difficult to achieve detail, especially when the frame is exposed both internally and externally.

Historically the regular application of lime-wash across both timbers and infill would have built up a continuous seal and there is a strong tradition of over-cladding with weatherboarding, tile-hanging, slates or plaster, especially in certain areas of the country (Brunskill, 1985 p.53). Internal lining such as that at the Old Mayor's Parlour is another solution; however, where aesthetic and historical arguments exist for exposing the timbers on both surfaces, an improved detail must be sought. Further analysis of this detail is explored in subsequent chapters. The results of the thermography also demonstrate the application of this technology for gaining additional information regarding construction, through non-destructive means. At the OMP and The Oaks, it was possible to identify modern concrete block infill and the possible existence of wattling or lathwork. Similarly, at nos.25 & 27 Church Street Saffron Walden and Old Stokes Farm, it was possible to start to identify the hidden timber-frame.

9.7.3 Pressure testing

Table 26. Summary of pressure testing results of three case studies.

	Air Permeability Index ($m^3/h/m^2$)	Effective leakage area (m^3)	Air change rate @50 Pa (Ac/hr)	Air change rate at atmospheric pressure (/hr)
Hacton Cruck (unlined)	154.0	32.64	129.9	6.5
Hacton Cruck (lined)	80.3	15.83	67.7	3.38
The Oaks (pre-retrofit)	17.8	4.71	16.5	0.83
The Oaks (post-retrofit)	11.7	1.83	10.8	0.54
Old Mayor's Parlour	17.6	1.74	22.5	1.12
No. 27 Church St, SW, 2012†	7.3	-	10	-
No. 27 Church St, SW.	14.2	1.36	18.8	0.94
Nos. 25&27 Church St, SW	58.6	13.12	56.6	2.83
Old Stokes Farm	19.0	9.43	18	0.9

† (Hubbard, 2012)

Table 26 summarises the results of all of the pressure testing undertaken at all five case studies. As can be seen, Hacton Cruck is by far the least airtight, even after torching of the

central section of thatched roof. As mentioned, this is most likely due to the gaps between infill panels and timber-frame, previously discussed under thermography, and the untorched ridge and location of historic fire-hole. The single glazed windows with no weather-stripping are another potential weakness, as they are at the Old Mayor's Parlour. The results from The Oaks post-retrofit show the positive impact that secondary glazing can have on overall airtightness and prove that air tightness index values close to those required for new-build, can be achieved for historic timber-framed buildings.

9.7.4 Hygrothermal comfort

The monitoring of hygrothermal comfort at four[59] of the case studies shows that even with improvements to the external envelope of these buildings, hygrothermal comfort conditions were rarely met. At Hacton Cruck, this can be attributed to the high air change rate that exceeds the capacity of the ground-sourced heat pump to heat the ever-changing air. The lack of perimeter insulation to the ground floor slab also greatly reduces the efficiency of the underfloor heating. The simple act of torching the exposed thatch ceiling has increased the percentage of time that hygrothermal comfort is achieved by 15%, the improved comfort is corroborated by the visitors' comments.

At The Old Mayor's Parlour and No. 25 Church Street, the initial lack of hygrothermal comfort can be attributed to the lack of heating. Whilst there is nothing to suggest that this situation will change in No.25, the subsequent monitoring in The Old Mayor's Parlour shows that hygrothermal comfort can be achieved.

At nos. 25 & 27 Church Street, Saffron Walden, the principal lack of hygrothermal comfort is due to low temperatures owing to the lack of heating as the houses are currently uninhabited. The use of conservation heating in the front bedrooms to reduce the risk of frost damage to the pargetting does however raise the temperature to within comfort

[59] No hygrothermal monitoring was undertaken at The Oaks.

levels. The high relative humidity on the ground floor is most likely due to the open connection to the underground cellar. However, this should be monitored once an airtight separation between cellar and habitable spaces has been completed.

At Old Stokes Farm, the measurements would suggest low levels of thermal comfort with hygrothermal comfort conditions being achieved less than half of the time. The occupants' perceptions do not however corroborate these findings. This may be due to comfort being provided through radiant sources, as radiation was not monitored. The use of black globe thermometers should be considered for future monitoring. It is however clear that the low temperature radiant underfloor heating does little to raise air temperatures and calls into question the use of such solutions in timber-framed buildings with low thermal mass and high air change rates. This is an area for further research.

Overall, the hygrothermal monitoring confirms that timber-framed buildings have poor thermal performance (Demaus, 2017). Although their occupants' perceptions appear to be influenced by their desire to live in these buildings and their predominantly rural locations and as such more accepting of these conditions. This area requires further research and it must still be assumed that historic timber-framed buildings are under pressure to improve and meet 21st century expectations.

9.7.5 Surface and Interstitial Moisture Content

At The Oaks, the increase in airtightness does not appear to have had a negative impact on the surface moisture content of the timber in the living room. However, in the parlour, the additional moisture loads created by its conversion to a bathroom have not been addressed. This highlights the need for controlled ventilation to be considered in conjunction with retrofit actions that reduce air infiltration.

Although no measurements of surface moisture were undertaken at The Old Mayor's Parlour, the combination of thermography and hygrothermal monitoring suggest that there may be an increased risk of condensation on the uninsulated 17th plastered ceiling. This underlines the challenge of both protecting historic fabric and avoiding large discrepancies in surface temperature.

The moisture monitoring at Old Stokes Farm demonstrates the danger of the use of vapour impermeable finishes in conjunction with timber-framed buildings.

9.8 Conclusions and further areas for research

The main issues that have been raised by the study and monitoring of these five case studies are:

- The real potential for improving thermal performance of infill panels
- The need for a holistic whole-house approach to retrofitting
- The problematic detail between panel infill material and timber-frame
- The frequent differences in surface temperatures between contiguous materials
- The real potential for improving airtightness through secondary glazing and simple actions such as plastering

These findings highlight that whilst it is possible to improve significantly the performance of the infill panels themselves, this in in itself does not guarantee an improvement to the internal hygrothermal comfort conditions. The airtightness of other elements of the building must also be considered, as must the critical junction between the infill and the timber-frame. Ensuring that this detail is, and remains, airtight is a challenge that is evident in all three case studies. Together with the identified differences in surface temperatures between timber-frame and infill, this fundamentally questions the practice of exposing timbers on both faces of the wall. Whilst historical integrity and aesthetics must also be

considered, from a technical perspective the use of internal lining or external cladding must always be recommended for the positive benefits that they afford.

The following areas will be explored in the subsequent chapters:

- Energy Efficiency of the five case study retrofits
- Interstitial hygrothermal conditions within replacement infill panels and the potential risk of raised moisture content.

In addition, possible future research could include:

- In situ U-value measurements and hygrothermal monitoring at The Oaks
- Surface moisture monitoring of timber-frames at Hacton Cruck and the frames and ceiling at the Old Mayors Parlour
- Repeat in situ U-value monitoring at Nos. 25 & 27 Church Street, Saffron Walden
- Further case studies

These five case studies only provide a small glimpse of the current state of historic timber-framed buildings in the UK. However, what they do demonstrate, is that low carbon retrofit of these properties is a reality, and one for which there is no one solution. It is hoped that these examples help to further the understanding of the complexity of this process and provide the basis for future guidance.

10 ENERGY SIMULATIONS

10.0 Introduction

The following chapter reviews the heating energy demand of each of the five previously described case studies using digital dynamic energy simulation software. It is acknowledged that every energy simulation software has its drawbacks and flaws. J.P. Waltz, the author of the Computerized Energy Simulation Handbook (Waltz, 2000) goes as far to say that "they're all terrible" (ibid, p8). However, if you have an informed understanding of the building you are modelling, and interrogate the results correctly; most can be a useful design tool (ibid). A key advantage of these software is the ability to compare between alternative design scenarios (ibid, p9). If the parameters for each scenario are constant, then the relative effect of specific changes can be evaluated. However, due to assumptions made regarding materiality, construction and occupant behaviour differences often exist between simulated and actual energy use (de Wilde, 2014).

In this chapter, the software DesignBuilder® was used to evaluate each of the retrofit solutions undertaken at the case studies. Each of the individual retrofit actions have been simulated separately in order to assess their specific impact on the buildings' heating energy demand. In addition, simulations of the combined effect of multiple retrofit actions, both those applied in reality and hypothetical scenarios, have been undertaken to compare the current and future potential performance of these buildings. It should be noted that the results presented are for comparative purposes only and may not truly represent the actual current or future energy use of the buildings in question.

10.1 Methodology

10.1.1 Energy Simulation and Choice of Software

The choice of software was governed by three principal factors. The first of these was to observe the selection of a software widely recognised by the scientific community and by

industry. This is important if the outcomes of these results are to be instrumental in informing industry guidance. The second was the availability of the software and the third was the preferred input method, either tabular or graphical. Table 27 shows some of the most common Building Energy Simulation Software and their availability at the Welsh School of Architecture.

Table 27. Common Building Energy Software

Generic Type	Software	Company/ Vendor	Available at WSA
Standalone software with Graphical Interface	TAS®	Environmental Design Solution Ltd	No
	DesignBuilder®*	DesignBuilder Software Ltd	Yes
	Ecotect®	Discontinued	No
Standalone software with no Graphical Interface	Energy Plus®*	US Department of Energy	Yes/Free
	HTB2	Welsh School of Architecture	Yes
Plugins for CAD: Sketch-up, Revit etc.	Sefaira Architecture®	Trimble Navigation Limited	No
	Autodesk Insight 360®	Autodesk	Yes
	Virtual Environment®	IES Ltd	No

* As noted below DesignBuilder is a graphical interface for EnergyPlus but runs as one standalone program.

Given the author's preference to input the data through a graphical interface, DesignBuilder® was chosen. The simulations presented in this chapter were completed using DesignBuilder® Version 4.2.0.54. This software provides the graphical interface for the dynamic simulation engine EnergyPlus® DLL v8.1.0.009 (Design Builder, 2014b), a building energy simulation software developed by the University of Illinois and the

University of California, for the Office of Building Technology of the Department of Energy of the United States of America (US Department of Energy, 2016 p.3). EnergyPlus® was developed to replace the US governments previous two programs DOE-2 and BLAST, which had become labyrinthine in their coding over their 20 year development (Crawley et al., 2001 p.319). The development of the software drew on many of the most successful features of its predecessors (ibid), using the load algorithms from BLAST and the system algorithms from DOE-2 (Zhu et al., 2013 p.323). Tests of DesignBuilder® following the standard of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) ASHRAE 140-2011, showed that results were within the specified bounds for 59 of the 63 Building Thermal Envelope and Fabric Load test cases dictated by the standard (Design Builder, 2014a). The four test cases, which fall outside the specific bounds, do so only very slightly with two of the test cases underestimating energy demand by -0.123 and -0.037 MWh and the other two test cases underestimating the minimum temperature by 0.1°C and 0.2°C (ibid). It should be noted that the use of the software has been approved for Building Regulation compliance by the governments of England (Cousens, 2014), Wales (Samuel, 2016), Scotland and Northern Ireland (Design Builder, 2016). However, it has been argued that the certification of simulation software is questionable (Waltz, 2000 p.8). Waltz argues that it is the operator's ability to input valid data, and draw the correct conclusions from the results that is more critical than the algorithms and programming of the software itself (ibid).

10.1.2 Restrictions of DesignBuilder® and Energy simulation Software in General

In order to simulate the heating demand the software must use averaged hourly weather data. This information represents a hypothetical climate based on historical climatic statistics. As such, the results represent only a hypothetical energy demand. However, as already discussed, as long as the same weather file is used consistently for each case study, then comparisons can be made between different scenarios within that case study. Details

of the different weather files used for the simulations presented in this chapter are detailed in section 10.1.3.

One of the main restrictions of any energy simulation software is the simplification required to both input and calculate the energy demand of the given building. The geometry of the building must be simplified, the materials must be chosen from a limited database or created. Beyond that, even the algorithms behind the calculations simplify the building physics. For example, for the building thermal zone calculation, EnergyPlus uses a heat balance model based on the assumption that the air in each building zone is homogenous with no stratification of temperature (Crawley et al., 2001 p.323). The heat balance model also assumes that the zones surfaces (walls, windows, ceilings and floors) have uniform surface temperatures; uniform irradiation, both long and short-wave; diffuse radiating surfaces; and one dimensional heat conduction (ibid). As such, there is no requirement for the height of differential wall materials to be accurately modelled. The complicated timber-frame, which creates cold bridges, was therefore simplified to block sub-surfaces, the area of which accurately represents the area of timber-frame, if not its precise location and configuration (Figure 266).

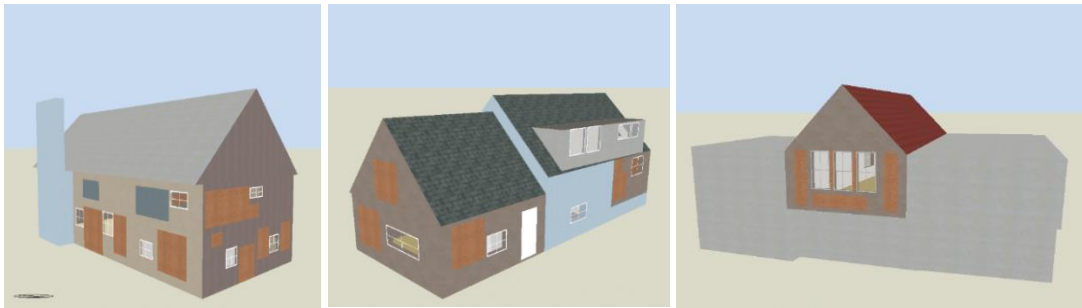

Figure 266. DesignBuilder models of (from left) Hacton Cruck, The Oaks and The Old Mayor's Parlour. Source: (Author's own, 2017)

Where possible the actual measured values for both U-values and air infiltration rates, obtained through the previously presented in situ monitoring, have been used. By doing so

research has shown that the simulations provide a better approximation of potential energy saving of retrofit actions (Chung, 2016).

10.1.3 Weather files and limitations

The software Meteonorm Version 6.1 was used to create weather files for each site, using the time period 1996-2005. This was chosen to have more recent data rather than the longer but older time period of 1961-1990.

Meteonorm™ creates hourly climate data for any site in the world by the interpolation of the meteorological data from surrounding weather stations. The accuracy of the resulting weather file is therefore determined by the number of weather stations used and their distance from the site. The UK in general is fairly well covered by meteorological stations, however this varies across the country. Secondly, in addition to interpolating the results from multiple sites, the software uses algorithms to transform daily averages into hourly values. A validation exercise undertaken by the software's developers found that for the hourly temperatures "the distribution of the daily values and their variation are well reproduced" (Meteotest, 2010 p.72). However the mean difference between the measured and calculated hourly precipitation across six European locations was -12.8%, even though the yearly total was only out by a mean difference of -1% (Meteotest, 2010 p.94). This is obviously not ideal given that DesignBuilder® is using the combined effect of hourly temperature, relative humidity, solar radiation, wind speed and direction, cloud cover and precipitation to model the resulting internal conditions. Ideally the simulations would be run using only measured data, however as few sites have their own meteorological stations with sufficient historic data, this is a limitation that is hard to avoid. The following results allow comparisons between options but will not predict the actual energy demand.

10.2 Case Study Modelling

10.2.1 Hacton Cruck

Figure 267. View from Northeast of DesignBuilder model of Hacton Cruck. Brown panels are simplification of timber-frame, whilst grey are wattle & daub. Source: (Author's own, 2017)

10.2.1.1 Data input

For Hacton Cruck, four scenarios of infill panels were simulated:

a) The first imagined that all original lath and plaster panels had survived;

b) the second imagined that all panels had been replaced with new wattle and daub;

c) the third that all had been replaced with the new multi-foil panels;

d) and the fourth simulated the as-built situation with a mixture of all three panel types, with proportions according to the architect's drawings.

The measured u-vales were used for each panel type. These four scenarios were repeated with both the pre- and post-torching air-change-rates and a third hypothetical air-change-rate of 0.5 ac/h. A summary of the scenarios simulated is presented in Table 28 with a detailed breakdown of the materials used and their thermal properties included in Table 36 appendix G.

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Table 28. Summary of scenarios simulated for Hacton Cruck. Actual scenarios in red.

Scenario	Name	Description	Air Pressure ac/h @50Pa	Air Pressure ac/h
1a	Lath & Plaster	All infill panels in lath & plaster	130	6.5
1b	Wattle & Daub	All infill panels in wattle & daub	130	6.5
1c	Multifoil	All infill panels with multifoil insulation	130	6.5
1d	**As-built**	**Mixture of panel infills as-built**	**130**	**6.5**
2a	Lath & Plaster	All infill panels in lath & plaster	68	3.4
2b	Wattle & Daub	All infill panels in wattle & daub	68	3.4
2c	Multifoil	All infill panels with multifoil insulation	68	3.4
2d	**As-built**	**Mixture of panel infills as-built**	**68**	**3.4**
3a	Lath & Plaster	All infill panels in lath & plaster	10	0.5
3b	Wattle & Daub	All infill panels in wattle & daub	10	0.5
3c	Multifoil	All infill panels with multifoil insulation	10	0.5
3d	As-built	Mixture of panel infills as-built	10	0.5

10.2.1.2 Results

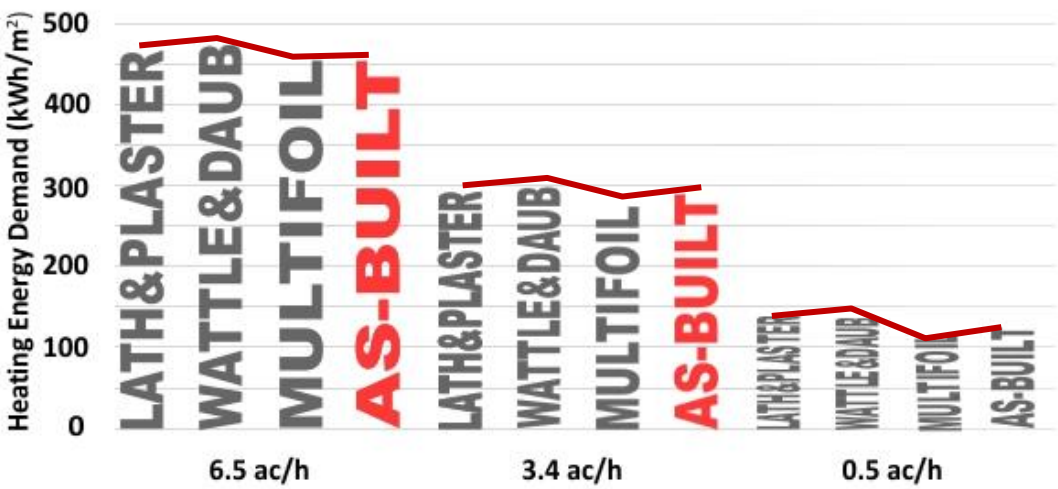

Figure 268. Simulated Heating Energy Demand (kWh/m²) for Hacton Cruck. Actual scenarios in red and hypothetical scenarios in grey. Source: (Author's own, 2017).

10.2.1.3 Analysis and discussion

Figure 268 shows clearly that the thermal performance of the infill panels has little effect on the heating energy demand pre-torching with the scenario with all multi-foil insulated panels creating only a 0.01% reduction when compared to the as-built. The impact of the fabric performance becomes more notable as airtightness is improved rising to 5% post-torching and 6% if the air change rate was limited to 0.5ac/h. However, it is the simple act of torching the underside of the thatched roof, thereby improving the airtightness, which sees the greatest reduction at 36%. If further work, such as improving the joint between panel and timber-frame, plugging post-holes and improving the airtightness of windows and doors, was undertaken to improve the airtightness to 0.5 ac/h then a reduction of 72% of heating demand could be achieved when compared to the pre-torched heating energy demand.

These results show that improving airtightness has a greater impact on reducing the heating energy demand, than the replacement of panel infills (Figure 268 & Figure 269). Only once improved airtightness has been achieved does the thermal performance of the building envelope become a critical factor. This underlines the importance of the order in which retrofit solutions are applied. Whilst for this specific property no historic fabric was lost in the upgrading of the infill panels, the results of these simulations should have significant weighting in the planning of future retrofits of historic timber-framed buildings. Simple measures that reduce air infiltration, such as the plastering of the thatched ceiling, should be implemented before considering work that requires the removal and destruction of existing historic fabric. Even a building with a highly thermally efficient envelope will have a high heating demand if poor airtightness requires the frequent re-heating of large volumes of air due to high air change rates.

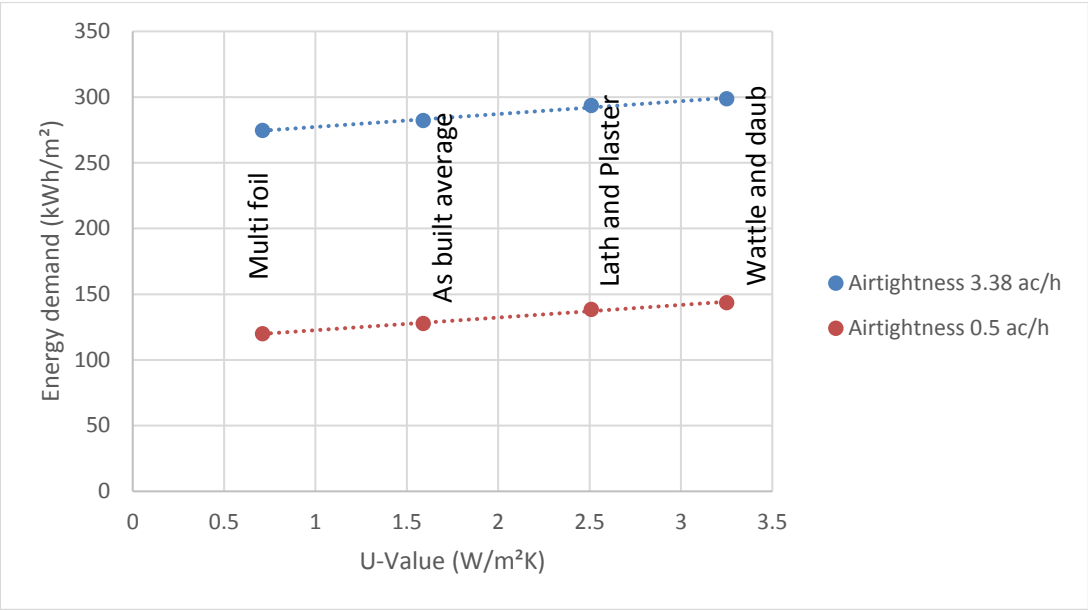

Figure 269 Graph of DesignBuilder simulation results comparing u-value of infill panels and heating energy demand at Hacton Cruck. Source: (Author's own, 2017)

At the same time, there is a balance to be achieved between increased airtightness and adequate ventilation. Care must be taken to ensure that internal relative humidity is controlled. This is not an issue at Hacton Cruck where the current air change rate of 3.4ac/h remains extremely high but would be so if further work continued to reduce the air infiltrations through the external envelope.

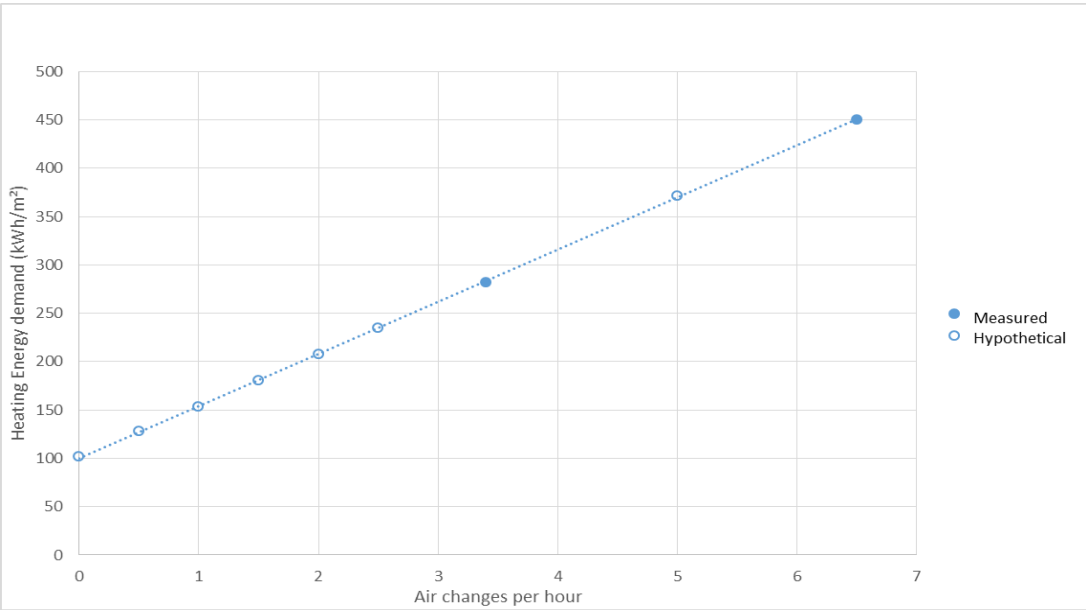

Figure 270. Graph of DesignBuilder simulation results comparing airtightness and heating energy demand at Hacton Cruck. Source: (Author's own, 2017)

Figure 270 shows that if the air change rate was hypothetically reduced to zero then the heating energy demand could be reduced to 100kWh/m², 35% of the current situation post-torching. However, this would be both impossible to achieve and undesirable as some degree of background ventilation is required for both the health of the occupants and building fabric.

10.2.2 The Oaks

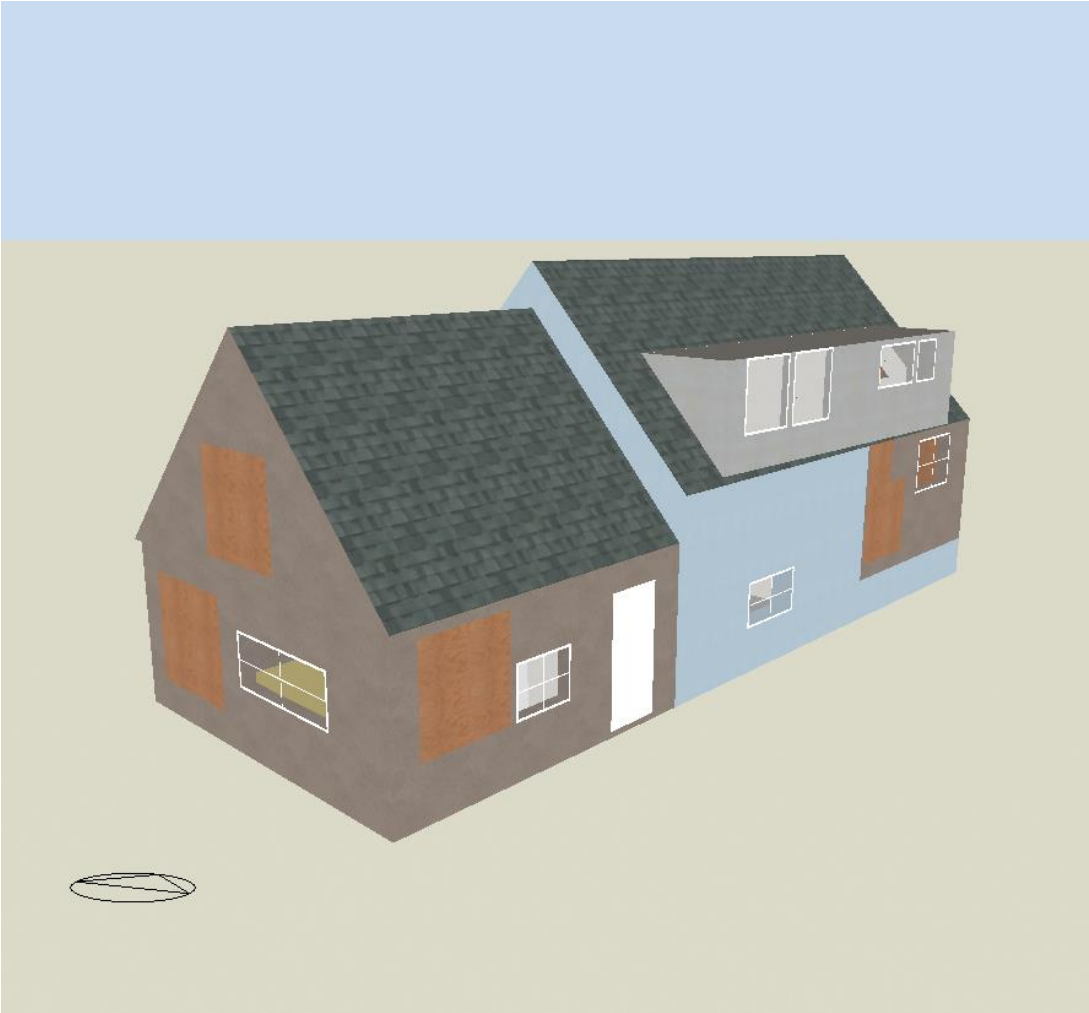

Figure 271. View from south of DesignBuilder model of The Oaks. Brown panels are a simplification of the timber-frame, beige the panel infill and light blue the stone walls. Source: (Author's own, 2017)

10.2.2.1 Data input

For The Oaks the two retrofit actions actually undertaken (secondary glazing and roof insulation) were simulated separately. In addition, two hypothetical additional retrofit actions were modelled. The first of these would replace all concrete block infill panels with wood fibre insulation and the second would replace all infill panels, including historic wattle and daub, with wood fibre. Scenarios with combinations of all retrofit actions, both real and hypothetical, were also simulated, including the current as-built situation.

Given the fact that the quantity of roof insulation for the pre-retrofit baseline situation was unknown, two different assumptions were simulated. The first (A) assumed no roof insulation was present, whilst the second (B) used the assumptions for existing buildings given by the Standard Assessment Procedure (SAP) appendix S10 were used (BRE, 2014 p.136). It was known that no work had taken place on the property for the past 20 years; therefore, the values for 1983-1990 were used assuming that some roof insulation may have been introduced around this time. These values are 100mm insulation with overall U of 0.5W/m²K for pitched roofs and 0.4W/m²K for flat roofs (BRE, 2014 p.136).

A summary of the scenarios simulated is presented in Table 29 with a detailed breakdown of the materials used and their thermal properties listed in Table 37 appendix G.

Table 29. Summary of scenarios simulated for The Oaks. Actual retrofit actions in orange and completed scenarios in red.

Scenario	Name	Description	Roof	Air Pressure ac/h @50Pa	Air Pressure ac/h
A1	Pre-Retrofit	Pre-retrofit assuming no roof insulation	Assumes no roof insulation pre-retrofit	16.5	0.83
A2a	**Secondary Glazing**	**Secondary glazing fitted to all windows as-built**		**10.8**	**0.54**
A2b	**Roof Insulation**	**New roof insulation installed as-built**		**10.8**	**0.54**
A2c	**Roof + Glazing**	**Roof insulation and secondary glazing as-built**		**10.8**	**0.54**
A3a	Wood fibre	Concrete block infill replaced with wood fibre insulation		16.5	0.83
A3b	Wood fibre all	All infill panels, including wattle and daub replaced with wood fibre insulation		16.5	0.83
A4a	Roof + Glazing + Walls	Roof insulation, secondary glazing and concrete blocks replaced with wood fibre		10.8	0.54
A4b	Roof + Glazing + Walls+	Roof insulation, secondary glazing and all infill panels replaced with wood fibre		10.8	0.54
B1	Pre-Retrofit	Pre-retrofit assuming 1983-1990 levels of roof insulation	1980 SAP	16.5	0.83
B2a	**Secondary Glazing**	**Secondary glazing fitted to all windows as-built**		**10.8**	**0.54**
B2b	**Roof Insulation**	**New roof insulation installed as-built**		**10.8**	**0.54**
B2c	**Roof + Glazing**	**Roof insulation and secondary glazing as-built**		**10.8**	**0.54**

10.2.2.2 Results

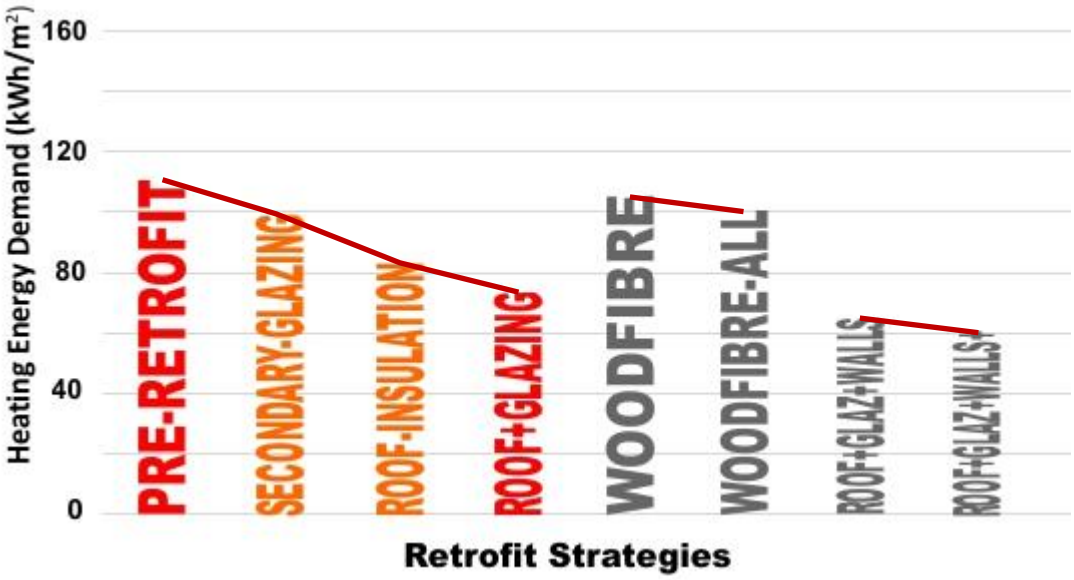

Figure 272. Simulated Heating Energy Demand (kWh/m²) for The Oaks, assuming no roof insulation was present pre-retrofit. Hypothetical scenarios in grey, individual retrofit actions in orange and as-built in red. Source: (Author's own, 2017)

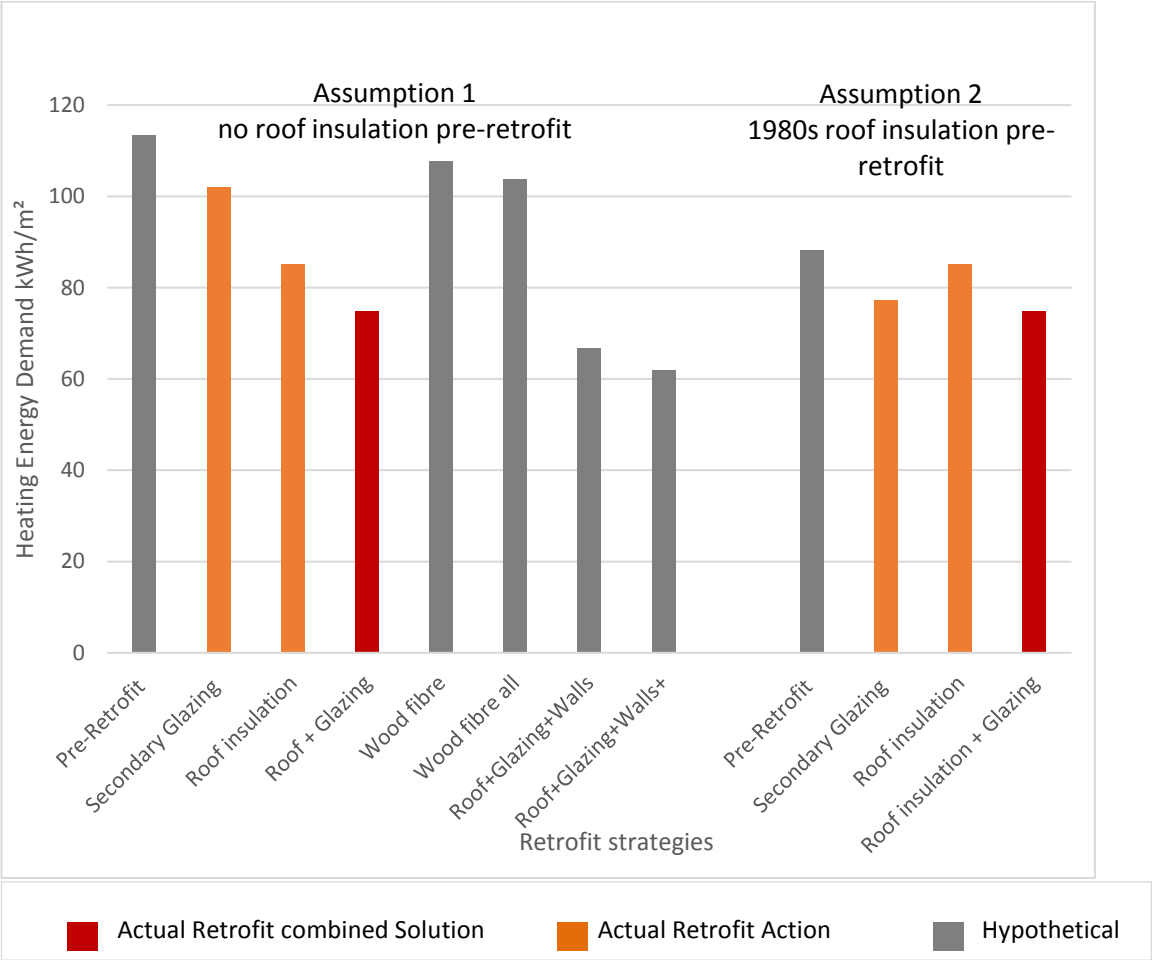

Figure 273. Results of DesignBuilder Simulation showing heating demand for individual and combined retrofit actions at The Oaks. Source: (Author's own, 2017)

10.2.2.3 Analysis and discussion

Assuming that no roof insulation was present pre-retrofit (Figure 272) it can be seen that just the installation of secondary glazing is more effective (10% reduction) than replacing all the infill panels (9% reduction). Whilst it can be argued that secondary glazing is visually intrusive, it is however, a fully reversible retrofit action and does not result in the loss of historic fabric. Assuming that no roof insulation was present pre-retrofit, the insulating of the roof is the retrofit action with the greatest individual benefit (25% reduction) which when combined with the secondary glazing results in an overall reduction of 34% and is the solution that was applied in reality. With the disruption involved, it is questionable whether the additional 11% reduction, achievable by replacing infill panels, would ever be justifiable.

When the simulations are re-run with the second assumption that some roof insulation was present pre-retrofit (Figure 273) it can be seen that a smaller overall reduction (15% rather than 34%) is achieved due to the greater efficiency of the pre-retrofit baseline situation. In this case, the new roof insulation fitted makes a limited impact with only a 4% reduction in heating demand, however just secondary glazing alone would have made a 15% reduction.

Whilst the increase in airtightness resulting from the installation of the secondary glazing is beneficial with regard to energy efficiency, there could be some issues concerning increased internal moisture levels. The surface moisture content monitoring of the timber presented in section 9.3.4 suggests that this is not the case in the living room, however the change of use of the parlour to a bathroom has resulted in an increase in timber moisture content, which is likely in part due to the lack of adequate forced ventilation.

10.2.3 The Old Mayor's Parlour

Figure 274. View from east of DesignBuilder model of The Old Mayor's Parlour. Source: (Author's own, 2017)

10.2.3.1 Data input

As with The Oaks, each real retrofit action at The Old Mayor's Parlour was simulated separately. These being the replacement of the infill and internal lining to the front east wall and the insulation of the rear west wall. In addition, hypothetical actions of insulating the roof with 20mm[60] wood fibre and installing secondary glazing were also simulated. Again, scenarios combining retrofit actions were also included. As the gallery is located on

[60] Due to the decorative 17th century ceilings, the insulation would need to be installed on top of the rafters and as such, the thickness is limited so as not to increase the overall roof height.

the first floor between adjacent buildings, these and the ground floor were modelled as adiabatic[61] volumes.

As no pressure testing was carried out pre-retrofit, it has been assumed that this was the same as that measured post-retrofit. This is not ideal for the purpose of this evaluation, as the internal lining may have increased the airtightness. However, as the major sources of infiltrations, the windows and door were not replaced, there may not have been any significant change. For the simulations of all scenarios including the hypothetical installation of secondary glazing, it has been assumed that the airtightness would be improved and a value of 0.54 air changes per hour (the same as measured post-retrofit at The Oaks) has been used.

A summary of the scenarios simulated is presented in Table 30 and a detailed breakdown of the materials used in the simulation and their thermal properties are listed in Table 38 appendix G.

Table 30. Summary of scenarios simulated for The Old Mayor's Parlour. Actual retrofit actions in orange and completed scenarios in red.

Scenario	Name	Description	Air Pressure ac/h @50Pa	Air Pressure ac/h
1	Pre-Retrofit	Pre-retrofit with concrete block infill panels	22.5	1.12
2a	**Front Wall**	**Replacement of infill with wood fibre insulation and internal insulation as-built**	**22.5**	**1.12**
2b	**Rear Wall**	**Insulation of rear (west) wall with multifoil insulation as-built**	**22.5**	**1.12**
2c	**Both Walls**	**Insulation of both front and rear walls as-built**	**22.5**	**1.12**
3	Secondary Glazing	Secondary glazing to all windows	10.8	0.54
4	Roof Insulation	20mm wood fibre insulation above ceiling	22.5	1.12
5a	Walls + Glazing	Insulation as-built plus secondary glazing	10.8	0.54
5b	Roof + Glazing	20mm roof insulation plus secondary glazing	22.5	1.12
5c	Roof + Walls + Glazing	Insulation to walls as built plus 20mm roof insulation plus secondary glazing	10.8	0.54

[61] Adiabatic- where no heat transfer occurs.

10.2.3.2 Results

Figure 275. Simulated Heating Energy Demand (kWh/m²) for The Old Mayor's Parlour Hypothetical scenarios in grey, individual retrofit actions in orange and as-built in red. Source: (Author's own, 2017)

10.2.3.3 Analysis and discussion

At the Old Mayor's Parlour the thermal upgrading of the front and rear walls achieve a 6% reduction for each wall and a combined reduction of 12%. It is interesting to note that, assuming secondary glazing would achieve a similar increase in airtightness as seen at the oaks, secondary glazing alone could potentially achieve a reduction of 15%. The introduction of 200mm wood fibre insulation to the roof could potentially have achieved a 17% reduction alone, or 42% when combined with the walls, and 58% combined with walls and secondary glazing. However, the architect's reluctance to intervene in the roof is understandable given the historic value of the 17th century plastered ceiling, nonetheless, as noted in the previous chapter, the thermography has identified a marked difference in surface temperature between insulated walls and uninsulated ceiling. Potentially this could lead to increased condensation on the ceiling. Intervening in the walls with their poor quality modern infill and avoiding work to the historic fabric of the ceiling would appear a sensible conservation approach, however, as discussed in section 9.4.4 if humidity within the room is not carefully controlled this decision may have detrimental consequences.

Given the small reductions in heating demand achieved by the insulation of the lower portion of the walls, this does perhaps, call into question that in this instance it may have been better not to intervene at all.

10.2.4 Nos. 25 & 27 Church Street, Saffron Walden

10.2.4.1 Data input

Figure 276. View from northwest of DesignBuilder model of no.25 (right) and no.27 (left) Church Street, Saffron Walden. Source: (Author's own, 2017)

For nos. 25 and 27 Church Street, Saffron Walden, simulations of heating energy demand were first undertaken for three different levels of airtightness. These were; the average airtightness as measured for the entire building (both houses joined) on 12th March 2017, the airtightness measured for just no. 27 on the same date, assuming that work could be undertaken to bring no. 25 up to the same standard, and the airtightness measured by Archimetrics in 2012 (Hubbard, 2012) assuming that minor retrofit actions (such as draft-stripping windows) could achieve this value again in the future for both houses. The results of these simulations are presented in Figure 277.

Following the simulations with different levels of airtightness, a series of scenarios with internal insulation were simulated. Due to the 17th century decorative pargeting, it is not recommendable that any of the panel infills are replaced and so internal insulation is the only option. Three different thicknesses of insulation (25mm, 50mm and 100mm) were simulated Figure 278. Due to concerns over increased risk of frost damage to the pargeting, simulations of a profiled section through a decorative element[62] were conducted with two-dimensional conduction heat transfer analysis software THERM® version 7.5 for each thickness of insulation. THERM® simulates the two dimensional heat flow through a construction element (wall, roof, floor etc.), allowing for the analysis of the temperature at different points through the thickness of that element. For these simulations, the default values for external temperature (0°C) and interior (21°C) were used. The results of these simulations are presented in Figure 279. A fourth scenario where only the ground floor walls are insulated was also simulated with DesignBuilder.

Finally, scenarios were simulated with retrofit actions involving the insulation of the roof and floor. A summary of the results of all DesignBuilder simulations for this property are presented in Figure 280.

A summary of the scenarios simulated is presented in Table 31 and a detailed breakdown of the materials used in the simulation and their thermal properties are listed in Table 39 appendix G.

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[62] The profile was taken through the location of the in situ U-value measurements and was created using laser scanning.

Table 31. Summary of scenarios simulated for nos. 25 and 27 Church Street. Actual situation in red. All others are hypothetical.

Scenario	Name	Description	Air Pressure ac/h @50Pa	Air Pressure ac/h
1	**Existing**	**Existing building in current situation**	**56.6**	**2.83**
2a	Current no.27	Airtightness of no.25 improved to same standard as current airtightness of no.27	19.6	0.98
2b	No.27 measured 2012	Airtightness improved to that measured in no.27 in 2012	10	0.5
3a	25mm Ins all walls	25mm internal wood fibre insulation	19.6	0.98
3b	50mm Ins. all walls	50mm internal wood fibre insulation	19.6	0.98
3c	100mm Ins. all walls	100mm internal wood fibre insulation	19.6	0.98
3d	25mm Ins. GF walls	25mm internal wood fibre insulation to ground floor walls only	19.6	0.98
4	25mm Ins. GF walls	25mm internal wood fibre insulation to ground floor walls only	56.6	2.83
5a	Roof Insulation	150mm roof insulation between rafters	19.6	0.98
5b	Floor Insulation	150mm floor insulation between beams	19.6	0.98
5c	Roof and Floor Ins.	150mm to both floor and roof	19.6	0.98
6a	Floor Insulation	150mm floor insulation between beams	56.6	2.83
6b	Roof and Floor Ins.	150mm to both floor and roof	56.6	2.83

10.2.4.2 Results

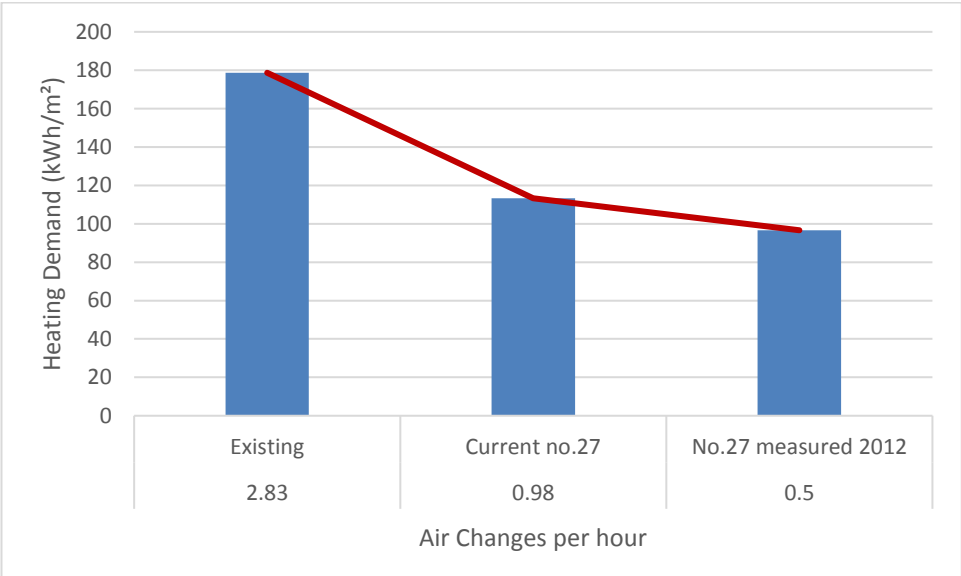

Figure 277. Simulated heating energy demand for nos. 25&27 Church Street, Saffron Walden three different levels of airtightness. Source: (Author's own, 2017).

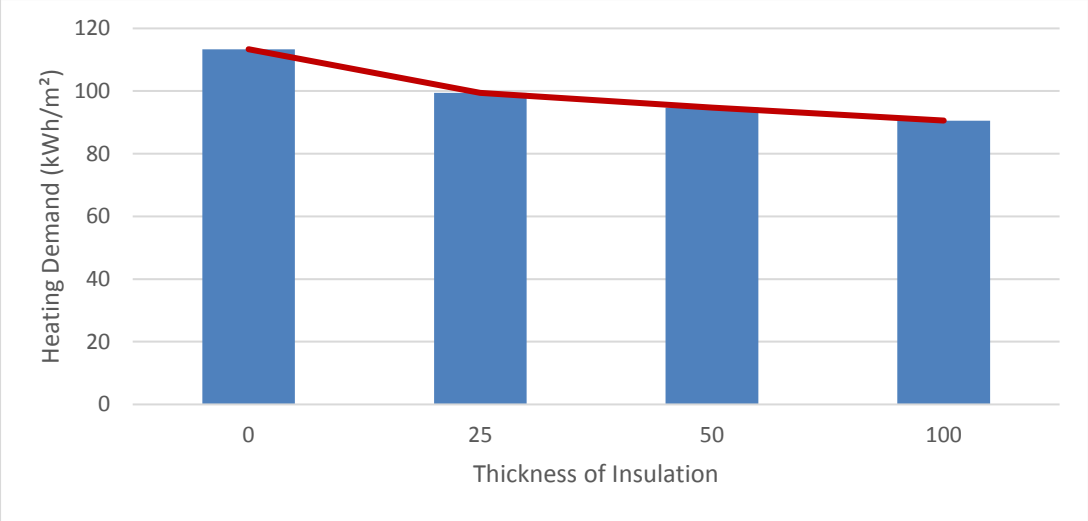

Figure 278. Simulated heating energy demand for nos. 25&27 Church Street, Saffron Walden with 0.98 air changes per hour and varying thicknesses of internal wood fibre wall insulation. Source: (Author's own, 2017).

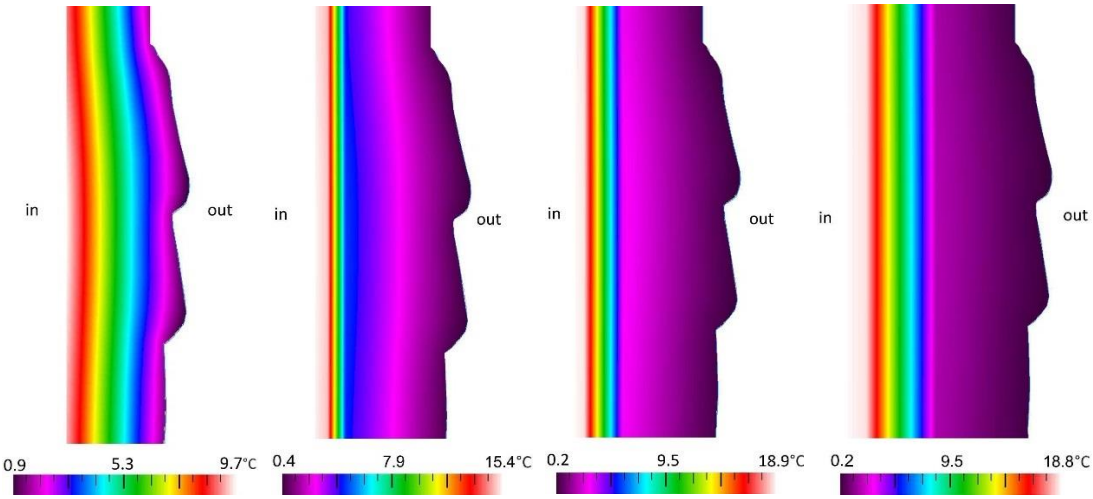

Figure 279. Simulations with THERM version 7.5 of wall section through decorative pargeting showing temperatures with (left to right) no insulation, 25mm, 50mm and 100mm wood fibre internal insulation. Exterior temperature 0°C and interior 21°C. Source: (Author's own, 2017)

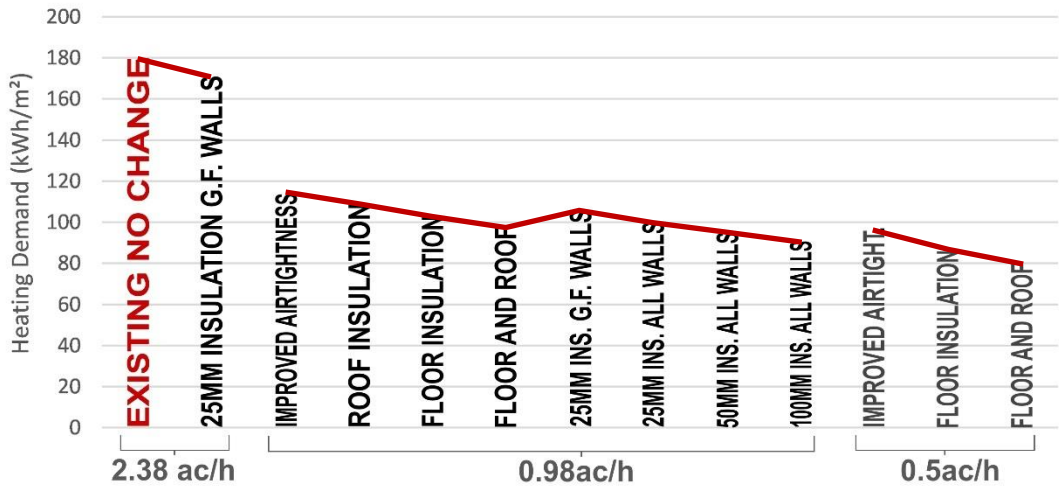

Figure 280. Simulated heating energy demand for nos. 25&27 Church Street, Saffron Walden for a range of hypothetical retrofit actions at three different levels of airtightness. Existing situation shown in red. Source: (Author's own, 2017)

10.2.4.3 Analysis and discussion

Figure 277 shows that if work was undertaken to bring the airtightness of no.25 up to the same level as measured in no.27 then there would be a 37% reduction in heating energy demand of the combined properties. This should be possible to achieve, as it would only include repairing broken plaster in walls and ceilings and sealing off the internal access to the cellar. The next step to return the house to the level of airtightness measured in 2012 should also be technically possible with the use of sealants, floor coverings and draught stripping of doors and windows. It may however be resisted by the owner on aesthetic and philosophical grounds, with regards to preserving breathability and authenticity, and in addition it may potentially lead to an increase in internal moisture conditions if controlled mechanical extraction was not installed for both the kitchen and bathroom. It is therefore debatable whether the additional 14% energy reduction is sufficient to merit such contentious measures.

Assuming that the two houses could be made as airtight as no.27 currently is, the introduction of insulation to all walls could make reductions in heating energy demand, ranging from 12%-20% depending on thickness (Figure 278 and Table 32). However, the simulations with THERM version 7.5 (Figure 279) show that any introduction of insulation will reduce the external surface temperature of the 17th century decorative pargeting, thereby raising the risk of frost damage. In the case of the 25mm insulation, this is still 0.4°C when the external air temperature is 0°C, however with both the 50mm and 100mm insulation this drops to 0.2°C, with much of the historic wall being below 1°C. Given the heritage value of this historic pargeting it is unlikely that potential risk of frost damage can be outweighed by the small reductions in energy demand that would be achieved. It would therefore be advisable not to install internal insulation to the upper storeys. As no decorative pargeting is present on the ground level, potentially this could be internally insulated with 25mm of insulation resulting in a 7% reduction in energy demand.

Alternatively, a 9% reduction could be achieved by insulating underneath the ground floor floorboards and the exposed floor over the carriageway or a 14% saving if combined with insulation of the roof.

Table 32. Percentage reduction in heating energy demand achieved by varying thicknesses of internally applied wood fibre insulation at nos. 25 and 27 church Street.

Thickness of insulation (mm)	Percentage reduction in heating energy demand (%)
25 walls	12
50 walls	16
100 walls	20
25 Ground floor walls only	7
150 floor	9
150 floor and roof	14

Again, improving airtightness achieves more substantial reductions than the thermal insulation of the historic envelope. In this particular case, the relatively poor thermal performance of the walls of the property could actually be viewed as beneficial due to the reduced risk of frost damage to the decorative pargeting, the building's most significant historical feature. This highlights that retrofit measures must be reviewed on a case-by-case basis and cannot be universal. This is contrary to the current situation where retrofit advice is often given as a "one case fits all", such as that provided on the Domestic Energy Performance Certificates (EPCs). Ironically, the EPC for this property (Sykes, 2008) advocated the use of external wall insulation and stated that its use "may improve the look of the home" (ibid p5, Clark, 2009 p.54). This clearly goes against the legislation governing EPCs which clearly states that listed buildings are exempt when "…minimum energy performance requirements would unacceptably alter their character or appearance" (2012 p.5)

10.2.5 Old Stokes Farm, Battisford, Suffolk

10.2.5.1 Data input

Figure 281. View from northwest of DesignBuilder model of Old Stokes Farm. Source: (Author's own, 2017)

The current situation at Old Stokes Farm was simulated using the wall u-value and airtightness as measured on 3rd April 2017 (see section 9.6.2). Given that the measured u-value was far worse than the calculated u-value for the current external wall build-up, a further two simulations were undertaken to simulate the outcome that the previous owner might have anticipated when the retrofit was undertaken. The first of these used the calculated u-value and measured airtightness, whilst the second assumed an improved airtightness with an air change rate of 0.5ac/h, a level seen to be achievable at The Oaks (section 9.3.1).

Based on the surviving infill panels in the west gable it has been assumed that the house originally had lath and plaster infill panels. Two hypothetical pre-retrofit simulations were undertaken based on this assumption, one with the measured air change rate (0.9ac/h),

and a second assuming that the lath and plaster junction with the timber-frame would be more airtight and would achieve an air change rate of 0.5ac/h.

Finally, four hypothetical retrofit actions were simulated. The first replaced all windows with triple glazing. As none of the current windows are original this would be viable and a preferable option to secondary glazing in terms of heat loss but as all current windows are already well fitting, it was assumed that this would not result in an increase in airtightness. The second hypothetical retrofit action assumed an increase in airtightness could be achieved by sealing all junctions between the gypsum plasterboard and timber-frame. The third proposes the replacement of all rigid polyisocyanurate thermal insulation with an equal thickness of sheep's wool, the replacement of external cement render with lime render on oak laths, and the replacement of internal gypsum plasterboard with lime plaster on oak lath. In the first instance, the airtightness is maintained at its current level, whilst the fourth and final simulation assumes that this revised construction would achieve an improved air change rate of 0.5ac/h. As the roof is already well insulated with 200mm of mineral wool, this was not proposed as a retrofit action.

A summary of the scenarios simulated is presented in Table 33 and a detailed breakdown of the materials used in the simulation and their thermal properties are listed in Table 40 appendix G.

Table 33. Summary of scenarios simulated for Old Stokes Farm. Actual situation in red. All others are hypothetical.

Scenario	Name	Description	Air Pressure ac/h @50Pa	Air Pressure ac/h
1a	Lath and Plaster	Assumed pre-retrofit state with current airtightness	18	0.9
1b	Airtight Lath & Plaster	Assumed pre-retrofit state with improved airtightness	10	0.5
2a	**Current Situation**	**Wall u-value and airtightness as measured**	**18**	**0.9**
2b	Current as Calculated	Calculated design u-value of wall but with airtightness as measured	18	0.9
2c	Airtight as calculated	Calculated design u-value of wall and improved airtightness	10	0.5
3	Triple Glazing	Current situation (2a) but with all windows replaced with triple glazing	18	0.9
4	Improved airtightness	Current situation (2a) but assuming improved airtightness	10	0.5
5a	Re-insulate Sheep's Wool	All infill replaced with sheep's wool lime plaster/render finishes.	18	0.9
5b	Airtight Sheep's Wool	All infill replaced with sheep's wool lime plaster/render finishes and improved airtightness	10	0.5

10.2.5.2 Results

Figure 282. Simulated heating energy demand for Old Stokes Farm, Battisford for a range of hypothetical pre and post-retrofit actions. Existing situation shown in red. Source: (Author's own, 2017)

10.2.5.3 Analysis and discussion

Figure 282 shows that it is possible that prior to the retrofit by the previous owner the energy demand for the house could have been almost equal to, if not better than the current situation, with an heating energy demand 1% lower than the house as it now stands. If the assumption that the original lath and plaster provided a more airtight junction with the timber-frame than the current unsealed plasterboard butt-jointed detail, then potentially the house may have been 10% more efficient before the retrofit was undertaken. Obviously, this was not the intended outcome. If the thermal performance of the walls had achieved their calculated design value of 0.921 W/m^2K, rather than the measured 1.8 W/m^2K then a 26% or 35% reduction in heating energy demand would have been accomplished depending on the airtightness achieved. This was not the case, as previously discussed in section 9.6.2, due to the poor detailing where ill-fitting rigid panels allow heat transfer through convection on all sides.

The replacement of all windows with triple glazing makes little difference to the heating energy demand with the simulation results showing only a 2% reduction. This is to be expected, as most of the windows are already double glazed units in modern timber frames.

If the rigid polyisocyanurate thermal insulation and gypsum plasterboard infill was replaced with sheep's wool and lime plaster on oak lath, then the simulation suggests that a 23% or 32% reduction in heating energy demand could be achieved depending on the resulting airtightness. These results assume that the sheep's wool and lime plaster detail would achieve the calculated design u-value, which may not be the case, but is more probable than that of the rigid polyisocyanurate and gypsum boards due to the materials abilities to adapt to the irregularities of the timber-frame fully filling the infill panel.

The results of the simulations of this final case study raise the issue of comparing simulations based on actual measured building performance (U-values and airtightness) compared with those based on with assumed values, whether these be for future or historic scenarios. When simulating proposed retrofit actions it is assumed that the built reality will achieve the design U-value and/or airtightness. However, as the measured values for this property show, this is not always guaranteed. This is especially true when the constructability and robustness of the details in question are not fully considered by the architect or builder. One can reasonably assume that a detail where the insulation and infill have no mechanical or chemical fixing or sealing to the timber-frame will not perform well, and hope that a detail carefully considered to adjust to irregularities and create flexible airtight junctions will. However, the potential for significant deviation between simulated and actual performance is a problem and one that must be considered at all stages of evaluating and proposing retrofit solutions.

10.3 Conclusions

The results of these simulations and associated in situ monitoring have highlighted that it is often apparently small measures, such as plastering ceilings and installing secondary glazing, which can have the most significant impact on reducing the heating demand of historic timber-framed buildings. It is interesting to note that property with the least intervention and the highest achieved reduction in heating demand was the property owned by National Trust, The Oaks. This is perhaps not surprising that an organisation with a large property portfolio of historic buildings should achieve the best balance between intervention, outlay and payback.

Predominantly it can be seen that it is the retrofit actions that improve airtightness that produce the greatest reductions in heating energy demand. Given that these retrofit actions are often modest in both economic and physical impact, they should always be

considered prior to the more invasive intervention of improving the thermal performance of external walls. Care must however be taken not to increase airtightness to the point that excessive internal relative humidity becomes a problem.

In most cases, it was shown that improving the thermal performance of the walls did not dramatically improve the building's thermal performance. Whilst no historic fabric was lost in these case studies, this may not be the case in the retrofit of other historic timber-framed buildings. The findings also clearly indicate that care must be taken not to create large discrepancies in internal surface temperatures that in turn could put at risk uninsulated historic building fabric, through the creation of cold bridges and increased localised condensation. Therefore, a possible strategy where the lack of historic infill material permits intervention, would be to improve the thermal performance of the infill panels only to the point where they provide an equal thermal transmittance as that of the surrounding frame. By doing so, some minimal reduction in energy demand could still be achieved, whilst at the same time equalising internal surface temperatures, thereby minimising the risk of concentrating condensation.

The differences between the five case studies highlight the need for the review of the retrofit of historic timber-framed buildings on a case-by-case basis. The significance and condition of each building element must be considered to ensure that the proposed retrofit action does not produce unintended consequences and/or the unnecessary loss of historic fabric.

The simple monitoring and simulation presented in this and the preceding chapters represents a methodology that can assist in the decision making process for the retrofit of historic timber-framed buildings. The calculation engine behind the simulations EnergyPlus® is an open source software and free to download, however many architects will find that the input of information is easier with a graphical interface such as

DesignBuilder®. The current cost of DesignBuilder® is £699 per annum (Design Builder, 2017). This cost may be acceptable to a sole practitioner if sufficient projects are undertaken but may be unacceptable for a one of project if it cannot be passed on to the client. At the same time, care must be taken in comparing simulations using measured data and those based on assumed performance and calculated design values. In order to obtain measured values it is unrealistic to expect architects and contractors to buy their own monitoring equipment, however companies do exist that provide these services.

The architect or building professional must also assess the constructability and robustness of the proposed details and evaluate their ability to achieve the desired result, be that reducing thermal transmitance, increasing airtightness or ideally both. It is therefore critical that some degree of this knowledge is taught as part of architectural education and made readily available through guidance documents, however much of it will only come through experience.

11 HYGROTHERMAL SIMULATION

11.0 Introduction

11.1 Potential risks of retrofitting

As previously discussed, the inappropriate introduction of thermal insulation to historic timber-framed buildings could potentially give rise to unintentional negative impacts, including increased moisture content and interstitial condensation leading to the deterioration of the built fabric, as well as associated health risks (WHO, 2008). The two biggest threats to timber-framed construction are insect infestation and fungal decay (McCaig and Ridout, 2012). The susceptibility to both increases as the moisture content of the timber rises. The optimum hygrothermal conditions for common insects and fungi are listed in Table 34.

Table 34 Hygrothermal conditions for common UK biological timber threats (McCaig and Ridout, 2012).

	Beetle and their larvae				**Fungi**		
							
Common name	Powder-post	House Longhorn	Wood-worm	Deathwatch	Dry Rot	Oak Rot	Cellar Rot
Latin name	*Lycus linearis Goeze & Lyctus brunneus*	*Hylotrupes w bajulus*	*Anobium punctatum*	*Xestobium rufovillosum*	*Serpula lacrymans*	*Donkioporia expansa*	*Coniophora puteana*
Moisture content	8-25%	15˚C-25%	>12%	>15%	>25%	>28%	>25%
Temperature	26 ˚C	20-30 ˚C	22 ˚C	>10 ˚C	17-23 ˚C	5-40 ˚C	20-32˚C

For the insects, both the hatching of eggs and development of the larvae are dependent on those hygrothermal values quoted in Table 34 being maintained. Powder-post eggs take 20 days to hatch (Ridout, 1999 p.70), House Longhorn 5-10 days (ibid, p.65), Woodworm 14-38 days (ibid, p.58) and Deathwatch 20 days (ibid, p.41). With Larval development times of 8-12 months for Powder-post (ibid, p.70), 3-6 years for House Longhorn (ibid, p.66), 3 or more years for Woodworm (ibid, p.59) and in some cases over 10 years for Deathwatch

beetles (ibid, p.42). However, for the fungi, the conditions need not be continuous to enable survival. Dry rot can survive in dry timber for up to 9 years at temperatures of 7.5°C (Rayner, 1988 p.456) but are killed at temperatures over 26°C (ibid, p.457), whereas cellar rot can survive up to temperatures of 65°C (ibid, p459). The hygrothermal conditions quoted in Table 34 are however required for growth, under which dry rot can grow at a rate of between 2.25mm-9mm per day (Ridout, 1999 p.83).

11.2 Research objectives

This chapter aims to study the hygrothermal performance of those replacement panel infill details previously presented in the literature review. These include details currently proposed by UK heritage bodies, in addition to hemp lime (Stanwix and Sparrow, 2014) and those details using cork, developed by the author in collaboration with Tŷ-Mawr Lime Ltd. By doing so, it is hoped to evaluate the potential risk of unintentional negative impacts on the historic fabric arising from the use of these details. This chapter therefore presents the results of the digital simulation of interstitial hygrothermal conditions for each of the thirteen details.

11.3 Methodology

A total of 13 retrofit details were studied as listed in Table 35. A thickness of 115mm was assumed for the timber-frame in each detail. Detail sections of the 13 are included in Appendix A.

Table 35. List of reviewed details

Code	Source	Description	U-Value (W/m²K)
S1a	SPAB[1] fig.12	Wattle and Daub + internal and external lime plaster.	2.83
S1b	SPAB[1] fig.12	As S1a but with foil backed plasterboard in place of internal lime plaster	2.53
S2	SPAB[1] fig.13	60mm glass wool + lime plaster on expanded metal lathe.	0.67
S3	SPAB[1] fig.14	Lime render, 50mm wood wool, 25mm glass wool, vapour barrier (VB), 25mm wood-fibre, internal skim coat.	0.63
S4	SPAB[1] fig.17	Lime render, 50mm wood wool, 25mm extruded polyurethane, VB, internal gypsum plaster.	0.62
S5	SPAB[1] fig.18	Half brick nogging, 12.5mm EPS + Internal lime plaster.	1.14
E1a	EH-1[2] pg325	Lime render, 15mm wood wool, Breather membrane (BM), 54mm cellulose fibre, 20mm wood-fibre board, VB, service void + plasterboard.	0.42
E1b	EH-1[2] pg325	As E1a but with no BM or VB	0.42
E2	EH-2[3] Fig.18	Historic infill retained, BM, 50mm wood-fibre to inside face + lime plaster.	0.64
E3	EH-2[3] Fig.19	As E2 but with 20mm air-gap in place of BM + plasterboard	0.59
HC1	Stanwix & Sparrow[4]	115mm hemp lime + internal and external lime plaster.	0.84
T1a	Tŷ-Mawr[5]	2x40mm cork board + internal and external lime plaster.	0.48
T1b	Tŷ-Mawr[5]	As T2 but with 2mm lime plaster between cork boards.	0.48

1 SPAB (Reid, 1989)
2 EH-1 (McCaig and Ridout, 2012)
3 EH-2 (Ogley, 2010)
4 (Stanwix and Sparrow, 2014)
5 Tŷ-Mawr- developed by author

Of these, five were taken from the SPAB Technical Pamphlet “Panel infilling to timber-framed buildings” (Reid, 1989), one from English Heritage’s book “Timber” from their series “Practical Building Conservation” (McCaig and Ridout, 2012), two from English Heritage’s pamphlet “Insulating timber-framed walls” in their “Energy Efficiency in Historic Buildings” series (Ogley, 2010), another from “The Hempcrete Book Designing and Building with Hemp-Lime” (Stanwix and Sparrow, 2014) and the final two details developed by the author in collaboration with the supplier of ecological building materials Tŷ-Mawr Lime Ltd. Eleven of the details are for replacement infill panels, whilst the remaining two are for internal insulation as suggested by English Heritage (Historic England, 2016a). Those details proposed by F.W.B Charles (Charles, 1984 p.131) and Brown (Brown, 1986 p.352) were not simulated as these are similar to the detail S3 from the SPAB pamphlet (Reid, 1989 p.9). Equally, the detail proposed by O. Prizeman was not simulated due to the lack of

hygrothermal properties for sheep's wool and the inability of the software to simulate a non-continuous heterogeneous layer as formed by the split oak laths.

11.3.1 Simulation with WUFI Pro5

The interstitial hygrothermal conditions within building elements may be studied either via steady-state calculations as defined by BS EN 13788:2012, often referred to as the "Glaser Method" (British Standards Institution, 2012) or via numerical simulation as defined by BS EN 15026:2007 (British Standards Institution, 2007a). Given the transient nature of the conditions that external walls are exposed to, the use of numerical simulation provides more detailed and accurate information. A number of software packages have been developed to undertake this type of simulation such as WUFI® (*Wärme und Feuchte Instationär*) and Delphin both developed by the Fraunhofer Institute and HygIRC developed by the National Research council Canada. WUFI® appears to be the most currently used software (Little et al., 2015 p.124) and has been used recently for work for Historic England (Baker, 2015), Historic Environment Scotland (Little et al., 2015) and SPAB (Browne, 2012). As such, WUFI® was chosen for the following simulations.

WUFI® is available in versions that study heat and moisture transfer in one dimension through multiple layers or in two dimensions, thereby allowing the study of non-continuous heterogenic constructions. The disadvantage of the 2D software is the additional time required for both the input of each construction and computation (Baker, 2015 p.17). In order to study a wider range of proposed infill details it was therefore decided to initially begin with WUFI® Pro5 (version 5.3), 1D software. The simulation with WUFI® 2D remains an area for future research. The limitations of the chosen software are discussed later in section 11.4.1

For the first round of simulation, a weather file for Hereford, UK, created with Meteonorm™ software (version 6.0), was used for the external climate, with the internal

climate being calculated according to BS EN 15026:2007 as recommended by the European SUSREF guidelines for modelling refurbishment of external walls (Peuhkuri et al., 2011). An orientation of 45˚ (southwest) was chosen to simulate the maximum effect of wind driven rain. All material data was taken from the existing software databases, except for hemp-lime which was supplied by A. Evrard (Evrard, 2008). The simulations were set to run from 1st October, this being the date of simulation[63], for a period of three years, this being the default. For all simulations, it was found that annual moisture equilibrium was attained within these three years and so longer simulation periods were deemed unnecessary.

11.3.2 Risk of interstitial condensation

Interstitial condensation occurs when the interstitial temperature drops below the corresponding dew-point temperature (British Standards Institution, 2012 p.12). Therefore, for each simulation the resultant interstitial temperatures and dew-point temperatures were compared to identify if temperatures drop below dew-point thereby producing the potential risk of interstitial condensation.

11.3.3 Review of total water content

The total water content of each construction was reviewed. The period taken for annual moisture equilibrium to be achieved, i.e. for built-in construction moisture from new wet trades to dry out, was calculated. This was done by comparing the first and second year results and identifying the point when the difference between the two is less than 0.1kg/m^2. This threshold was chosen due to minor variations in simulation, which resulted in the difference never being zero. The results are presented in Figure 285. The total water content for the second year of simulation, once annual moisture equilibrium has been attained, is presented in Figure 286.

[63] the consequences of this decision are discussed in section 11.5.2.1

11.3.4 Risk of biological attack

The hygrothermal conditions in each layer were then compared against the criteria presented in Table 34 to assess the potential risk of biological attack of timber in contact with the layer. In order to focus on the long-term impacts, for this analysis, the initial drying period of the constructions was ignored and only the results from the second year of simulation were analysed. That is to say that the details were analysed once they had reached an annual moisture equilibrium. The results are presented in Figure 288. For those constructions with drying periods longer than a month, the risk during this period was reviewed separately.

To convert the gravimetric moisture content (%) quoted in Table 34, to gravimetric water content (kg/m^3) produced by the simulation, the following formulae were used:

$u = \frac{M_w}{M_t}$ and $M_t = M_w + M_{dry}$

Where:

u = Gravimetric moisture content (%)

M_w = Gravimetric water content (kg/m^3)

M_{dry} = Dry density of timber (kg/m^3)

Giving $M_w = \frac{M_{dry} \text{ x } u}{1-u}$

As the majority of UK timber-framed buildings are primarily constructed of oak, a dry density of 720kg/m^3 was used (TRADA, 2015b).

11.3.5 Effects of Orientation

Following the initial round of simulations of all 13 panels with a southwest orientation, the simulations were repeated with the panels facing each of the cardinal points. This allows for the study of the effect of exposure to climatic factors that differ according to orientation, such as wind-driven rain and solar radiation. The results of these simulations are presented in section 11.5.4.

11.3.6 Effects of Climate

To broaden the study beyond those timber-framed buildings located in Herefordshire, five further sites were chosen across England. Each location was chosen to be representative of areas where timber-framed construction is common, except in the case of Hawkshead in Cumbria where only one timber-framed building survives. This location was included to study the effect of a colder, damper climate and identify any specific challenges that this might present. The choice of sites also covers all case studies contained in this thesis. The locations are shown on a map of southern Britain showing the distribution of timber-framed buildings (Figure 283).

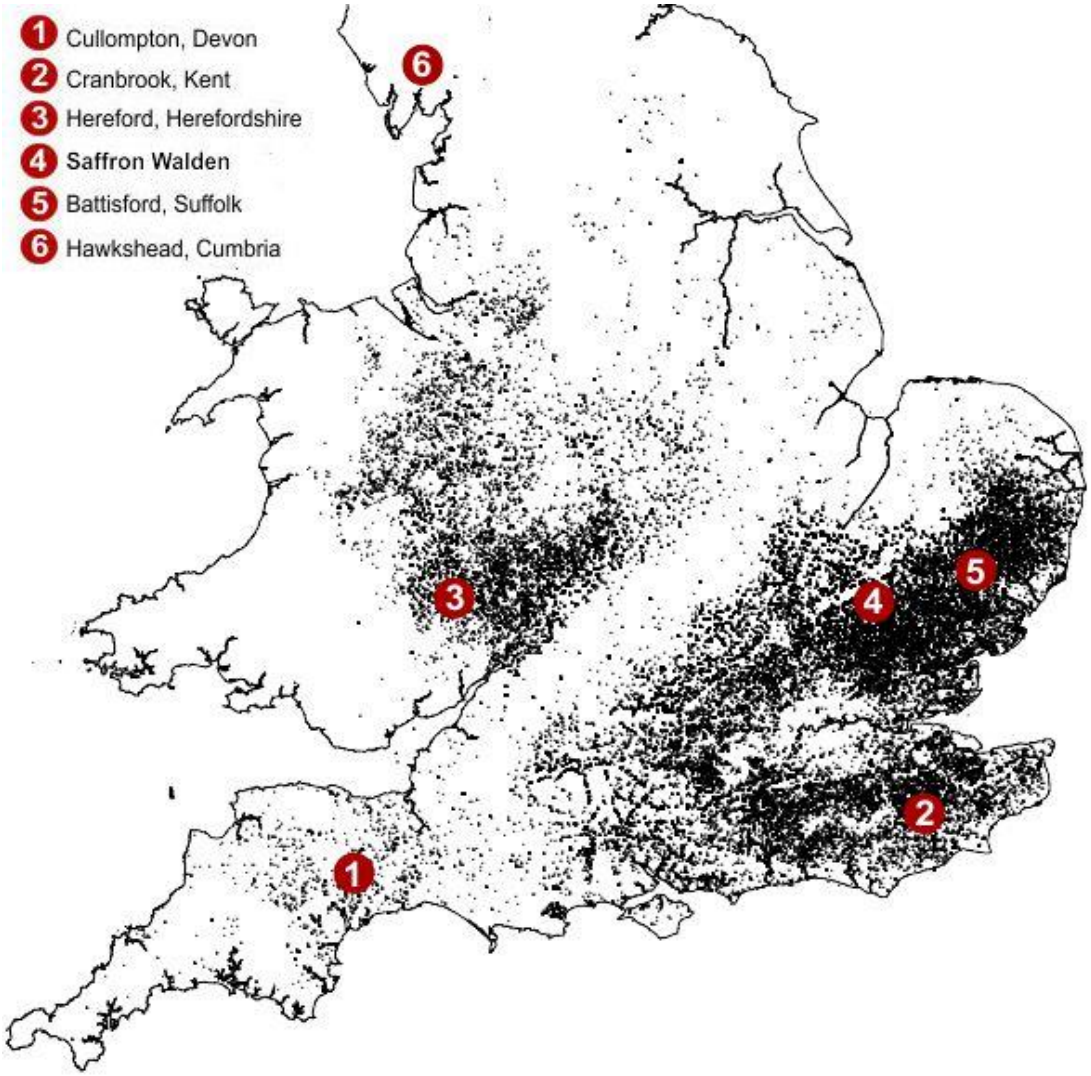

Figure 283. Location of simulations overlaid on distribution of surviving timber-framed buildings. Source: (Author's own, 2017).

Weather files were created for each of these locations using Meteonorm™ software version 6.1. These were then used to compare the six climates, focusing on air temperature, relative humidity and precipitation. Subsequently the weather files were used to repeat the WUFI® Pro 5 simulations for the 13 panels with a southwest orientation. The results of these simulations are presented in section 11.5.5.

11.4 Limitations of Simulations

Before reviewing the results, it is important to discuss the limitations of the simulations. These limitations relate to the software used for simulation WUFI® Pro 5 and the weather data generated using the software Meteonorm™.

11.4.1 Limitations of WUFI® Pro 5

As with any simulation, the results obtained are only an approximation and do not fully represent the reality of the conditions within a real wall. WUFI® Pro 5.3 simulates the transient interstitial hygrothermal conditions, in only one dimension, between idealized, homogeneous, continuous layers. This one dimensionality cannot simulate the critical junctions between frame and panel, nor the heterogeneous, non-continuous layers that are the reality of real-life infill panels. For example the wattlework in a wattle and daub panel must be simulated either as a continuous layer of timber or by ignoring the withies and staves entirely. To some extent, these limitations can be overcome by the use of Fraunhofer's WUFI 2D-3 and as previously mentioned this is an interesting area for future research. However, other limitations would remain due to the limited material database provided with the WUFI software. Whilst the database is quite extensive, no specific database for UK products nor UK historical construction materials exists. Substitutions for equivalent materials, principally from Germany, must therefore be made. A full list of materials used for simulation is presented in Appendix H.

11.4.2 Limitations of weather data

As previously stated, the weather files used for these simulations were all generated using the software Meteonorm™ as such the same limitations as described in the previous chapter, section 10.1.3 also apply.

11.5 Results and analysis

There follow the results of the initial simulations of the 13 construction details with a southwest orientation using the Hereford weather file.

11.5.1 Risk of Interstitial Condensation

The results of the simulations would suggest that none of the proposed constructions had the risk of interstitial condensation. At times, the interstitial temperature did drop close to the dew-point (Figure 284) but at no time did it drop below.

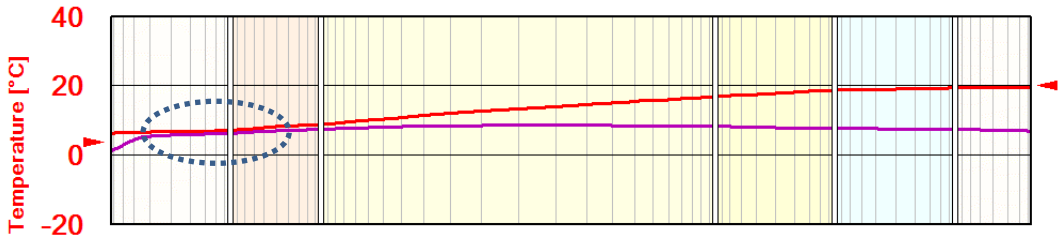

Figure 284.Screen shot from WUFI® for detail E1b showing interstitial temperature (red) and dew-point temperature (purple) almost touching but not crossing. Source: (Author's own, 2017)

11.5.2 Total Water Content

11.5.2.1 Drying time

The time taken to reach annual moisture equilibrium is presented in Figure 285. This shows that the wattle and daub (S1a&b) and the hemp-lime (HC1) have the longest drying times, the hemp lime (HC1) taking 118 days, almost 4 months. When the start date of the simulation was moved from 1st October to 1st June this reduced the drying times by 63% for S1a, 50% for S1b and 54% for HC1. This highlights the need for retrofit work, especially that using materials with high built-in moisture contents, to be programmed to allow drying over the summer months.

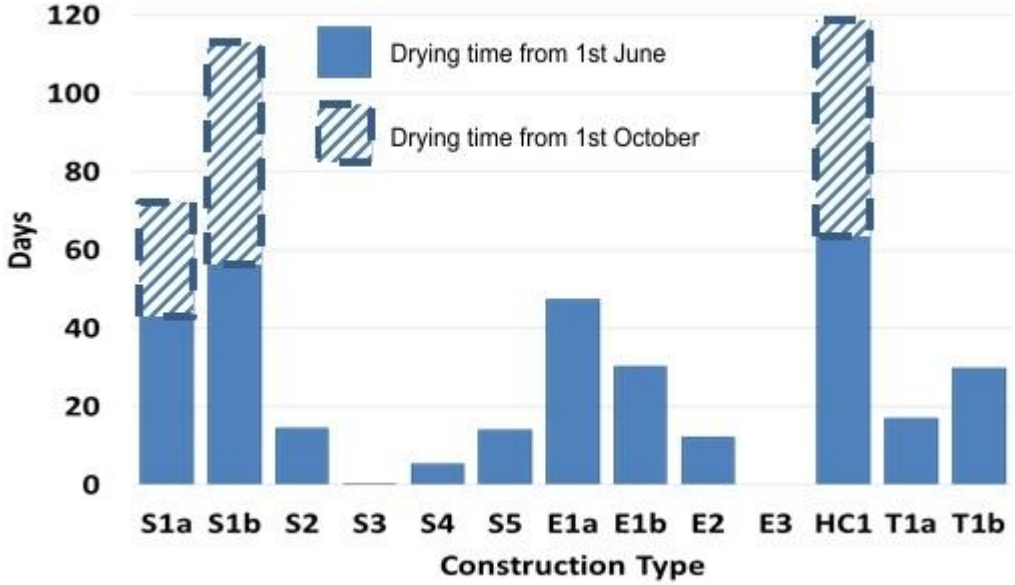

Figure 285. Drying period for constructions. Source: (Author's own, 2017)

11.5.2.2 Total Water in 2nd Year

The total water content for the second year of simulation, once annual moisture equilibrium has been attained, are presented in Figure 285. This shows that the two internally insulated details as proposed by English Heritage (E2 & E3) have higher total water contents for approximately half the year, with an average of 5.6 kg/m^2, reaching a maximum of 12.7 kg/m^2.

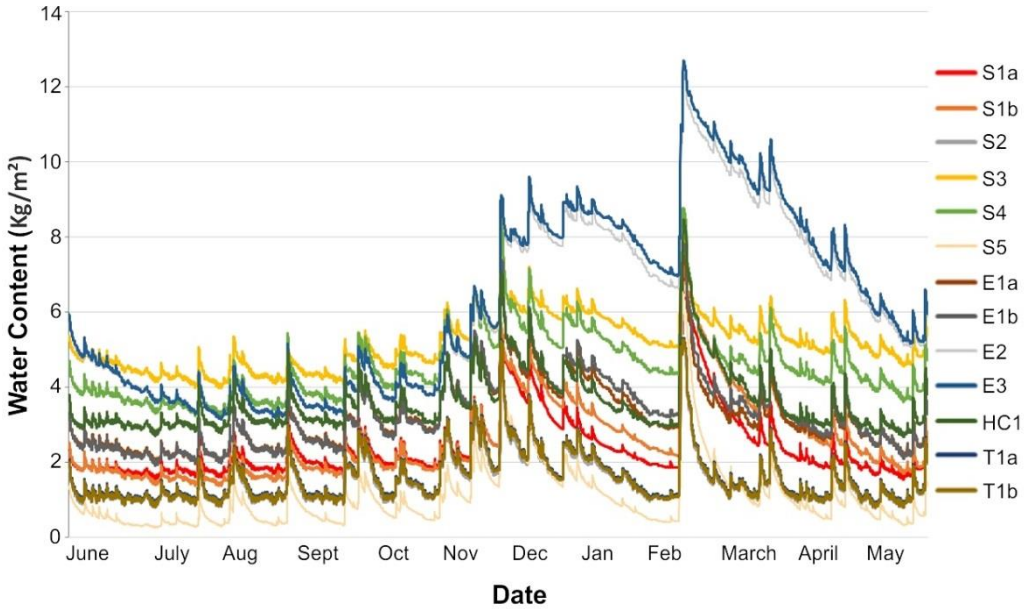

Figure 286. Total water content of constructions in second year of simulation, with south-westerly orientation in Herefordshire. Source: (Author's own, 2017).

Additional simulations were conducted to assess the influence of insulation thickness on water content for details E2 & E3. These showed that total water content increases with insulation thickness, with a 19% increase in average total water content when the insulation thickness is doubled from 50mm to 100mm, and a further 25% increase in average total water content when the thickness is doubled again. The increase in moisture content was principally confined to the historic fabric. This is due to the cooling of the external wattle and daub reducing its ability to dry out. No potential threat of interstitial condensation was identified by these additional simulations. Even when internal insulation was increased to 200mm there remained a difference between temperature and dew-point of +0.25˚C.

The second highest total water content was seen in the SPAB details with artificial insulation used in conjunction with wood-wool and vapour barriers (S3 & S4), with an average total water content of 4.9 kg/m^2, reaching a maximum of 8.8 kg/m^2. Interestingly the hemp-lime construction (HC1), once it has dried, has a similar total water content (average 3.5 kg/m^2) to the English Heritage replacement infill details (E1a&b) (both 3.1 kg/m^2).

There are conflicting results with regards to the inclusion of membranes in the build-up. In the case of E1a&b the introduction of an internal vapour barrier and external breather membrane (E1a) results in marginally lower water content during winter months. However, the introduction of a vapour barrier on the inside of a traditional wattle and daub wall (S1b) has the inverse effect, with higher water content in winter. It should be noted that the simulation obviously assumes a perfectly fitted vapour barrier with no holes and research by the Fraunhofer Institute has shown that just a 1mm hole can increase the moisture transfer by 1600 times (Thorpe, 2010 p.44).

The four details with the lowest total water content are the SPAB detail with glass fibre, metal lathe and lime plaster (S2), the two cork details (T1a&b) and the SPAB detail for insulating retained brick nogging (S5). The latter being the lowest. The addition of 2mm of lime mortar between the cork layers in T1b made negligible difference, with an increase of 0.05kg/m^2 total moisture content.

That brick infill has the least total water content would appear to go against anecdotal evidence that suggests that brick nogging is a poor infill material, holding damp and promoting decay (Reid, 1989, Harris, 2010). This highlights the fact that the simulation is only concentrating on the moisture moving between, and held within, the homogenous, continuous layers of the infill materials. It is not reflecting the moisture movement and accumulation that could occur at the junction with the timber frame, nor what occurs when layers are heterogeneous and non-continuous as in the case of the brickwork. For this reason, physical monitoring is an important area for future research.

11.5.3 Risk of Biological Attack

The comparison between the simulated interstitial hygrothermal conditions and the conditions that are favourable for the growth of fungi and infestation by insects (Figure 287) would at appear to suggests that there exists some risk of insect infestation from the Deathwatch Beetle (*Xestobium rufovillosum*), the Powderpost Beetle (*Lycus linearis Goeze & Lyctus brunneus*), the House Longhorn Beetle (*Hylotrupesw bajulus*) and from Woodworm (*Anobium punctatum*) but not from fungal decay. There follows a more detailed analysis of the risk from each of the beetles.

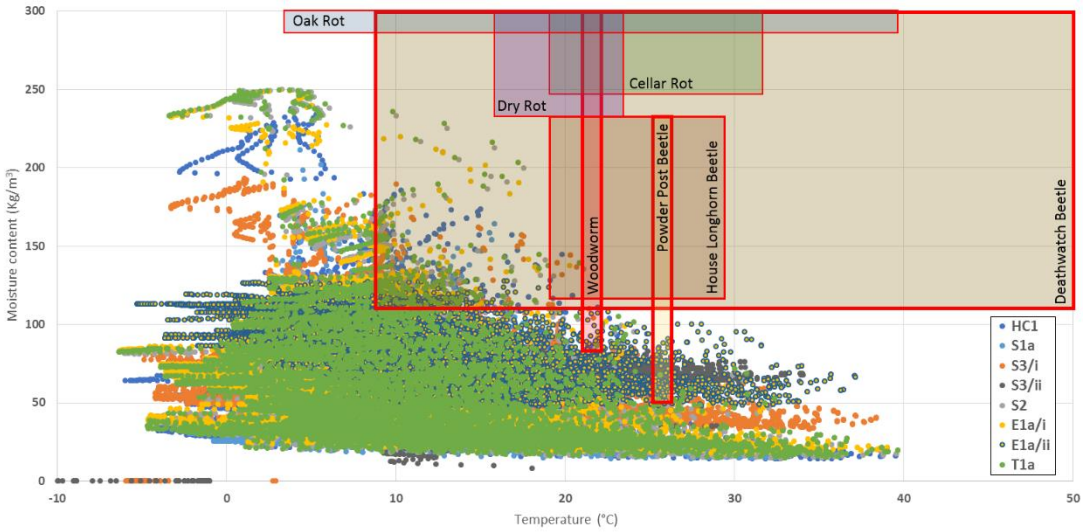

Figure 287. Simulated Hygrothermal conditions for southwest facing panels in Hereford with favourable conditions for biological attack highlighted. Source: (Author, 2017)

1.1.1.1. Deathwatch Beetle (*Xestobium rufovillosum*)

Figure 288 shows the number of hours that suitable hygrothermal conditions exist for the survival of the deathwatch beetle in each of the thirteen simulations.

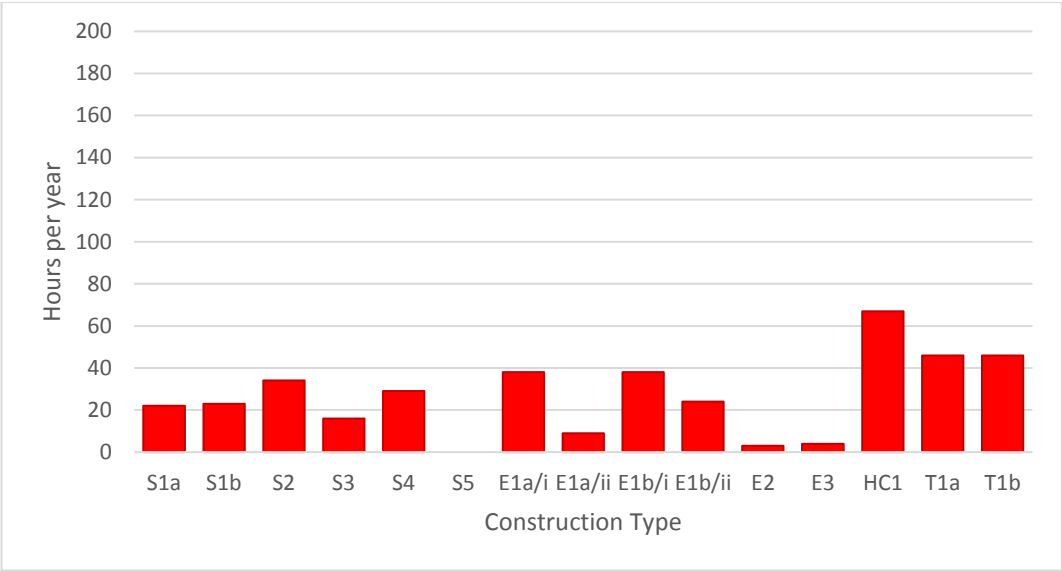

Figure 288. Presence of hygrothermal conditions favourable for Deathwatch Beetle infestation. Source: (Author's own, 2017)

The construction with the greatest potential risk of attack is the hemp-lime (HC1) with 67hrs per annum of favourable conditions in the external lime plaster layer. These hours are spread over 15 instances, the duration of which range from 1 to 14hrs, with an average of 4.5hrs. During the initial drying period, which was studied separately, an instance of prolonged favourable hygrothermal conditions lasting 39hrs was also identified.

The cork board details (T1a&b) have the second highest potential risk of attack with 46 and 45hrs respectively. These hours are spread over 10 instances, with a 4.6hrs average duration, the longest being 14hrs and shortest only one. In the case of the English Heritage replacement infill details (E1a and b) the potential risk spreads from the external render (E1a/i and E1b/i), into the underlying layer of wood-wool board (E1a/ii and E1b/ii). The detail with an external breather membrane (E1a/ii) has 8hrs of favourable conditions within this secondary layer, whilst that without a membrane (E1b/ii) has three times this with 23hrs spread over 5 instances per year with a duration ranging from 2 to 9hrs, and an average of 5.75hrs. The occurrence of these conditions deeper within the construction may or may not be of greater concern. On the one hand, the area in question is less accessible

to the insects, however once there they will be protected from the elements, predators and detection, and it may therefore provide an ideal incubation site. This also highlights the importance of the vapour permeability (or breathability) of the construction to allow any moisture trapped within to dry out.

It is also interesting to note that the high water content identified in section 11.5.2.2 in the Historic England internal insulation details (E2 and E3) does not translate to a risk from deathwatch beetle and in fact these two constructions have the second lowest risk, second only to the construction with brick nogging. This is due to the higher thermal mass of the external substrates (brick and wattle-an-daub) which prevent the higher temperatures seen in those plaster layers over lightweight insulation.

Overall, there appears to be no serious risk posed by these constructions with a South-westerly orientation in Herefordshire. Given that this beetle can only infest sapwood and wood already modified by fungi (McCaig and Ridout, 2012), the threat is already minimal and none of the details present a sufficient duration of favourable conditions to allow the gestation of the insects eggs.

1.1.1.2. Powderpost Beetle (*Lycus linearis Goeze & Lyctus brunneus*)

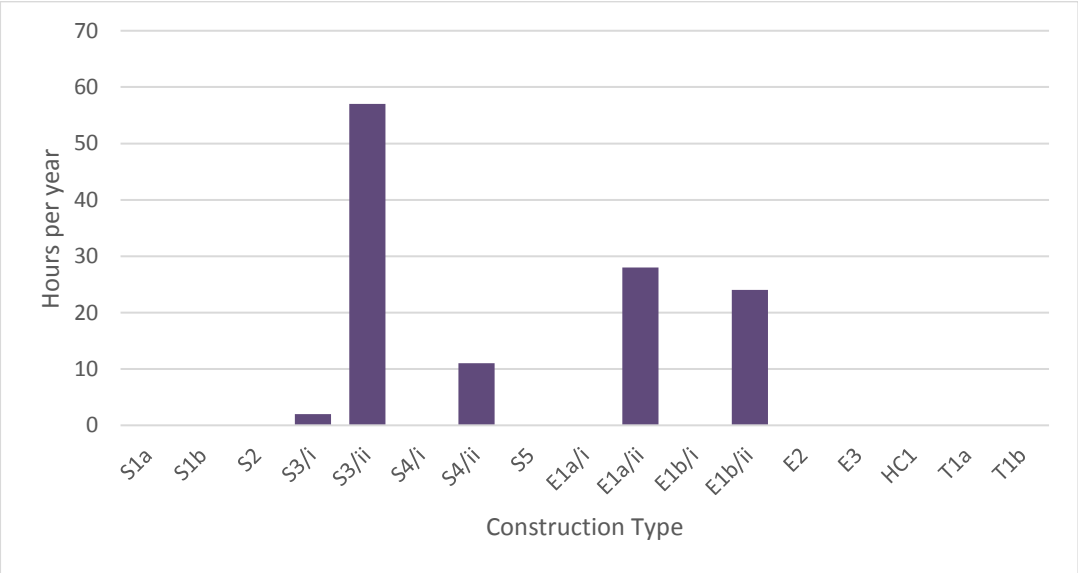

Figure 289. Presence of hygrothermal conditions favourable for Powderpost Beetle infestation. Source: (Author's own, 2017)

With the threat from powderpost beetle (Figure 289)[64] the conditions occur only in a few of the constructions and always in the second layer in from the external face. The construction with the highest risk from powderpost beetle is the SPAB detail with glass wool insulation (S3) where 2hrs of favourable conditions exist in the external render and 57hrs within the mineral wool. These 57hrs occur sporadically over 44 instances with an average duration of 1.3hrs, a maximum of 5hrs and a minimum of 1hr, occurring in the afternoon when direct solar radiation falls on the panel face, heating the layer of lime plaster overlying the thermal insulation. The Historic England replacement infill details (E1a and E1b) suffer the same problem although with a reduced frequency, with the detail with breather membranes (E1a) registering a total of 28hrs over 21 instances with an average duration of 1.3hrs, a maximum of 4hrs and a minimum of 1hr. The detail without breather membranes (E1b) registers 24hrs, over 20 instances with and average duration of 1.1hrs, a maximum of 2hrs and a minimum of 1hr. The only other panel with favourable conditions for powderpost beetle is the SPAB detail with polyurethane foam insulation (S4) and this is only for 11hrs over 8 instances with an average duration of 1.4hrs, a maximum of 2hrs and a minimum of 1hr.

[64] Note the reduced scale of y-axis from that used for Deathwatch beetle

1.1.1.3. House Longhorn Beetle (*Hylotrupesw bajulus*)

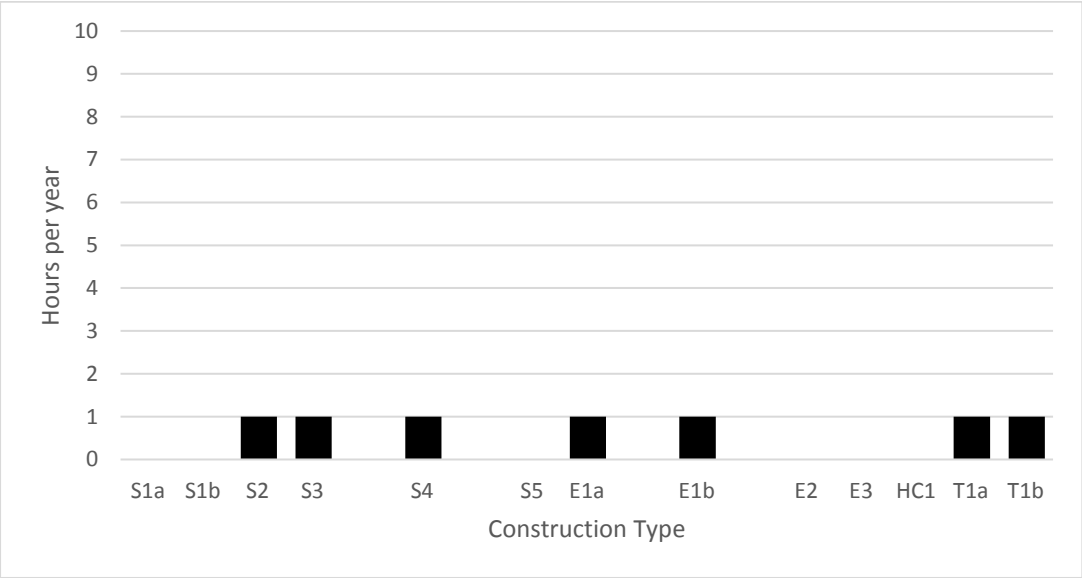

Figure 290. Presence of hygrothermal conditions favourable for House Longhorn Beetle infestation. Source: (Author's own, 2017)

The occurrence of conditions favourable to House Longhorn Beetle (Figure 290)[65] is very low with only one hour of suitable hygrothermal conditions arising over the simulated year in seven of the constructions.

1.1.1.4. Woodworm (*Anobium punctatum*)

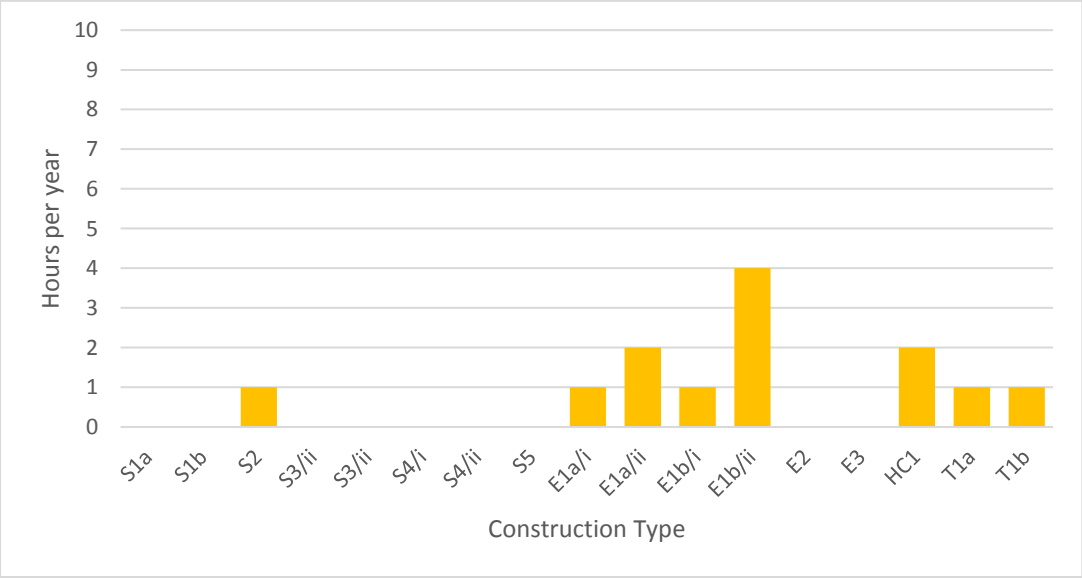

Figure 291. Presence of hygrothermal conditions favourable for Woodworm infestation. Source: (Author's own, 2017)

[65] Note y-axis reduced again

A similar pattern is seen with the conditions favourable to Woodworm (Figure 291), although the total number of hours rises to four in the case of the woodfibre insulation layer of the Historic England detail with no vapour barrier (E1b/ii), with these occurring as 4 separate instances.

1.1.1.5. Biological threat: Summary

Therefore out of all the potential biological risks it would appear that the deathwatch beetle (*Xestobium rufovillosum*) followed by the powderpost beetle (*Lycus linearis Goeze & Lyctus brunneus*) are the two biggest threats, however even for these, the occurrences of favourable hygrothermal conditions are sporadic and of very limited duration. As such, this simulation would suggest that none of the proposed panel details would create conditions that put the historic fabric in danger for a southwest facing panel in Hereford. That said, it should be noted the limitations of this simulation previously stated. There follows a review of the results obtained from simulation of different orientations of these panels with the Hereford climate file.

11.5.4 Effect of Orientation

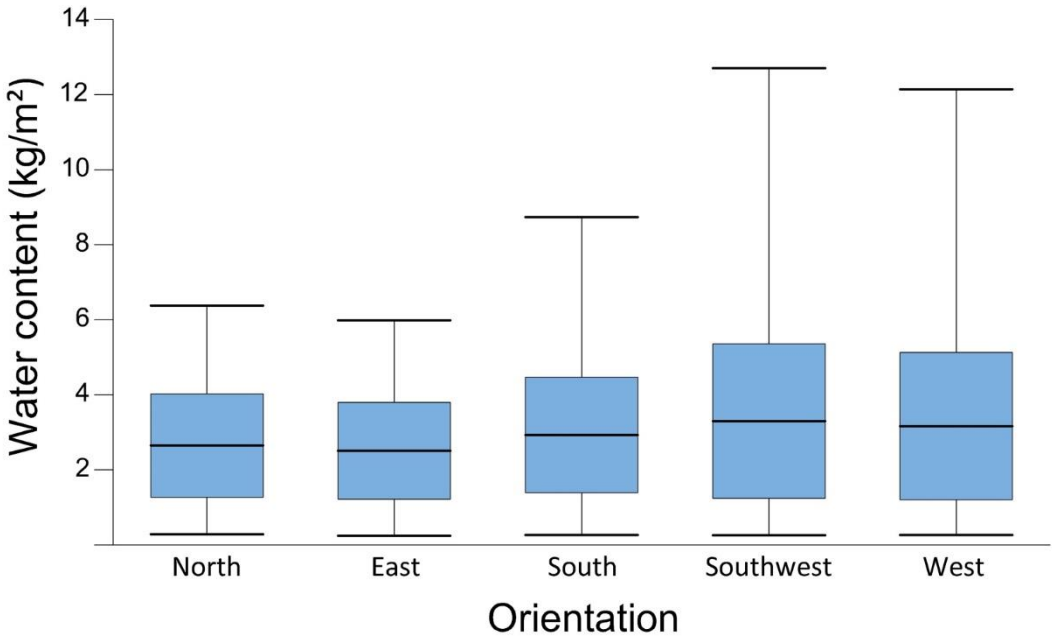

Figure 292. Water content of all panel details, showing maximum, minimum, average and standard deviation for five orientations in Herefordshire. Source: (Author's own, 2017)

Figure 292 shows the average, maximum, minimum and standard deviation for the water content of all 13 of the replacement infill panel details with 5 different orientations, simulated using the weather file for Herefordshire. The orientations simulated are the cardinal points and the previously presented south-westerly orientation. This clearly shows that the assumption that the south-westerly orientation does have an overall higher water content due to the wind driven rain, with an average of 3.3kg/m², a maximum of 12.7kg/m², a minimum of 0.3 kg/m² and a standard deviation of 2.1 kg/m². The westerly orientation has the second highest maximum and average, followed by the southerly. The easterly orientation has the lowest overall moisture content with an average of 2.2 kg/m², a maximum of 5.8 kg/m², a minimum of 0.2 kg/m² and a standard deviation of 1.3 kg/m².

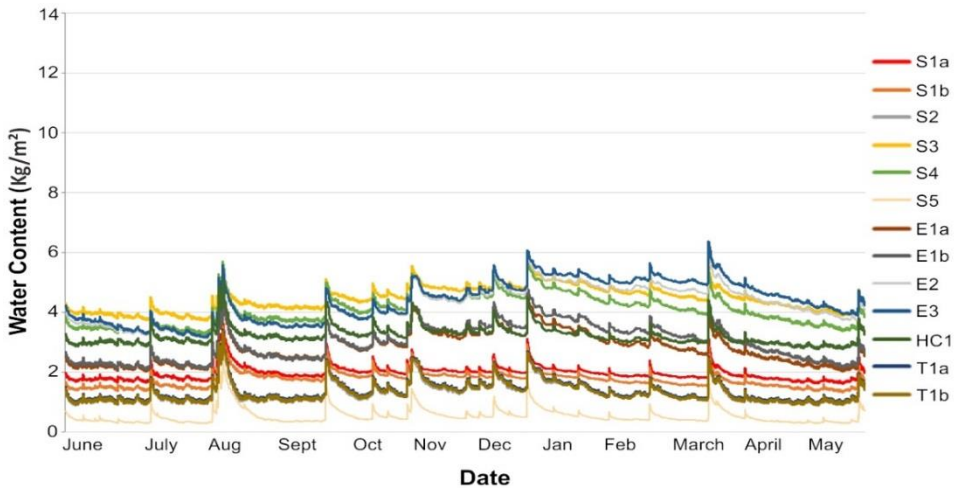

Figure 293. Total water content of constructions in second year of simulation, with Northerly orientation in Herefordshire. Source: (Author's own, 2017).

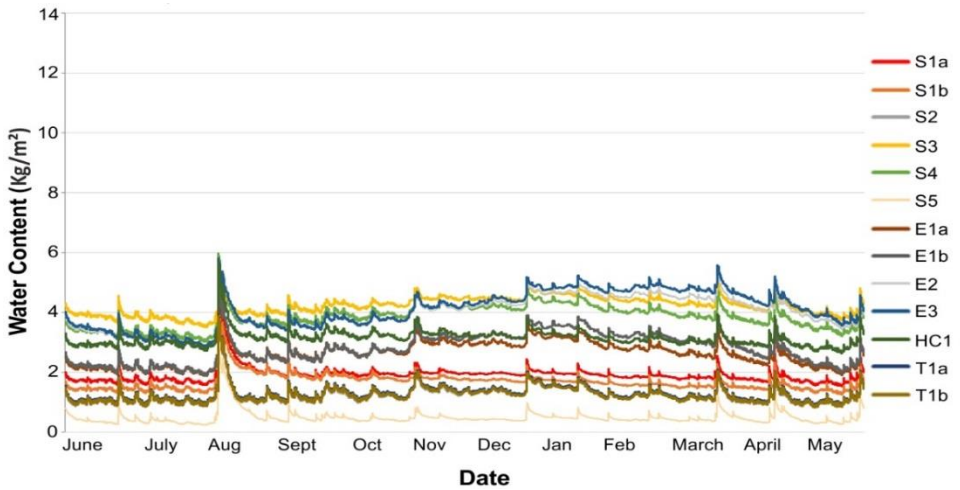

Figure 294. Total water content of constructions in second year of simulation, with easterly orientation in Herefordshire. Source: (Author's own, 2017).

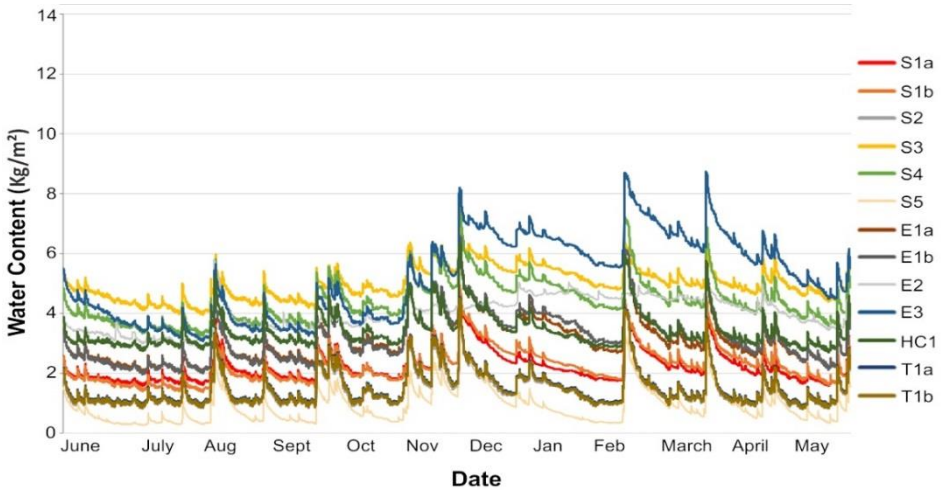

Figure 295. Total water content of constructions in second year of simulation, with southerly orientation in Herefordshire. Source: (Author's own, 2017).

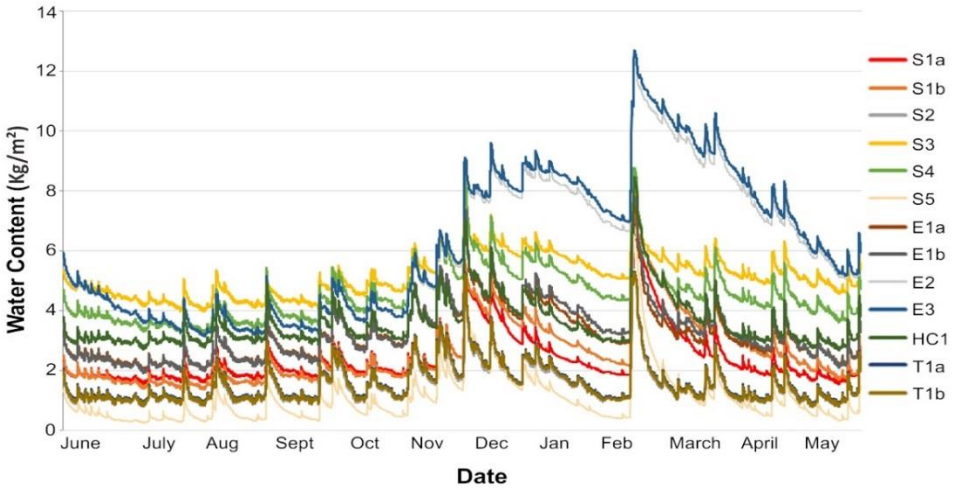

Figure 296. Total water content of constructions in second year of simulation, with south-westerly orientation in Herefordshire. Source: (Author's own, 2017).

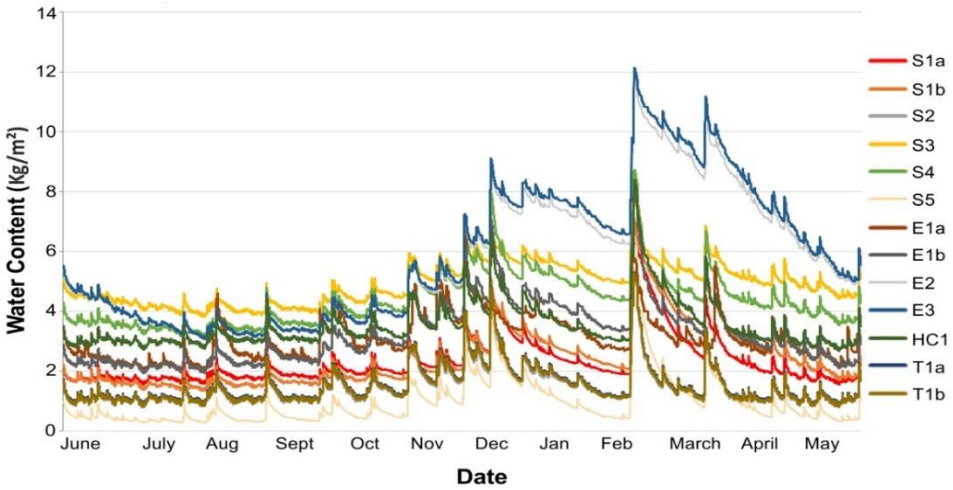

Figure 297. Total water content of constructions in second year of simulation, with westerly orientation in Herefordshire. Source: (Author's own, 2017).

When looking at the annual pattern of total moisture content for the panel details for each orientation it can be seen that the northerly and easterly orientations do not demonstrate the high peaks in late February caused by wind-driven rain, as shared by the south-westerly, westerly and to a lesser extent southerly orientations. The northerly and easterly do present a well-defined increase in total moisture content in August. Looking at the interstitial thermal conditions at this precise time (Figure 298) it can be seen that the temperature and dew-point temperature are practically touching in the external plaster layer, suggesting the presence of interstitial condensation. Given that no rainfall was being simulated at this time, it is clear that in this instance the increase in water content is due to interstitial condensation.

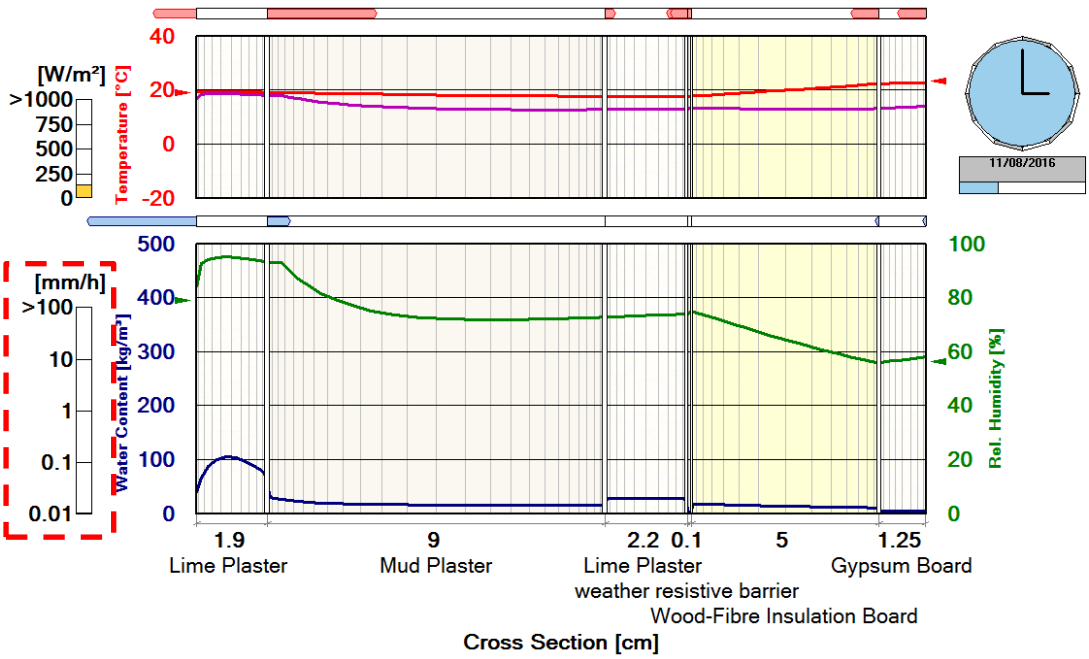

Figure 298. Screen shot of WUFI® animation of detail E3 with northerly orientation in Herefordshire on 11/08/2016 showing increased moisture content due to interstitial condensation in external lime plaster (left). Lack of rain highlighted. Source: (Author's own using WUFI® Pro5, 2017)

The total number of hours where favourable conditions for the biological threats are created for the different orientations are presented in Figure 299.

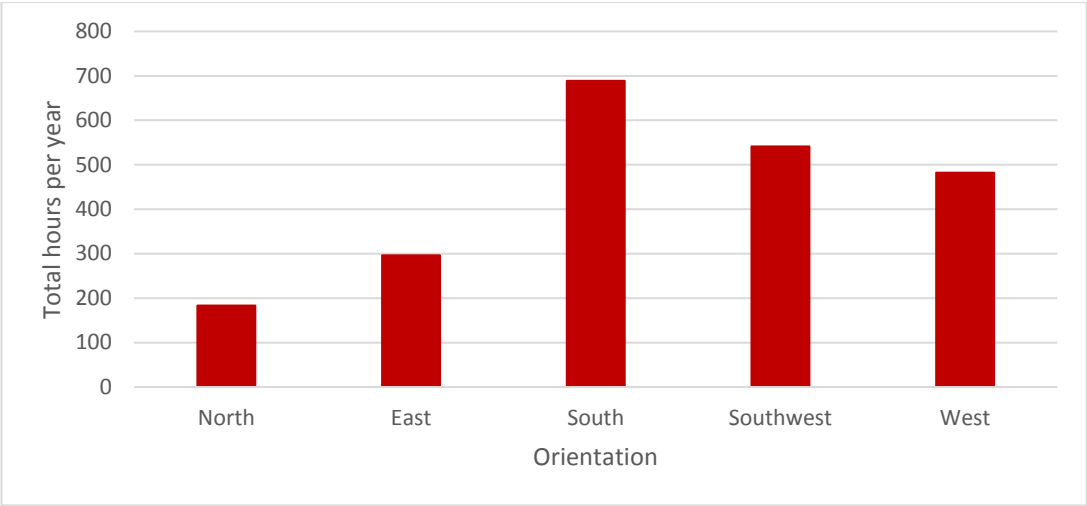

Figure 299. Total hours per year where hygrothermal conditions for biological attack are produced in all 13 panels, dependant on orientation in Herefordshire. (Source: (Author's own, 2017)

It had been assumed that the greatest risk would exist for southwest facing panels due to this being the prevailing direction for wind-driven rain for this location. However it can be seen that overall the panels facing south (Figure 302) have more hours with hygrothermal conditions suitable for insect infestation, followed by those facing southwest and west. This highlights the importance of direct solar radiation in the creation of the required temperatures and not just the exposure to moisture.

There follows the details for each of the details according to orientation (Figure 300 to Figure 304) overleaf.

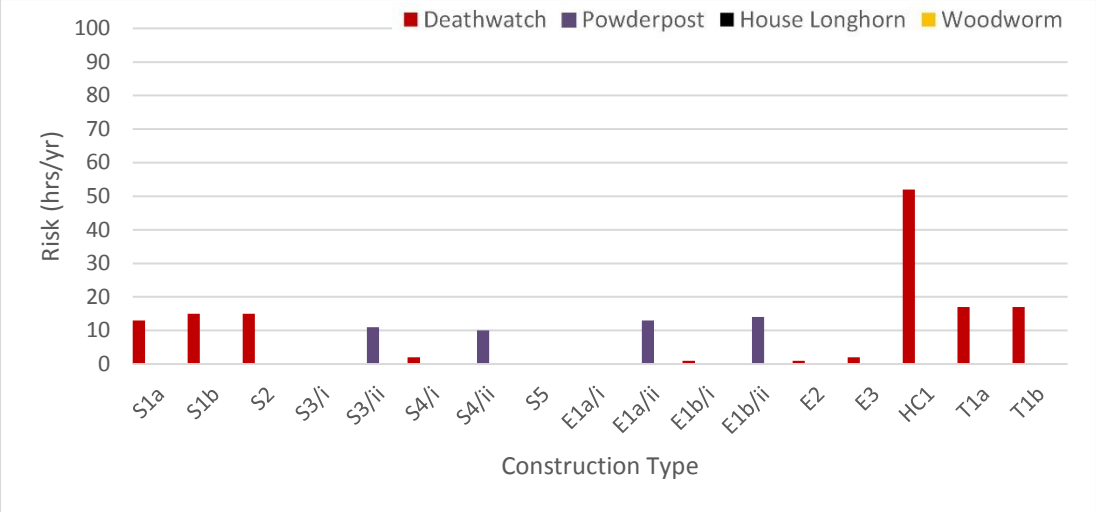

Figure 300. Risk of insect infestation for North facing panel in Hereford. Source: (Author's own, 2017)

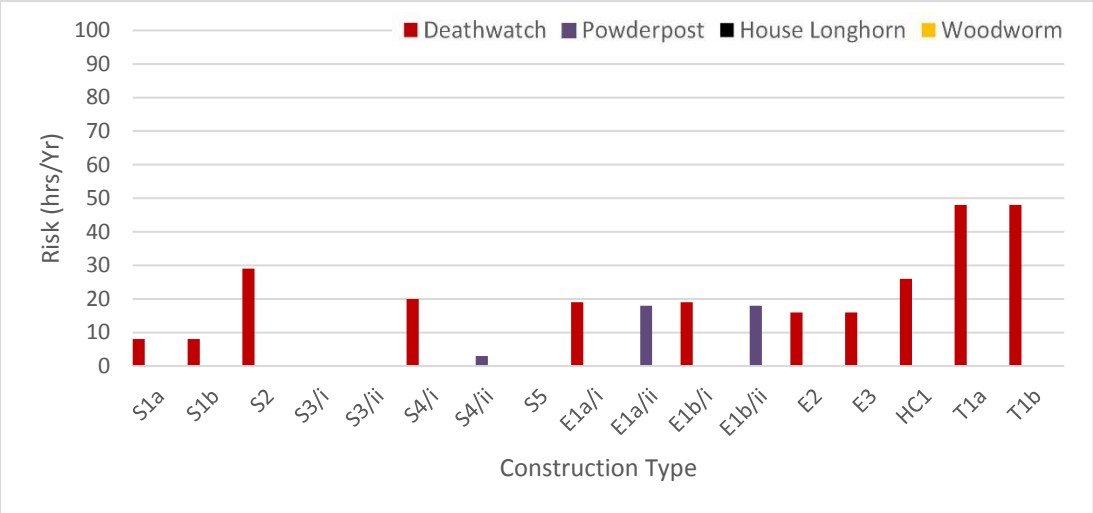

Figure 301. Risk of insect infestation for East facing panel in Hereford. Source: (Author's own, 2017)

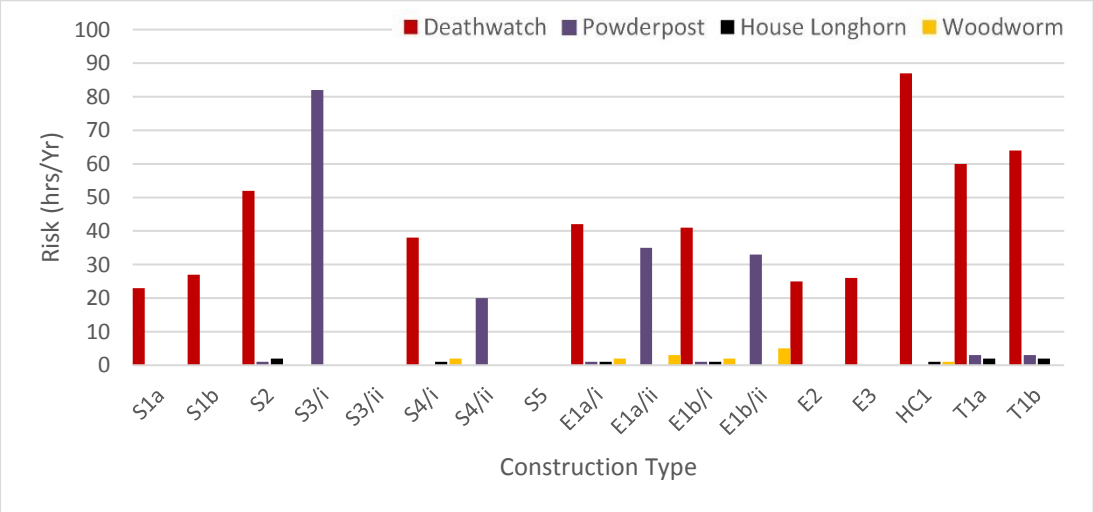

Figure 302. Risk of insect infestation for South facing panel in Hereford. Source: (Author's own, 2017)

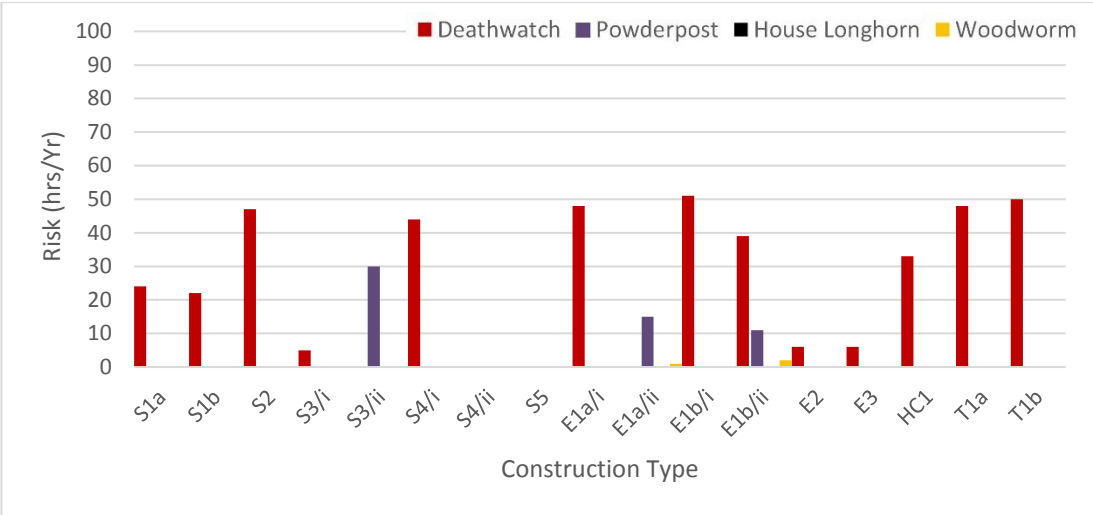

Figure 303. Risk of insect infestation for West facing panel in Hereford. Source: (Author's own, 2017)

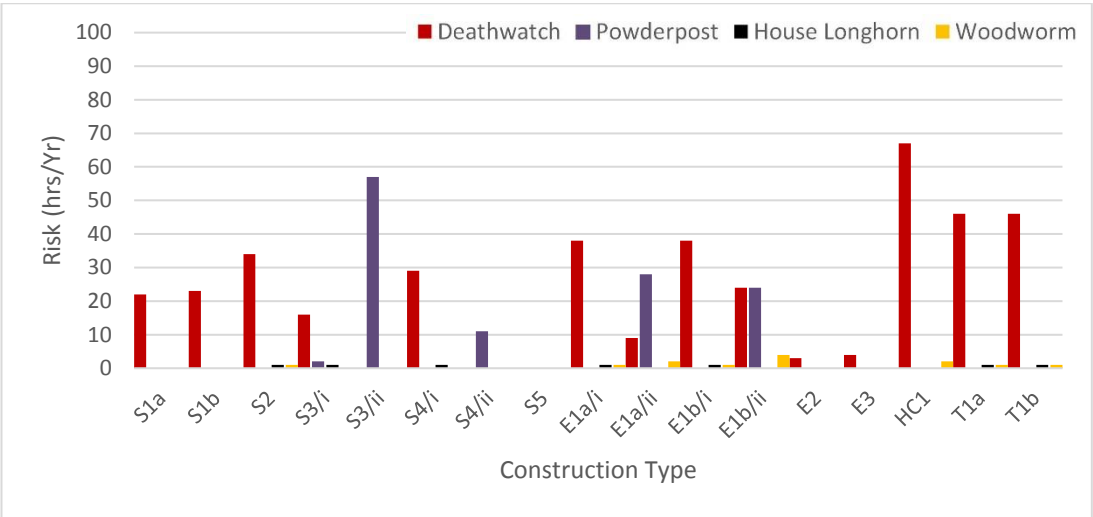

Figure 304. Risk of insect infestation for Southwest facing panel in Hereford. Source: (Author's own, 2017)

From these, it is interesting to note that for the Historic England details (E1a with membranes and E1b without membranes) a slightly higher risk of infestation from deathwatch beetles exists for west facing panels (Figure 303). These panels (E1a and E1b) are also the only ones that have a risk of infestation from powderpost beetle for all orientations, with this occurring in the second layer of construction (E1a/ii and E1b/ii), the woodfibre insulation. It should however be noted that even in the worst affected orientation, south facing, there are only favourable conditions for 0.4% of the year or 35 days, with these conditions being divided typically into sporadic events lasting one to two hours, with a maximum of only five consecutive hours. These durations are insufficient for

the gestation of the eggs, which takes 20 days (Ridout, 1999 p.41) and as such, no real risk is present.

When hygrothermal conditions for each orientation are plotted as temperature against moisture content (Figure 305-Figure 309) it can been seen how each one differs.

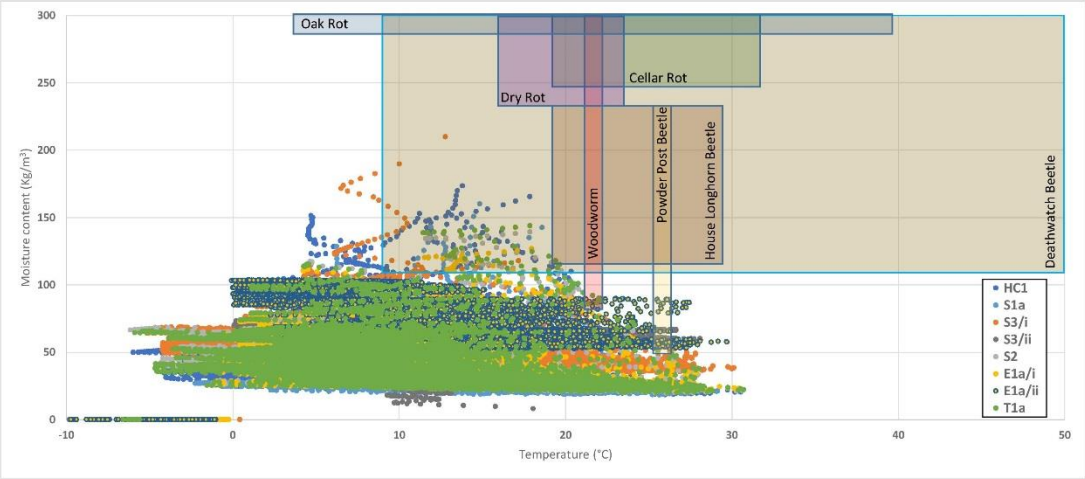

Figure 305. Simulated Hygrothermal conditions for north facing panels in Hereford with favourable conditions for biological attack highlighted. Source: (Author, 2017)

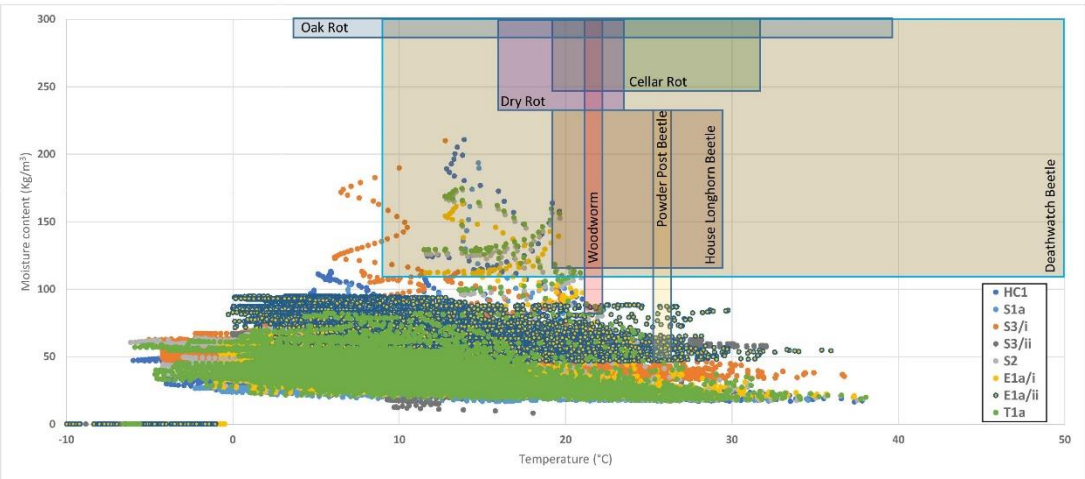

Figure 306. Simulated Hygrothermal conditions for east facing panels in Hereford with favourable conditions for biological attack highlighted. Source: (Author, 2017)

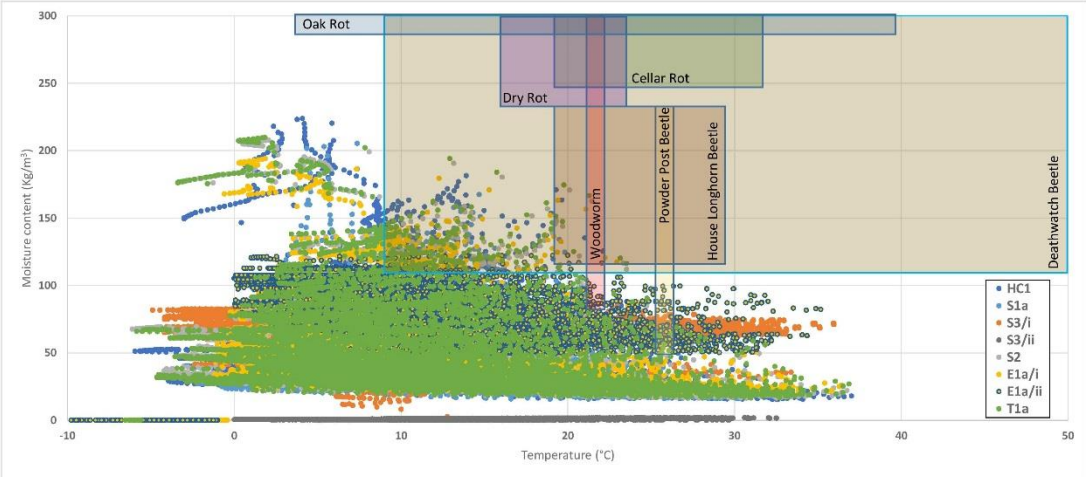

Figure 307. Simulated Hygrothermal conditions for south facing panels in Hereford with favourable conditions for biological attack highlighted. Source: (Author, 2017)

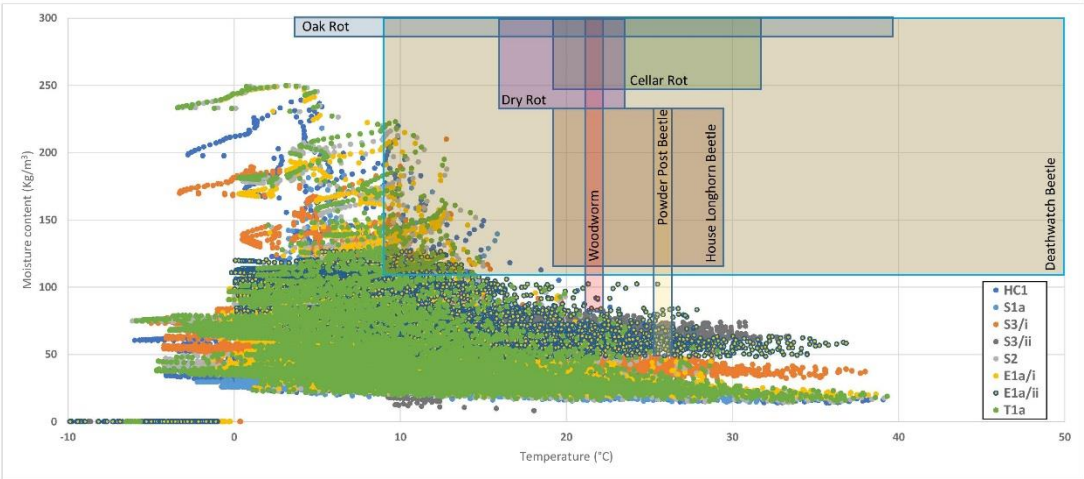

Figure 308. Simulated Hygrothermal conditions for west facing panels in Hereford with favourable conditions for biological attack highlighted. Source: (Author, 2017)

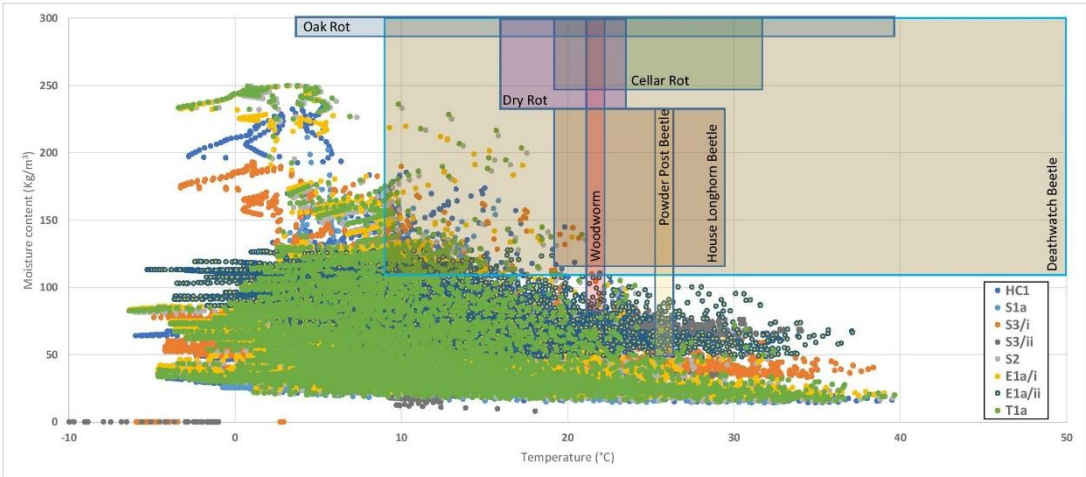

Figure 309. Simulated Hygrothermal conditions for southwest facing panels in Hereford with favourable conditions for biological attack highlighted. Source: (Author, 2017)

East facing panels have the lowest moisture content (Figure 306) with an average of 33kg/m², a maximum of 211kg/m², a minimum of 1.6kg/m² and a standard deviation of 13kg/m², followed by those facing north (Figure 305) with an average of 36 kg/m², a maximum of 173 kg/m², a minimum of 1.9 kg/m² and a standard deviation of 15 kg/m². This is perhaps to be expected as the Meteonorm™ climate data shows that the northeast is the orientation least affected by wind-driven rain in Britain. As would be expected the north facing panels (Figure 305) have the lowest maximum temperatures (30°C) due to lack of solar radiation. West (Figure 308) and southwest (Figure 309) have the highest moisture content (with averages of 42kg/m² and 44kg/m² respectively), however it is the south (Figure 307) and southwest (Figure 309) where higher temperatures (up to 40°C) combine with this higher moisture content to form a greater frequency of conditions favourable to insect attack.

In none of these simulations of varying orientation in Hereford were any conditions favourable for fungal growth detected.

11.5.5 Effect of Climate

There follows the results of the simulations of the six selected geographical locations across England. Figure 310 shows the climates generated using the software Meteonorm™ version 6.1 for each of the six locations. Saffron Walden in North Essex continues to have the warmest, driest climate with an annual average temperature of 11.5°C and an annual rainfall of 487mm, whilst Hawkshead in Cumbria has the coolest (9.6°C), dampest climate, with almost double the average annual rainfall (856mm).

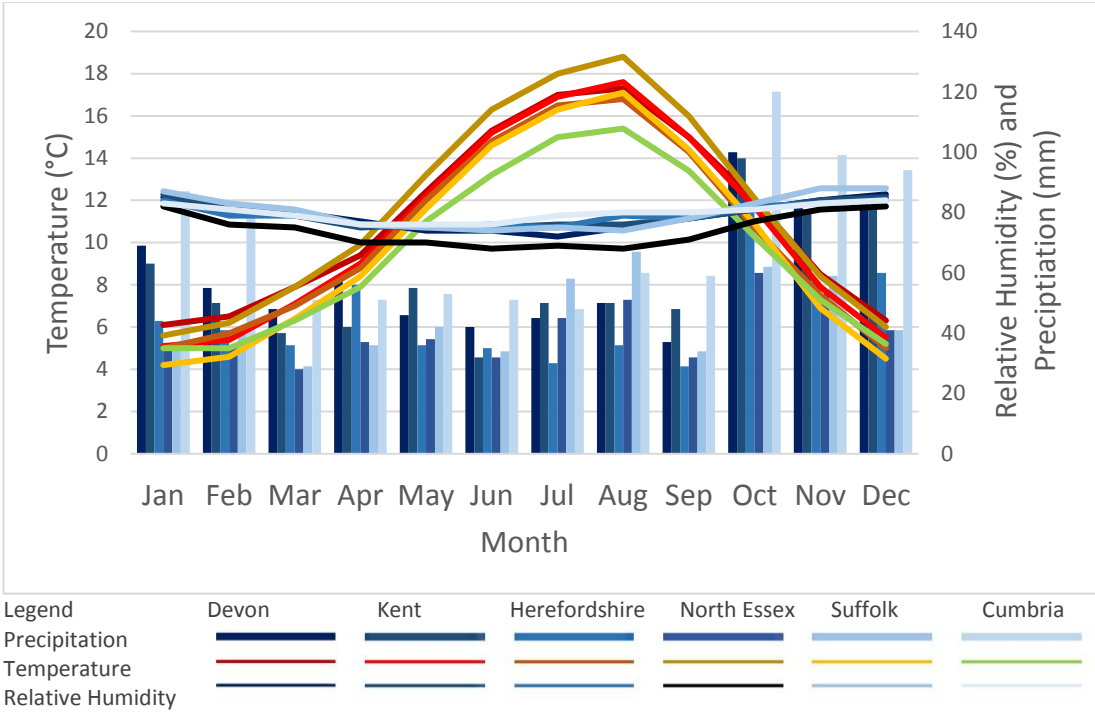

Figure 310. Climatic data for six English locations simulated. Source: (Author's own based on Meteonorm™ Version 6.1)

The other four locations are fairly similar in terms of average monthly temperatures and relative humidity. Cumbria has the highest precipitation in autumn, winter and spring, followed by Devon, which in fact exceeds Cumbria's rainfall in April. Kent follows a similar pattern to Devon with a slightly reduced rainfall. However, a very different pattern is seen in Battisford in Suffolk as previously noted (section 8.0.3) where the winter is relatively dry and the maximum levels of precipitation are experienced in the summer months, a pattern shared by Saffron Walden to a far lesser extent.

There follows the results of the simulations of southwest facing panels in each of these six locations (Figure 311 to Figure 316). This orientation was chosen due to the potential highest risk as shown by the previous section.

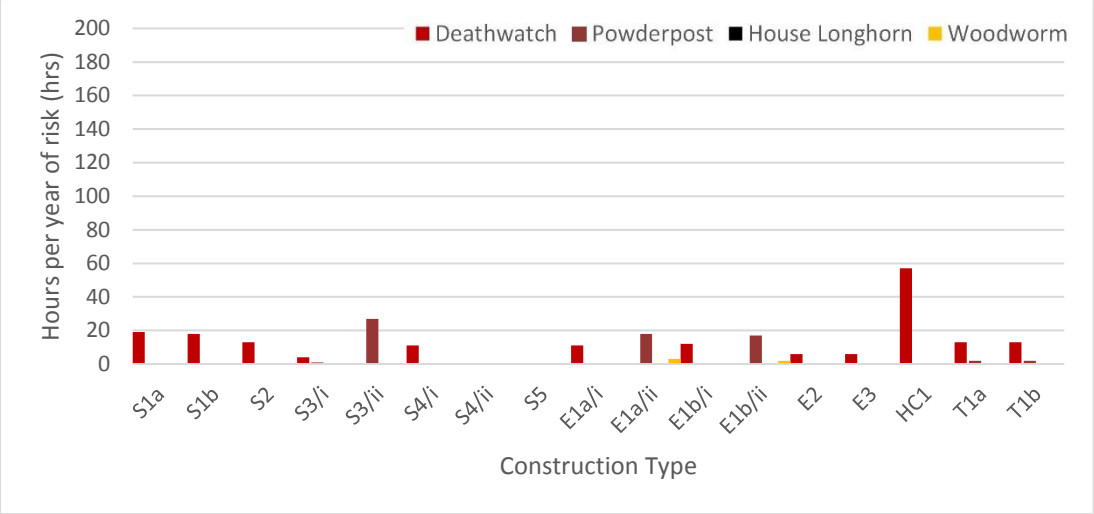

Figure 311. Risk of insect infestation for southwest facing panel in Cullompton, Devon. Source: (Author's own, 2017)

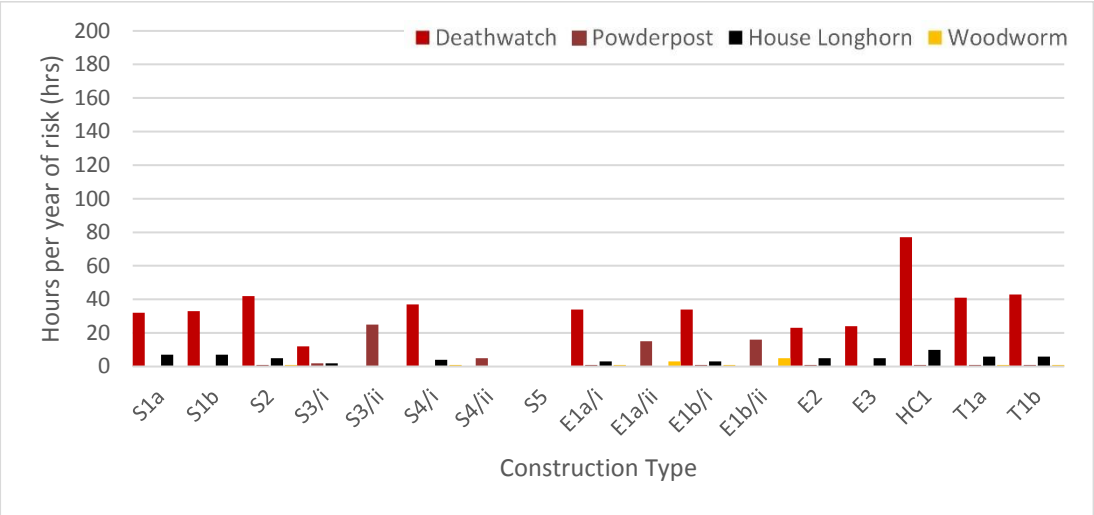

Figure 312. Risk of insect infestation for southwest facing panel in Cranbrook, Kent. Source: (Author's own, 2017)

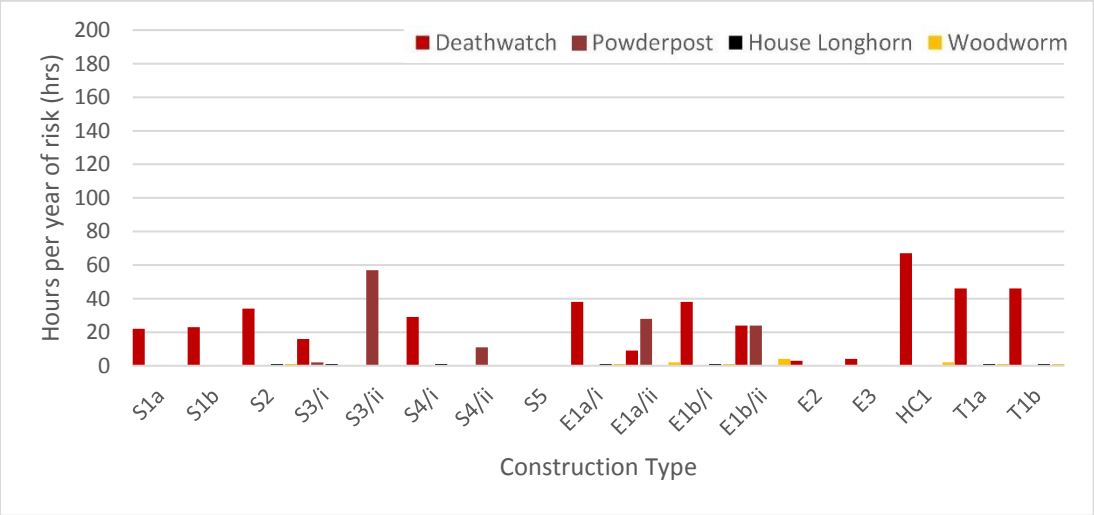

Figure 313. Risk of insect infestation for southwest facing panel in Hereford, Herefordshire. Source: (Author's own, 2017)

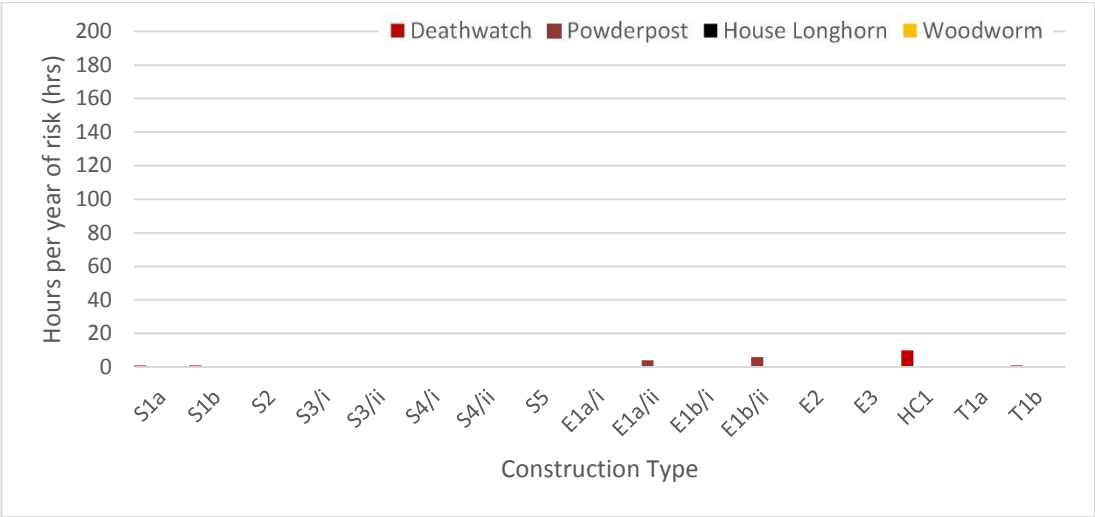

Figure 314. Risk of insect infestation for southwest facing panel in Saffron Walden, North Essex. Source: (Author's own, 2017)

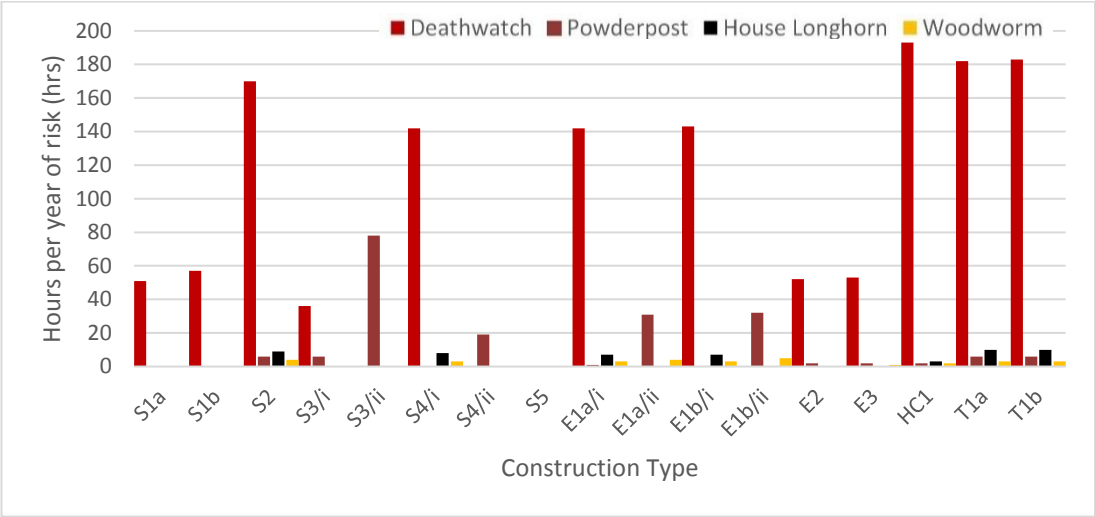

Figure 315. Risk of insect infestation for southwest facing panel in Battisford, Suffolk. Source: (Author's own, 2017)

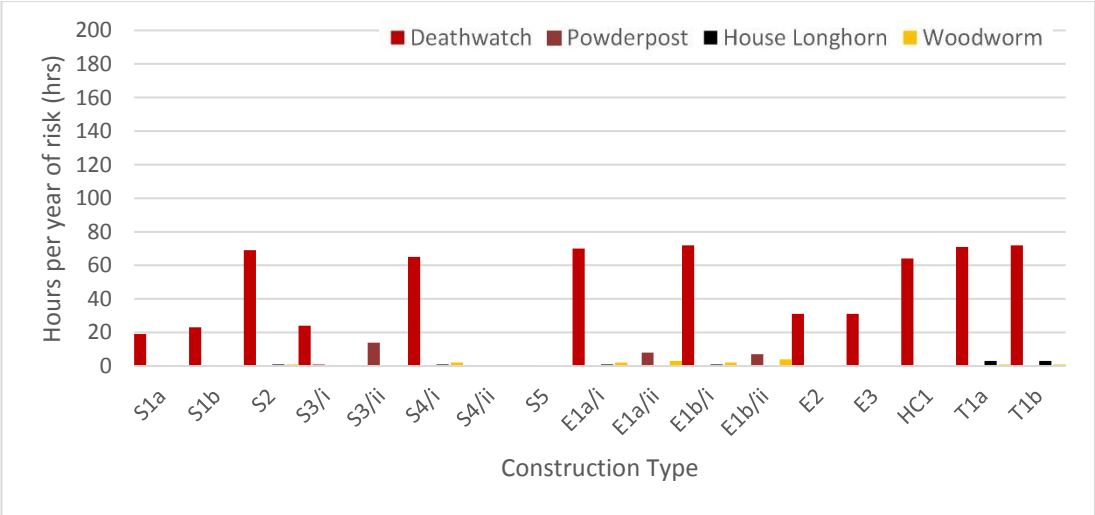

Figure 316. Risk of insect infestation for southwest facing panel in Hawkshead, Cumbria. Source: (Author's own, 2017)

The results of the simulations in the six different geographical locations show that the specific climate of the location has a major impact on the risk of biological attack. The location with the lowest risk is Saffron Walden in North Essex (Figure 314), whereas the location with the highest risk is Battisford in Suffolk (Figure 315). This is extremely interesting considering that the two locations are only 51km apart. The biggest difference between the two climates is the high levels of precipitation in Battisford in the summer months, July (58mm) and August (67mm) (Figure 310). This creates high moisture content (up to 248kg/m²) in the southwest facing panels coinciding with the summer maximum temperatures (19.3°C), thereby creating the warm moist conditions conducive to insect attack (Figure 317). It is interesting to note that East Anglia, where Battisford is located, has the highest concentration of plastered timber-framed buildings where the plaster completely covers the timbers, as noted in chapter 6. Perhaps this could be linked to the specific climatic conditions of this region and the increased risk of insect infestation. Currently there is some debate as to whether climate change will lead to increased summer rainfall. Overall the predictions point to lower precipitation levels in the summer (Environment Agency, 2014), however, there are suggestions that there may be an increase in hourly rainfall intensities due to convection induced precipitation (thunderstorms) (Kendon et al., 2014 p.570). If this is the case then the climate seen at Battisford may become more common across the country, thereby increasing the risk of biological attack. This is an interesting area for further research.

As seen previously in the simulations for Hereford, the most common risk across all six sites is from the deathwatch beetle, although in Cranbrook in Kent there appears a low-level risk from the House Longhorn Beetle across almost all of the different infill panels. For deathwatch beetle, the highest risk exists at Battisford with the hempcrete infill detail, where favourable conditions exist for a total of 193 hours over the simulated year, with the longest continual episode lasting 42 hours. Over all six sites hempcrete is the detail most at

risk, followed by cork, except in the case of Hawkshead in Cumbria where the Historic England detail with woodfibre insulation, both with and without membranes, produce more hours of favourable conditions for infestation with 70 and 72 hours respectively. Of these hours, 54 of them are consecutive.

The simulated hygrothermal conditions for the southwest panel using the Battisford, Suffolk, weather file is shown in Figure 317, with the conditions required for the survival of biological threats overlaid.

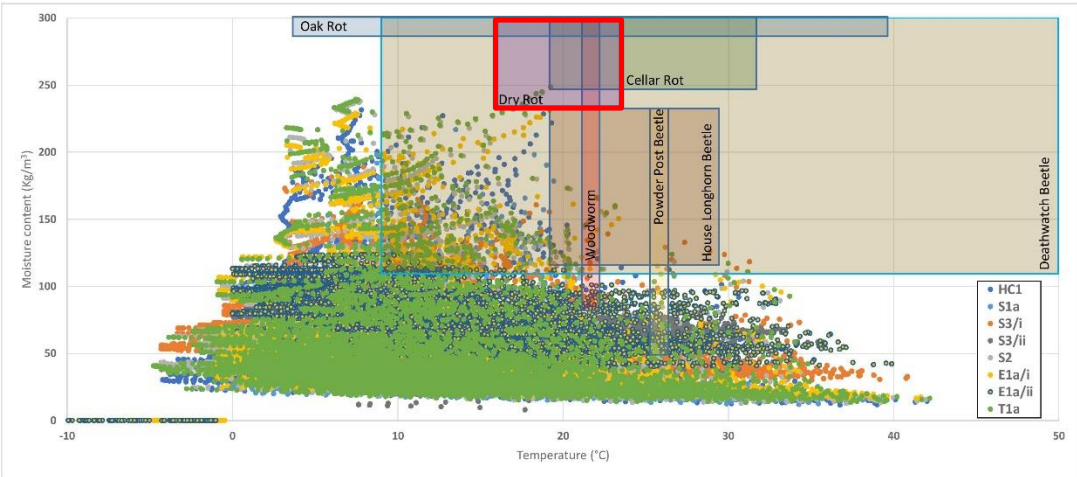

Figure 317. Simulated Hygrothermal conditions for southwest facing panels in Battisford, Suffolk with favourable conditions for biological attack overlaid and the occurrence of conditions favourable to dry rot highlighted. Source: (Author, 2017)

In addition to the previously discussed threats from wood-boring insects, Figure 317 also shows that there are occasions of conditions favourable to dry rot occurring within the panels retrofitted with mineral wool (S2) and cork (T1a and T1b). It should however be noted that these conditions only occur one for a duration of three hours during a summer downpour and rapidly dry out. As such, in reality, this is not a real risk.

11.5.6 Overall comparison of construction details

Comparing the results of all the simulations presented in this chapter there are a number of observations that can be made:

- It would appear that in general, the replacement wattle and daub panels (S1a and S1b) and the internally insulated wattle and daub panels (E2 and E3) present the least number of hours with hygrothermal conditions favouring biological attack. Although the drying time for new wattle and daub (section 11.5.2.1) are relatively high and the review of total moisture content in section 11.5.2.2 identified high total moisture content in the internally insulated details, these conditions do not appear to translate into hygrothermal condition favourable to biological agents.
- The artificial materials contained in the out-dated SPAB details (S2-S5) do not appear to create the expected increased risk due to trapped moisture, with only an increased risk of powderpost beetle being identified in the panel with glass wool (S2) and extruded polyurethane (S4).
- Overall, the natural based materials used in the Historic England details, the hempcrete detail and the cork details appear to fare the worst in many of the simulations.

11.6 Conclusions

Overall, it would appear that the simulations have not identified any proposed infill details that create hygrothermal conditions that pose a major threat to the surrounding timber-framed construction. Although some details gave rise to conditions that coincide with those favourable to the biological threats, these conditions existed only sporadically, with their duration being limited in most cases to a period of a few hours. Nor was any case of interstitial condensation identified, with moisture increases being due to climatic factors such as wind driven rain.

Within the details studied there was a wide range of resulting total water contents, however these did not necessarily translate into conditions favourable for biological attack. As would be expected, techniques with high built-in moisture, (wattle and daub and hemp-

lime) have long drying periods. Care should therefore be taken as to the timing of such work.

Of all the biological threats, the deathwatch beetle (*Xestobium rufovillosum*) was the one with the greatest number of hours created in its favour, followed by the powderpost beetle (*Lycus linearis Goeze & Lyctus brunneus*), with very few instances of conditions for fungal decay being identified. The creation of the interstitial hygrothermal conditions were seen to be highly dependent on orientation and local climatic conditions. The climate of Suffolk, which one would consider to be a dry climate, was shown to present more risk than the cold northern climate of Cumbria due to the coincidence of summer thunderstorms, high temperatures and greater solar radiation. This highlights that the results contained within this chapter cannot be easily extrapolated for all timber-framed buildings and that these results should not be used to inform individual retrofit projects. It also suggests that if climate change should potentially create warmer wetter summers, the biological risk posed to timber-framed buildings will increase.

It is also important to reiterate that the simulations presented in this chapter represent the moisture movement between idealized, homogenous, continuous layers of the infill materials. They do not reflect the moisture movement and potential accumulation at the junction with the timber-frame, nor the reality of heterogeneous and non-continuous layers present in actual constructions. The following chapter looks into how physical monitoring may help to provide a better understanding of real interstitial hygrothermal conditions. Future research with WUFI 2D version 3 should also be considered but are not included in the scope of this thesis.

12 FINDINGS AND RECOMMENDATIONS

12.0 Findings and Recommendations

Based on the principle findings of the research presented in this thesis there follows the major recommendations that should inform guidance on the low energy retrofit of historic timber-framed buildings in the UK.

- **Prioritise the retention of wattle-and-daub**

From the information available from the designation descriptions, written at the time of listing, it would appear that only 2% of the surviving timber framed buildings have wattle-and-daub infill panels. Whilst it is possible that more exist, hidden by plaster or overcladding, every effort should be made to retain any examples due to their rarity. Equally, other historic infill materials should also be retained wherever possible. Whilst the in situ U-value measurements do show that modern insulation materials can potentially be used to achieve infill panels that are more thermally efficient, this is only the case where the details used are robust and are well implemented. As was shown at Old Stokes Farm, poorly installed modern insulation can create walls that have higher thermal transmittance than unadulterated historic fabric such as the 17th century pargetted walls at no.27 Church Street, Saffron Walden. In addition, the energy simulations have shown that the thermal upgrading of infill panels has only a negligible effect on the overall heating energy demand. As such, the replacement of infill panels should only be considered as part of a holistic strategy for the whole building.

- **Improve airtightness before addressing envelope thermal performance**

From the results of thermography, pressure testing and energy simulations it can be seen that improving the airtightness of timber-framed buildings is more critical than altering the thermal performance of the walls. Simple retrofit actions such as the installation of secondary glazing, draught-stripping and plastering can all assist in lowering air change

rates, reducing the volume of air that is heated and minimising uncomfortable cold draughts. However, care must be taken to ensure that adequate ventilation is provided both for the health of the occupants and to avoid the increase in internal humidity. Special attention should be given to areas of high moisture creation such as kitchens and bathrooms to ensure the extraction of water vapour and to avoid any increase in condensation and surface moisture content such as may potentially be occurring in the bathroom at The Oaks, Brockhampton. In order to achieve this, mechanical extraction may be required.

Even with the use of the aforementioned retrofit actions to improve airtightness, a critical weakness remains, inherent in timber-framed buildings where the frame is exposed both internally and externally. This weakness is the junction between the infill panel and the timber frame. As discussed, this weakness may not have been so acute historically with the continual build-up of limewash, the use of continual plaster or pargeting, external over cladding or internal wooden panelling. However, with the Victorian obsession of exposing the historic fabric now accepted by many as these buildings original state, alternative details need to be explored. Some of the details contained within the literature review begin to explore this detail, such as F.W.B Charles´s “floating” subframe, the use of sealant tapes or the post application of natural fibres and lime plaster, however this remains an area for future research.

- **Undertake interstitial hygrothermal simulation for replacement infill panels**

If no historic infill is present, or cannot be saved, and the decision to replace infill panels is taken, then the proposed details should be simulated to predict if hygrothermal conditions may be created that could favour insect attach or fungal decay. This simulation must be conducted for each of the orientations in which the proposed panels will be situated, as the interstitial hygrothermal conditions are highly dependent on both orientation and climate.

It cannot be assumed that an essentially dry climate presents no potential risks, as was seen with the simulations for Suffolk, where summer thunderstorms produced an overall higher risk than that seen in cold wet Cumbria. Even though simulation is encouraged, it should be acknowledged that WUFI Pro® represents the idealised movement of moisture through homogeneous, continuous layers, and as such is a poor representation of the reality found in timber-framed buildings.

- **Avoid large discrepancies in surface temperature**

The use of thermography has identified large discrepancies at all case studies, this could lead to condensation, increased surface moisture content and mould growth. A potential strategy would be therefore to, improve the thermal performance of infill panels to the point that they match the thermal transmittance of the surrounding frame where possible. This would allow for some reduction in heating energy demand, whilst at the same time equalising internal surface temperatures, thereby minimising the risk of localised condensation.

- **Use in situ monitoring and energy simulation to guide energy retrofit decisions**

Where possible all projects considering the energy retrofit of historic timber-framed buildings should employ the use of in situ U-value measurements and pressure testing both to understand the existing situation and provide accurate data for the simulation of potential retrofit actions and solutions. Through simple energy simulations, options can be discounted that would unnecessarily involve the destruction of historic fabric and the wastage of resources, both economic and material.

- **Target guidance at those most in need of it**

The case studies highlight the need for guidance to be both available and applicable to individual homeowners, sole practitioner architects and small conservation contractors. Only one of the case studies was managed by a heritage institution and it was notable that this was the retrofit with the least intervention and maximum benefit. This is not by chance, and is the direct result of research undertaken by the National Trust to improve the energy performance of their let property portfolio with a minimum impact on historic fabric and lowest financial outlay. Whilst this is highly commendable, it is unrealistic to expect the guardians of most of the surviving historic timber-framed buildings to follow suit. Informed guidance is therefore essential. Where possible, reference should be made in all general guidance on energy retrofit to the specific challenges inherent in the thermal upgrading of historic buildings, including those of timber frame construction. Whilst it is not necessary that general guidance covers the subject in detail, it is essential that these challenges are highlighted to ensure that appropriate advice and guidance is sought.

- **Treat every retrofit on a case-by-case basis**

Finally, it is essential that the review of energy retrofit solutions should be undertaken on a case-by-case basis. Whilst some general rules can be applied, the work contained in this thesis highlights the wide range of structural techniques, infill materials, cladding materials, uses, climates and orientations each requiring detailed analysis and bespoke solutions. Each of these buildings is unique and requires retrofit solutions that are equally so. That said, as detailed above there are some key recommendations that should be considered for all energy retrofits of timber-framed buildings.

13 CONCLUSIONS

13.0 Introduction

The decline of timber framing as a common structural technique in the 18th and 19th centuries means that the majority of the surviving examples of historic timber-framed buildings found in the UK are over 200 years old, with over 80% of the buildings covered by this thesis having stood for more than 300 years. The use of timber dates back to the very beginning of construction, with evidence of timber framing across the British Isles, even in areas such as Scotland and Ireland where no surviving examples are to be found. At the same time, these buildings hold a special place in the British and more specifically English collective consciousness. They embody a connection to the past, to the countryside and the rural idyll, not only representing the countryside but physically made of it. They provide evidence of the skill and love of the craftsman in an increasingly mechanised and impersonal world, epitomising the desire to return to a time before it, escape from the city created by it and reject the perfection it has enabled. Yet the continuing existence of timber-framed buildings is not guaranteed, especially with the risk of climate change. The lack of surviving examples in Scotland, Ireland and the North of England bears testament to their inherent fragility. As such, any intervention, no matter how well intentioned, must be undertaken with the greatest care and should be informed by guidance grounded in rigorous research. If not, the consequences as illustrated by the case study of Old Stokes Farm can be highly destructive.

Most general literature concerning the energy retrofit of buildings either totally ignores the specific challenges posed by historic buildings or focuses only on the legislative and aesthetic issues. Where technical factors are explored, the majority of research focuses on solid masonry walling, which although representing a large proportion of the UK historic building stock, is not the only traditional construction technique that must be addressed. Guidance does exist for the retrofit of historic timber-framed buildings, yet there is little

academic research available to validate the advice that it offers. The research presented in this thesis does not pretend to provide all the answers but hopes to begin research that will inform guidance and allow the continued use and survival of these buildings.

13.1 Surviving Timber-Framed Buildings

Approximately 68,000 timber-framed buildings survive in the UK, of which 70% are dwellings. The main concentration of these can be found in East Anglia and the South East of England, with 74% located in these two regions. A second concentration containing 13% of the surviving timber-framed buildings is situated in the West Midlands and Welsh Marches, and a third much smaller grouping (6.5%) in the South West of England. Within the first two concentrations, there is a notable absence of surviving examples within the major urbanised areas, with only 433 buildings within the metropolitan boundary of London and 82 within the West Midlands Conurbation. This is evidence of both the great fires of the 17th century and the laws prohibiting timber construction that followed, in addition to the economic pressures to redevelop that exist in these urban environments. As such, the retrofit of historic timber-framed buildings is predominantly a rural issue. This has the benefit that often the inhabitants are willing to accept a degree of discomfort that comes with living in these buildings, as it is seen as part of a life choice, intrinsic to living in the country, as seen at Hacton Cruck, The Oaks and Old Stokes Farm. At the same time, it has the disadvantage, due to their remote locations, that work to these buildings may take place unobserved by the relevant authorities, and without receiving the necessary guidance, resulting in cases such as Old Stokes Farm. With the ever-decreasing number of historic building advisers in local authorities, this problem may be set to increase.

Outside cities, the two principal factors in the location of the surviving timber-framed buildings are topography and geology, given that these two factors govern secondary phenomena such as climate and the historic availability of building materials. One of the

most striking features in their distribution is that only 3.5% are built over the limestone belt running from the Severn Estuary to the Wash. This is most probably due to three key factors, the availability of good quality building stone; the poor thin soils and subsequent lack of historic forests; and the resulting open landscape. The reliance on locally available building materials is highlighted by only 0.5% of surviving timber-framed buildings being located outside a 5km radius of areas where woodland was recorded in the Doomsday Book. Whilst at the same time, where no forests existed, the open fields led to the development of a settlement pattern of urban centres rather than scattered dwellings, a pattern further compounded by the Parliamentary Enclosure Acts of the 17th and 18th centuries. This further confirms the hypothesis that timber-framed buildings would appear to have survived longer in rural areas of disparate habitation due to the lower risk of fire and reduced economic pressures for redevelopment.

Climatic factors, principally resulting from topography and primarily related to moisture, are also a key factor in the distribution of surviving timber-framed buildings. These buildings have survived on sites which are typically at higher altitudes than the average UK dwelling, between 20m and 100m above sea level, away from the humid coasts and valley bottoms but not at elevations over 200m, where increased rainfall and lower temperatures counteract the benefits of altitude. It is clear from the study of the representative sample of surviving buildings that simple bioclimatic considerations have been instrumental in their orientation. Principal facades are generally arranged to receive some direct solar radiation during the majority of the year, with a preference of easterly and southeasterly aspects to maximise the warming benefit of the morning sun following the cold night hours. Equally, the southwest is less popular due to the prevailing winds and wind driven rain. Simulation of interstitial hygrothermal conditions of infill panels show an increased risk from insect attack and fungal decay for elevations orientated towards the south and southwest.

The final major influencing factor in the survival of timber-framed buildings is the relative economic affluence, both current and historic, of the areas where they are still to be found. This wealth, historically arising from the wool trade and other middle class professions, allowed a superior quality of construction that has lasted to this day. Equally, the continuing prosperity of these regions has allowed the maintenance necessary to ensure their survival. However, coupled with the previously mentioned fact that 70% of these buildings are dwellings, the relative affluence of their owners presents additional challenges. Whilst for other typologies such as solid walled terraced housing there may be concern over fuel poverty and people's economic ability to heat their domestic environment, the distribution of timber-framed buildings in more wealthy areas leads to other risks. Those with the financial ability will look to improve their home to meet their expectations of comfort. As such, reliable informed guidance is essential to ensure they do so in the manner most appropriate to the historic fabric of these buildings. Secondly, their relative prosperity will enable mobility, allowing them to relocate to other more efficient properties if thermal comfort cannot be attained. These buildings need to continue to be inhabited if their survival is to be ensured, and therefore a balance must be achieved between protecting their historic built fabric and meeting the expected levels of internal comfort.

13.2 Current approaches to energy retrofit of historic timber-framed buildings

The literature review and case studies showed a variety of approaches to the energy retrofit of historic timber-framed buildings. These range from conservative repair, to restoration, from limited intervention, to wholesale removal and replacement of all infill

panels. In all but The Oaks, the strategies adopted have been based on the owner's, architect's or contractor's professional judgement and intuition, rather than on a holistic evaluation of the desired outcomes. As such, the monitoring and simulation of their performance suggest that alternative strategies may have resulted in more favourable results, or that retrofit actions were undertaken in the wrong order, with heavily invasive interventions being undertaken before simple issues that improve airtightness had been resolved. It is therefore essential that future guidance stresses the need for simulations and assessments of potential solutions prior to any work being undertaken, and that the order of interventions is considered. This guidance must however acknowledge the variety of drivers that lie behind the motivation for individuals and organisations to occupy and care for these buildings. It must also recognise that many engaged in this work are sole practitioners and small conservation contracts, therefore recommendations must be appropriate and realistic. By doing so historic fabric can be saved from needless destruction, money can be saved and the desired outcome of improved thermal efficiency can be achieved.

The interstitial hygrothermal simulation of the replacement panel infill details currently proposed by UK heritage bodies appears to suggest that there is no serious risk of biological attack, at least in those locations and climates simulated. Out of all the biological risks identified, Deathwatch Beetle (*Xestobium rufovillosum*) would appear to be the greatest, with locations with higher levels of summer rain being at greater risk than cool damp climates. That said, the duration of favourable conditions encountered do not suggest that any real threat is generated. However, this is not to say that risks do not exist under climatic conditions yet unstudied, and the simulations do show that both climate and orientation are highly influential and therefore simulation should be undertaken on a case-by-case basis. At the same time, there is not sufficient confidence that simulations truly

represent the reality of the heterogeneous constructions and most critically the junction between the infill and timber-frame. Further research in this area is needed.

There follows the primary recommendations that arise from the research presented in this thesis.

13.3 Areas for future research

As previously stated, the research presented in this thesis only begins to address the work necessary to provide robust, informed guidance for the retrofit of historic timber-framed buildings. Much work is still required in order to ensure that the balance is met between the ongoing inhabitation of these buildings and the conservation of their built fabric. There follows a summary of other areas for future research that have been identified.

13.3.1 Historic Timber Framing World Wide

- The quantification and distribution of surviving historic timber-framed buildings across the globe. This could concentrate on only those buildings with solid infill panels, similar to those found in the UK and covered in this thesis, or it could be broadened out to encompass timber-clad construction such as that found in Scandinavia, Eastern Europe and the Americas; solid log construction as found in Scandinavia, Central and Eastern Europe and North America; and other historic timber constructions that may be encountered.
- The historical inter-relationship between regional timber constructional techniques and their influence in the development of the use of timber across the globe.
- Archival materials should be used to corroborate the findings regarding orientation made in chapter 7. This research could be extended to a large sample and could possibly look at buildings outside the UK.

13.3.2 Climate change

- The correlation of the distribution of surviving timber-framed buildings and climate change projection data such as that available from the Met Office. This would enable the study of the potential risks and the quantification of those properties that may be affected by a changing climate.
- The use of climate change projection data in conjunction with energy simulation of proposed energy retrofit strategies for historic timber-framed buildings
- The use of climate change projection data in conjunction with dynamic simulation of interstitial hygrothermal conditions within existing and proposed panel infill details. This would identify those details, both historical and proposed, that may have increased periods of conditions favourable for insect attack and fungal decay in the future.

13.3.3 Monitoring

- Additional case studies of both properties where retrofit has taken place and where original fabric remains will continue to build a more complete picture of the performance of these buildings and the benefits and dangers of their retrofit. It is intended by the author to continue monitoring at nos. 25 & 27 Church Street, Saffron Walden, Old Stokes Farm and The Oaks. In addition, as stated in the recommendations, it is hoped that many future retrofit projects will undertake monitoring as part of their decision making process and to review the success post occupation and that the results of this monitoring will be made public.
- Further in situ U-value monitoring of traditional panel infills to assess their performance and provide improved data for energy simulations.
- Co-heating tests could be conducted on historic timber-framed buildings.

13.3.4 Simulation

- WUFI2D-3®

13.3.5 Experimental Work

- The need for more open source hygrothermal data for historic British materials, with all parameters necessary for incorporation in software such as WUFI® is essential for these tools to become a reliable tool in the retrofit of all historic buildings.
- Physical monitoring of test panels would help validate the results so far obtained through simulation. The author has already begun monitoring panels between dual climate controlled chambers at the University of Bath's Building Research Park, the results of which he hopes to publish shortly. In addition longer term monitoring of physical test panels is required and funding for this is currently being sought.

This highlights the quantity of research still to be done. However, it is hoped that this thesis marks the beginning of the work that will lead to the production of guidance that will in turn enable timber-framed buildings to be continue to be a functional part of 21st Century Britain, and for centuries to come, just as they have been for over 900 years.

14 GLOSSARY

Air-tightness	A building's resistance to uncontrolled air flow through cracks, permeable materials, unintentional openings and unions within the construction of the external building envelope (British Standards Institution, 2015b p.1). Typically measured under pressure as "air permeability index" the volume of air passing through the external envelope per unit of area per unit of time ($m^3/hr/m^2$@50Pa); "air change rate" the number of times the entire volume of air inside the building is exchanged per unit of time (/hr); and "effective leakage area" the calculated sum of all unintentional openings (m^2) (ibid, p.2).
Bioclimatic	Designed to work with the local climate to provide hygrothermal comfort with limited external input of energy (Olgyay and Olgyay, 1963).
Box Framing	Timber-framed construction technique where a series of timber frames – wall frames, cross frames and floor frames- form the main structure (Harris, 2016 p.94, Brunskill, 1985 p.48). This is in contrast to "cruck" construction, *see below*.
Close Studding	A wall framing style where vertical uprights (studs) are placed close together forming tall rectangular panels, spanning either the entire storey or split by a middle rail (Brunskill, 1985 p.152).
Conservation Areas	Areas of special architectural or historic interest the character or appearance of which it is desirable to preserve or enhance protected under the Planning (Listed Buildings and Conservation Areas) Act 1990 for England and Wales (1990 p.42) and the Scottish Act of 1997.
Cob	Earth construction of mud and straw (and possibly other aggregates) where the mixture is applied wet in layers (Clifton-Taylor, 1987 p.272, Innocent, 1971 p.136).
Cruck	Inclined timbers, known as cruck blades, rising from low down in the external walls to the apex of the roof (Mercer, 1975 p.97, Peate, 1940 p.160). The cruck blades are often curved, book-matched timbers and take the structural load of the roof (Brunskill, 1985 p.118)
Dendrochronology	The science of dating of timbers by study of the tree-ring numbers and widths (Harris, 2010 p.94)
Dew Point Temperature	The atmospheric temperature (varying according to pressure and humidity) below which water droplets begin to condense (Soanes and Stevenson, 2005)
Dry-bulb Temperature	The ambient temperature of the air measured excluding the effects of moisture and radiation.
Deep renovation	Defined by the EU Energy Efficiency Directive as "refurbishment that reduces both the delivered and the final energy consumption of a building by a significant percentage

	compared with the pre-renovation levels leading to a very high energy performance" (OJEU, 2012 p.315/3).
Energy Retrofit	The alteration of a building with the purpose of improving its energy efficiency.
Greenhouse gases	Gases contributing to climate change, including carbon dioxide, methane, nitrous oxide, hydroflurocarbons, perfluorocarbons and sulphur hexafluroride (2008a p.44). Of these carbon dioxide is the most linked to building energy retrofit due to it arising from the combustion of fossil fuels (Nichol et al., 2012 p.160)
Heat-flux (W/m^2)	The flow of heat energy per unit of area per unit of time. Its SI units are Watts (Joules per second) per square metre (British Standards Institution, 1996).
Hygroscopic	Tending to absorb moisture from the air (Soanes and Stevenson, 2005).
Hygrothermal	Relating to both temperature and moisture (Merriam-Webster, 2018).
Interstitial Condensation	The introduction of moisture within a structure due to the internal temperature of a construction dropping below the dew point temperature causing water vapour to condense (British Standards Institution, 2012).
Lath	A thin flat strip of wood, especially one of a series forming a foundation for the plaster of a wall (Soanes and Stevenson, 2005).
Limewash	A mixture of lime and water used for coating walls (ibid)
Listed Building	Buildings of special architectural or historic interest, listed as such under the Planning (Listed Buildings and Conservation Areas) Act 1990 for England and Wales (1990 p.1) and the Scottish Act of 1997.
Moisture Buffering	The ability of internal surface materials to control the internal relative humidity through the absorption and desorption of airborne moisture (El Diasty et al., 1992).
Moisture Content	The ratio of water present in a material obtained by comparing the weight of the wet material with the weight of the same material when oven-dry (Pinchin, 2008 p.34).
Nogging	The use of masonry as panel infill. Most commonly brick nogging, although stone and flint nogging can also be found (Brunskill, 1985 p.152)
Pargetting	A decorative use of plaster as a cladding (Brunskill, 1985 p.110), applied externally to the timber frame (Harris, 2010 p.95)

Relative Humidity	The amount of water vapour present in air expressed as a percentage of the amount needed for saturation at the same temperature (Soanes and Stevenson, 2005).
Square Framing	Panels approximately square (Brunskill, 1985 p.154). Common configurations include three panels per storey, two panels per storey and some with panels spanning a whole storey (Smith, 1965 p136). *Compare to "close studding"*
Stave	A vertical wooden post (Soanes and Stevenson, 2005) in the context of this thesis used to refer to the vertical element around which laths or withies (thin branches) are woven in wattlework.
Thermal Conductivity (K-Value or λ)	Intrinsic property of a material to conduct heat. SI units W/mK (British Standards Institution, 1996)
Thermal Transmittance (U-Value)	The rate of heat transfer across a building element. Heat flow rate in the steady state divided by area and by the temperature difference between the surroundings on each side of a System: SI units W/m2K (British Standards Institution, 1996)
Thermography	The use of a camera that measures infrared radiation (Young, 2015). The technique is specifically used in this thesis to assess the thermal performance of building envelopes but can also be used to assess moisture content, electrical faults and construction anomalies (ibid)
Vapour Permeability	The ability of a material to allow the passage of water vapour, often referred to as "breathability" (Hughes, 1986 p.1). A measure of vapour permeability is the "Vapour diffusion thickness" or sd-value. This is the equivalent thickness of stagnant air (m) that would provide the same vapour diffusion resistance. The higher the sd-value, the less vapour permeable.
Wattle-and-daub	A traditional panel infill consisting of clay render (daub) supported by a network of woven thin timber members (wattlework) (Brunskill, 1985 p.185). *For a detailed description, see page 78*

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APPENDIX A

Replacement Panel Infill Details

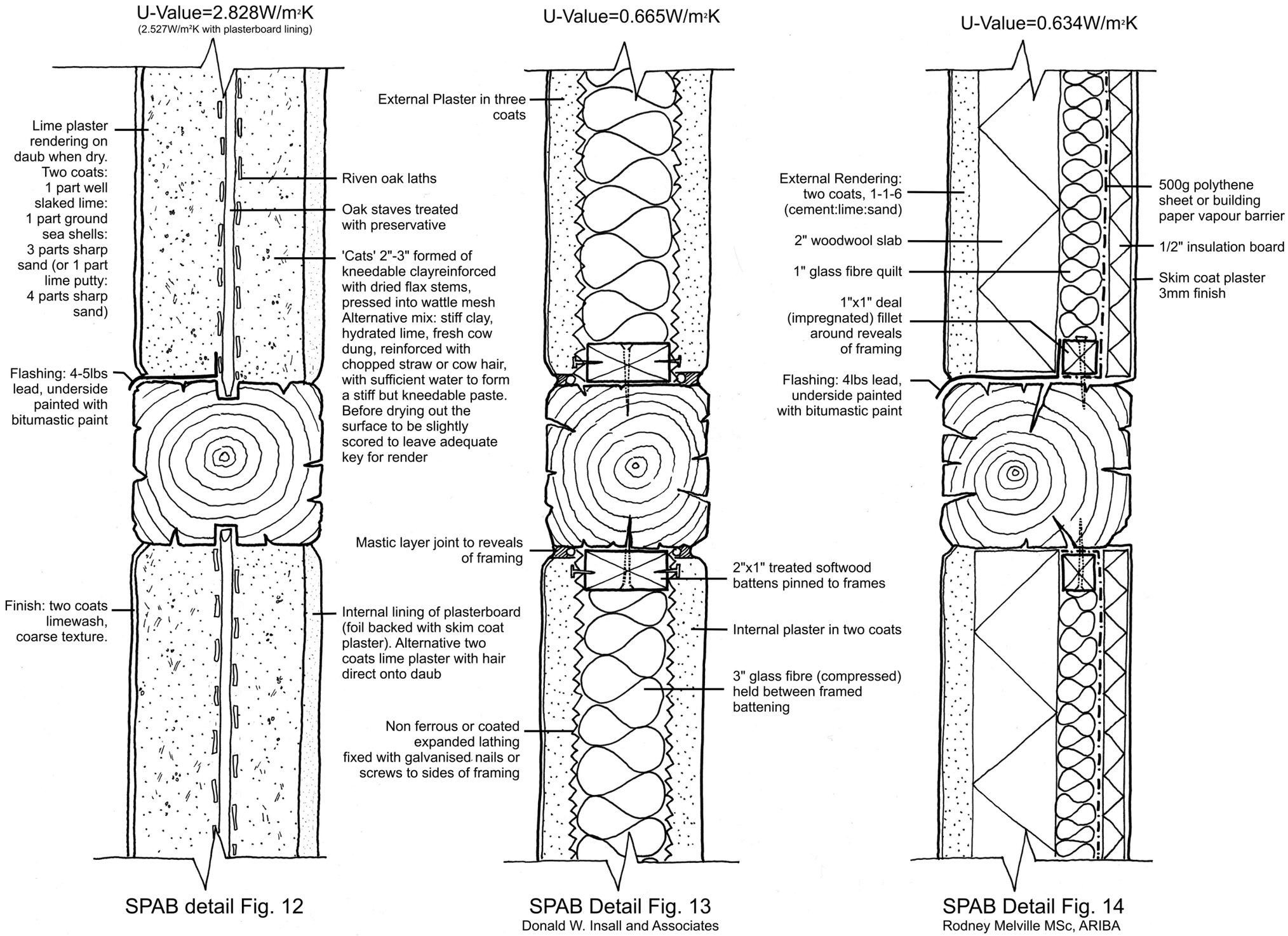
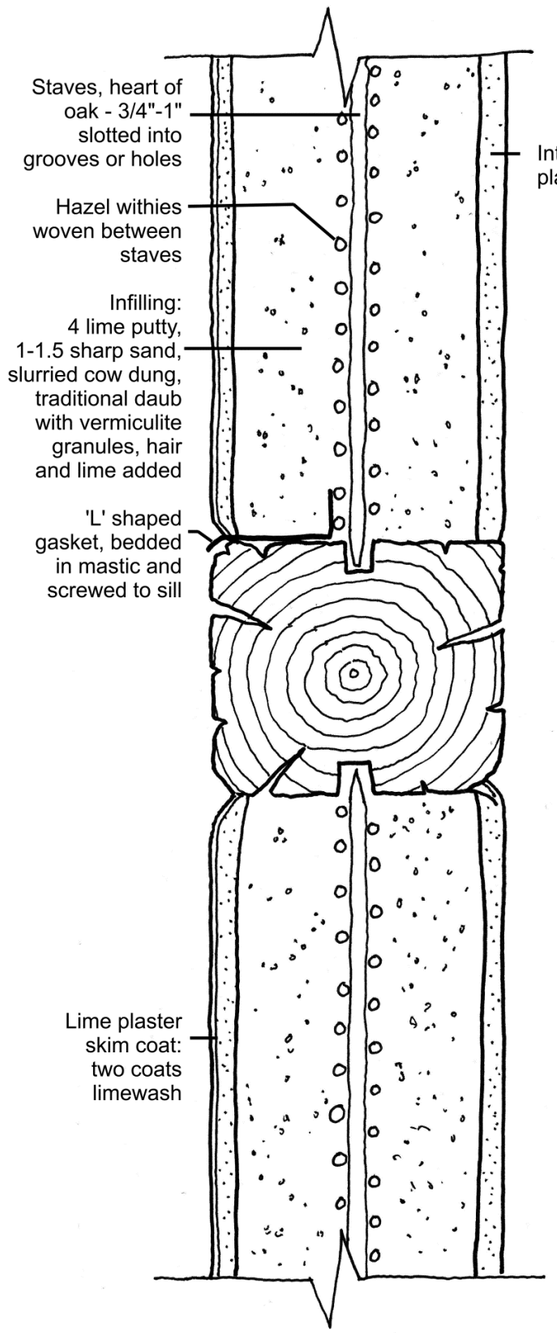
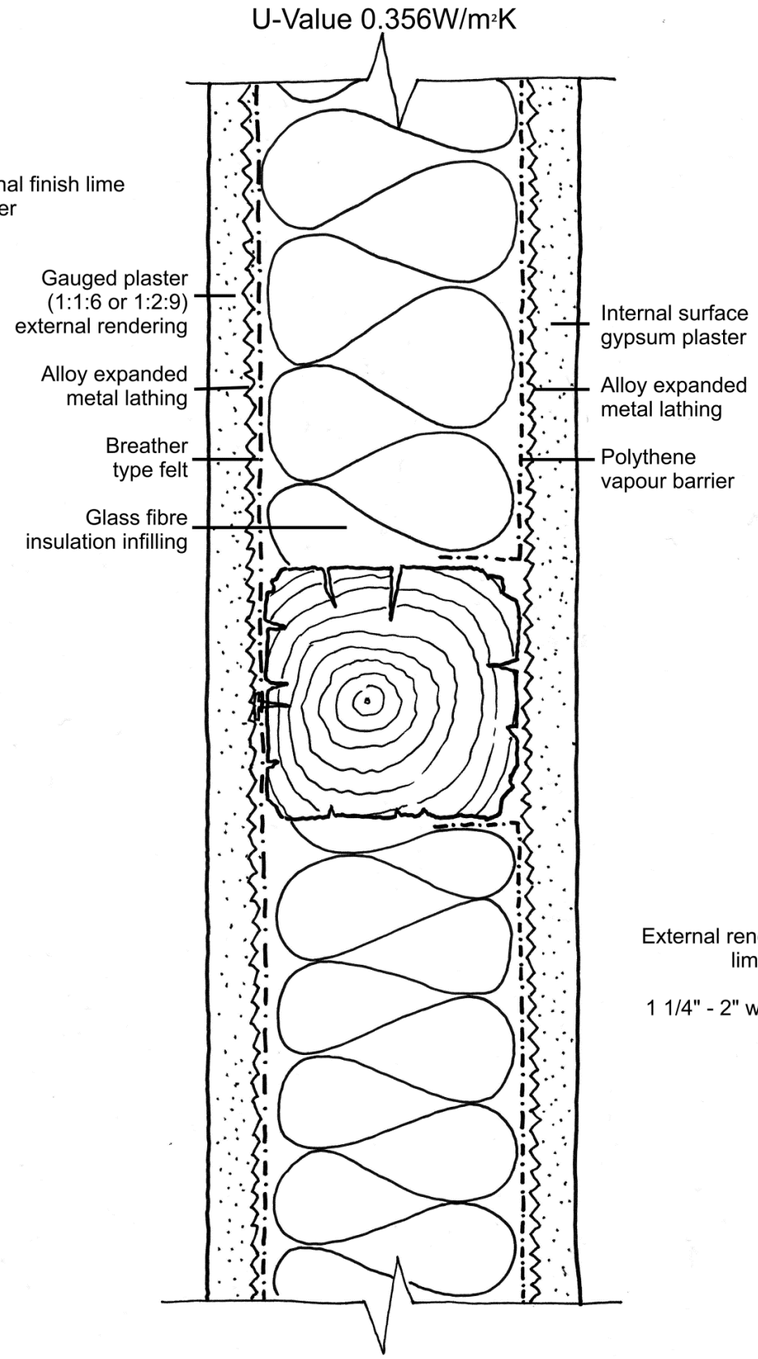


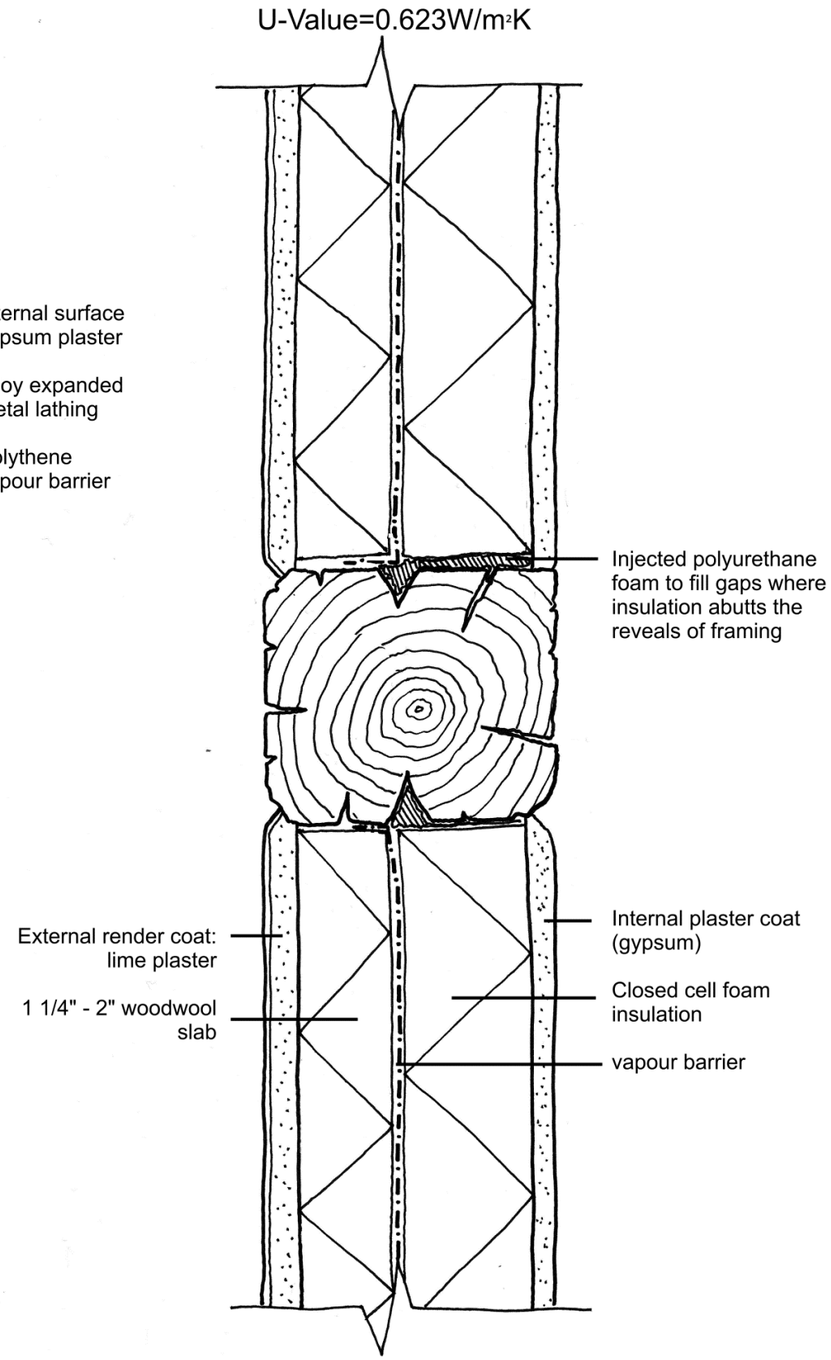
Figure 318. Replacement panel infill details. Source: (Author's own based on (Reid, 1989 p.8-9)



SPAB Detail Fig.15
(Untried) John Schofield



SPAB Detail Fig. 16
Architrects of the Essex County Councill



SPAB Detail Fig.17
Andrew Thomas RIBA

Figure 319. Replacement panel infill details. Source: (Author's own based on (Reid, 1989 p.9)

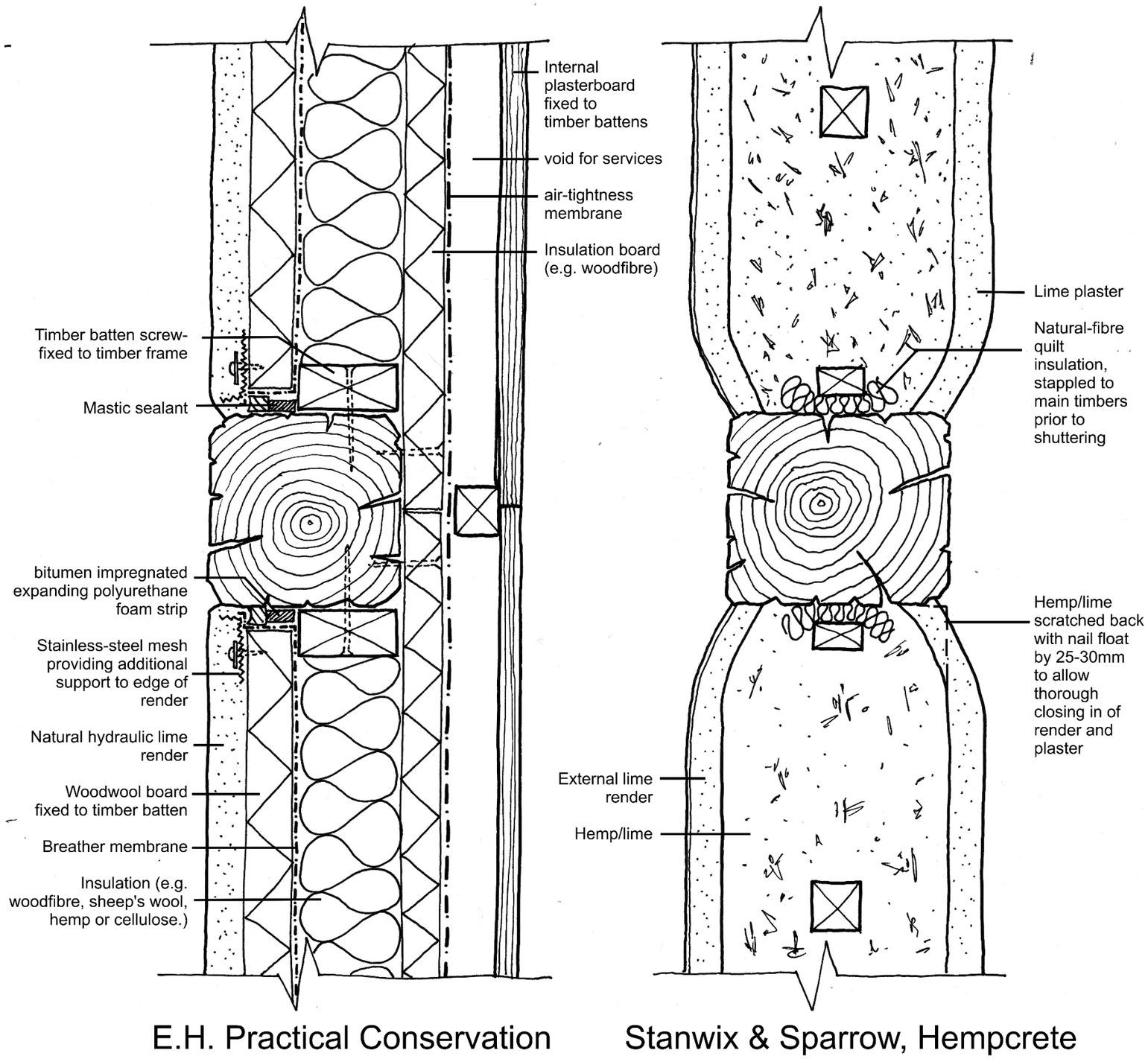


Figure 320. Replacement panel infill details. Source: (Author's own based on (McCaig and Ridout, 2012, Stanwix and Sparrow, 2014)

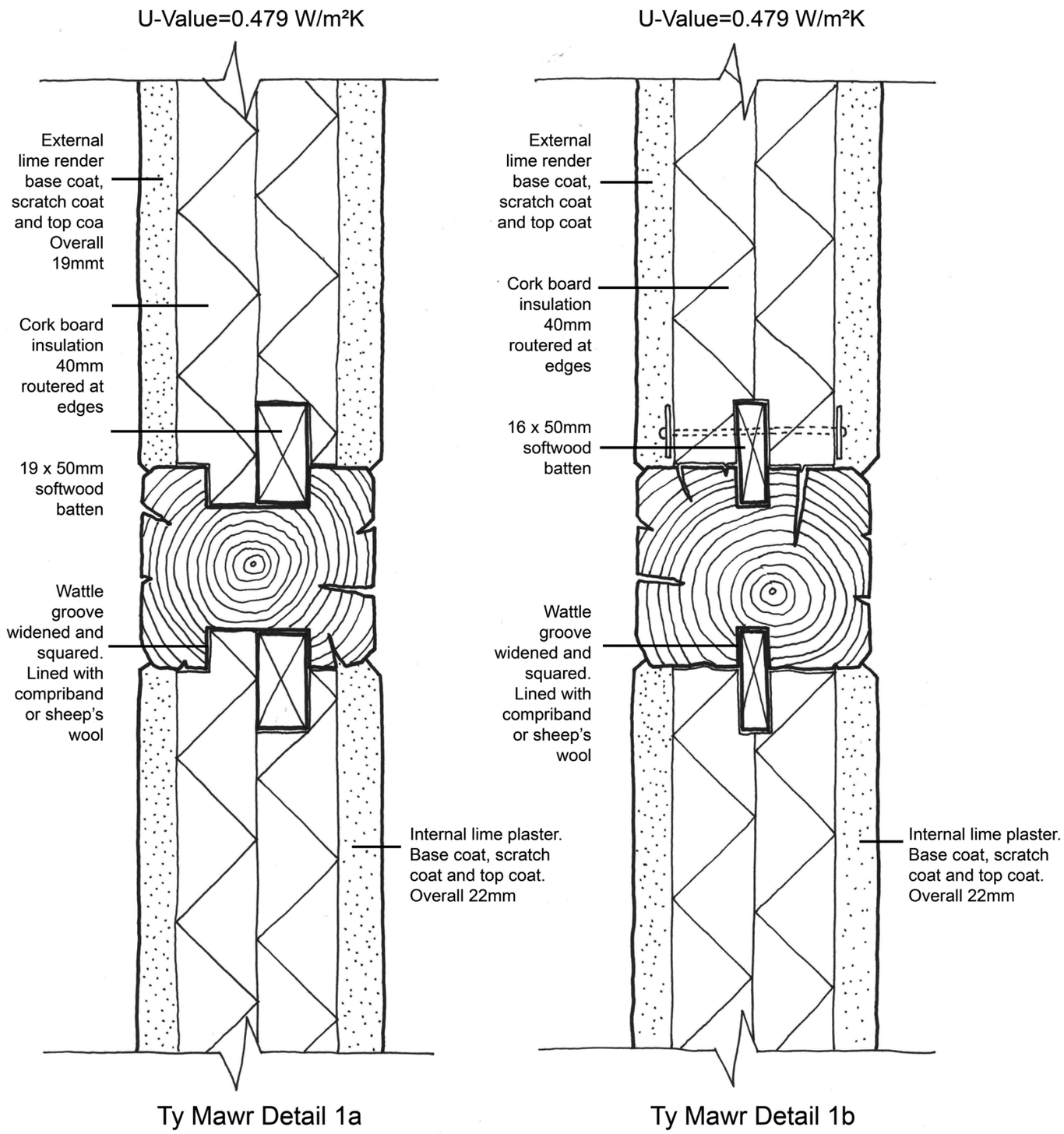


Figure 321. Replacement panel infill details. Source: (Author's own developed in association with Ty Mawr Lime Ltd.)

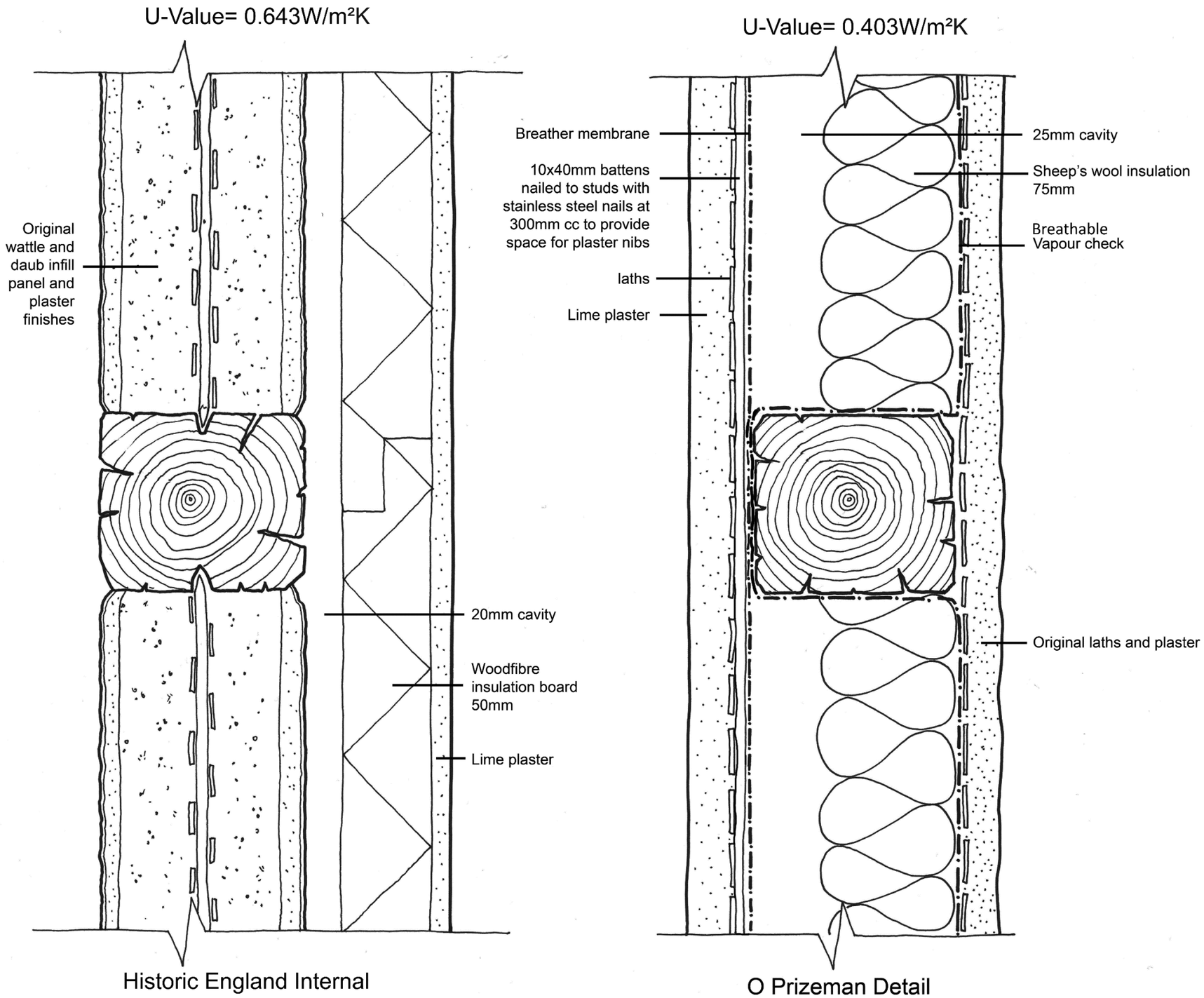


Figure 322. Replacement panel infill details. Source: (Author's own based on (Ogley, 2010) and a detail by O. Prizeman©)

APPENDIX B

Methodology for pre-processing of raw data sets -Chapter 6

A dataset was requested from Historic England searching the National Listings (Historic England, 2014) using the search parameters “Pre-1850, Timber Framed Building; Jettied Building; Jettied House; Continuous Jetty House; End Jetty House; Wealden House; Single Ended Wealden House; Timber Framed Barn; Cruck Barn; Timber Framed House; Box Frame House; Cruck House; Base Cruck House.” The resulting dataset initially comprised of 66,397 entries. However, it was known that some entries would cover multiple properties, some would be for demolished or be “former timber-frame” buildings and some would have been encased entirely with brick and stone, and thereby fall outside the scope of this study. It was therefore necessary to review the designation description for each entry. As this information was not supplied by Historic England as part of the initial dataset and a request for it to be added was denied, web data scraping using Kimono Labs Google Chrome extension (now discontinued) was undertaken to extract the information from the National Listings website using the URLs provided in the original dataset. Buildings listed as “former timber-frame” and those subsequently entirely encased with a continuous masonry envelope were deleted. List entries covering multiple buildings were duplicated to create one entry per building. The resulting dataset contained 66,975 buildings.

In addition to allowing the filtering out of the aforementioned categories, the designation description also allowed the classification of the entries according to age, building type (domestic, commercial/public or ancillary) and panel infill material. Microsoft Excel was used to enable this classification. In order to reduce the variables being searched for, the following macro was run to replace possible similar descriptions with common words. For example the words ‘dwelling’, ‘cottage’ and ‘lodge’ were replaced with the word ‘house’ and ‘tilehung’, ‘tile-hung’ and ‘tile hang’ were replaced with ‘tile hung’. The macro also ensured that all dates were presented in the same format and all text was in lowercase:

```
Sub HE_CleanUp()
'
' HE_CleanUp Macro
' Clean up kimono labs workbook
'

    Cells.Replace What:="C14", Replacement:="c14", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="C15", Replacement:="c15", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="C16", Replacement:="c16", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="C17", Replacement:="c17", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="C18", Replacement:="c18", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="C19", Replacement:="c19", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False

    Cells.Replace What:="Cl4", Replacement:="c14", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="Cl5", Replacement:="c15", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="Cl6", Replacement:="c16", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="Cl7", Replacement:="c17", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="Cl8", Replacement:="c18", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="Cl9", Replacement:="c19", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="late mediaeval", Replacement:="c15", LookAt:=xlPart, SearchOrder
_
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False

    Cells.Replace What:="1300", Replacement:="c14", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="1400", Replacement:="c15", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="1500", Replacement:="c16", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="1600", Replacement:="c17", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="1700", Replacement:="c18", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="1800", Replacement:="c19", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False

    Cells.Replace What:="B", Replacement:="b", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="C", Replacement:="c", LookAt:=xlPart, SearchOrder _
```

```
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
Cells.Replace What:="D", Replacement:="d", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
Cells.Replace What:="G", Replacement:="g", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
Cells.Replace What:="H", Replacement:="h", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
Cells.Replace What:="I", Replacement:="i", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
Cells.Replace What:="L", Replacement:="l", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
Cells.Replace What:="M", Replacement:="m", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
Cells.Replace What:="O", Replacement:="o", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
Cells.Replace What:="P", Replacement:="p", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
Cells.Replace What:="S", Replacement:="s", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
Cells.Replace What:="W", Replacement:="w", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False

Cells.Replace What:="stable", Replacement:="barn", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
Cells.Replace What:="pig sty", Replacement:="barn", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
Cells.Replace What:="dovecote", Replacement:="barn", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
Cells.Replace What:="outhouse", Replacement:="barn", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
Cells.Replace What:="gazebo", Replacement:="barn", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
Cells.Replace What:="kiln", Replacement:="barn", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
Cells.Replace What:="outbuilding", Replacement:="barn", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
 Cells.Replace What:="cartshed", Replacement:="barn", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
Cells.Replace What:="granary", Replacement:="barn", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False

Cells.Replace What:="dwelling", Replacement:="house", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
Cells.Replace What:="cottage", Replacement:="house", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
Cells.Replace What:="lodge", Replacement:="house", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False

Cells.Replace What:="pub", Replacement:="shop", LookAt:=xlPart, SearchOrder _
   :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
```

```
    Cells.Replace What:="public house", Replacement:="shop", LookAt:=xlPart, SearchOrder
_
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="office", Replacement:="shop", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="cafe", Replacement:="shop", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="café", Replacement:="shop", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="restaurant", Replacement:="shop", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="hotel", Replacement:="shop", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="guest house", Replacement:="shop", LookAt:=xlPart, SearchOrder
_
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False

    Cells.Replace What:="nogging", Replacement:="infill", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="noggin", Replacement:="infill", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="nogged", Replacement:="infill", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="nagging", Replacement:="infill", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="panel", Replacement:="infill", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="stucco", Replacement:="plaster", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="render", Replacement:="plaster", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="roughcast", Replacement:="plaster", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="rough cast", Replacement:="plaster", LookAt:=xlPart, SearchOrder
_
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="rough-cast", Replacement:="plaster", LookAt:=xlPart, SearchOrder
_
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="parget", Replacement:="plaster", LookAt:=xlPart, SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="pebble dash", Replacement:="plaster", LookAt:=xlPart,
SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="pebbledash", Replacement:="plaster", LookAt:=xlPart, SearchOrder
_
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
    Cells.Replace What:="pebble-dash", Replacement:="plaster", LookAt:=xlPart,
SearchOrder _
        :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
```

```
   Cells.Replace What:="weather board", Replacement:="weatherboarded", LookAt:=xlPart,
SearchOrder _
      :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
   Cells.Replace What:="weather-board", Replacement:="weatherboarded", LookAt:=xlPart,
SearchOrder _
      :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False

   Cells.Replace What:="tilehung", Replacement:="tile hung", LookAt:=xlPart, SearchOrder
_
      :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
   Cells.Replace What:="tile-hung", Replacement:="tile hung", LookAt:=xlPart, SearchOrder
_
      :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
   Cells.Replace What:="tile hang", Replacement:="tile hung", LookAt:=xlPart, SearchOrder
_
      :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False

   Cells.Replace What:="bishops", Replacement:="bish", LookAt:=xlPart, SearchOrder _
      :=xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False
```

The following formulae where then used in excel to search the designation text and return a numerical value based on the relevant category.

For age the following formula was used:

```
=VALUE(IF(ISNUMBER(FIND("C14",A02)),"14",IF(ISNUMBER(FIND("C15",A02)),"15",IF(ISNUMBER(FIN
D("C16",A02)),"16",IF(ISNUMBER(FIND("C17",A02)),"17",IF(ISNUMBER(FIND("C18",A02)),"18",IF(ISN
UMBER(FIND("C19",A02)),"19","Null")))))))
```

For building use:

```
=VALUE(IF(ISNUMBER(FIND("church",A644)),"1",IF(ISNUMBER(FIND("barn",A644)),"2",IF(ISNUMBER
(FIND("house",A644)),"3",IF(ISNUMBER(FIND("cottage",A644)),"3",IF(ISNUMBER(FIND("inn",A644)),"
4",IF(ISNUMBER(FIND("pub",A644)),"4",IF(ISNUMBER(FIND("office",A644)),"4",IF(ISNUMBER(FIND("
shop",A644)),"4",IF(ISNUMBER(FIND("dwelling",A644)),"1","Null")))))))))
```

And for panel infill type:

```
=VALUE(IF(ISNUMBER(FIND("brick infill",A644)),"1",IF(ISNUMBER(FIND("brick
nogging",A644)),"1",IF(ISNUMBER(FIND("plaster",A644)),"2",IF(ISNUMBER(FIND("stucco",A644)),"2",
```

```
IF(ISNUMBER(FIND("roughcast",A644)),"2",IF(ISNUMBER(FIND("daub",A644)),"3",IF(ISNUMBER(FIND
("weatherboard",A644)),"4",IF(ISNUMBER(FIND("weatherboarded",A644)),"4","Null")))))))))
```

Where Excel was unable to find any of the requested key words, zero would be returned. This most commonly occured with regards to panel infill and building use. In these instances, Google Street View was used to view the property and complete the data manually.

A similar exercise was completed for Wales using the lists from Peter Smith's "Houses of the Welsh Countryside" (Smith, 1988) updated with information from Richard Suggett (Suggett, 2005) and cross-referenced with the National Monuments Record of Wales (RCAHMW, 2014). This resulted in a Welsh dataset with 1020 buildings. Finally, similar exercises were undertaken for Scotland and Northern Ireland using Historic environment Scotland's 'Heritage Portal' (Historic Environment Scotland, 2016a) and the Department for the environment for Northern Ireland's 'Northern Ireland Building Database (Department of the Environment, 2017). These returned a result of just three buildings for Scotland and none for Northern Ireland, and even the three surviving Scottish buildings, all in Edinburgh, are predominantly stone buildings with timber-framed upper storeys or projecting galleries.

APPENDIX C

Plans of Case Study Buildings

Appendix C1

Plans, Elevations and Sections of Hacton Cruck

Address: Hacton Lane, Hereford, Herefordshire HR2 9JU, UK

Grid Reference: SO 38782 41829

Designation list entry number: 1111811

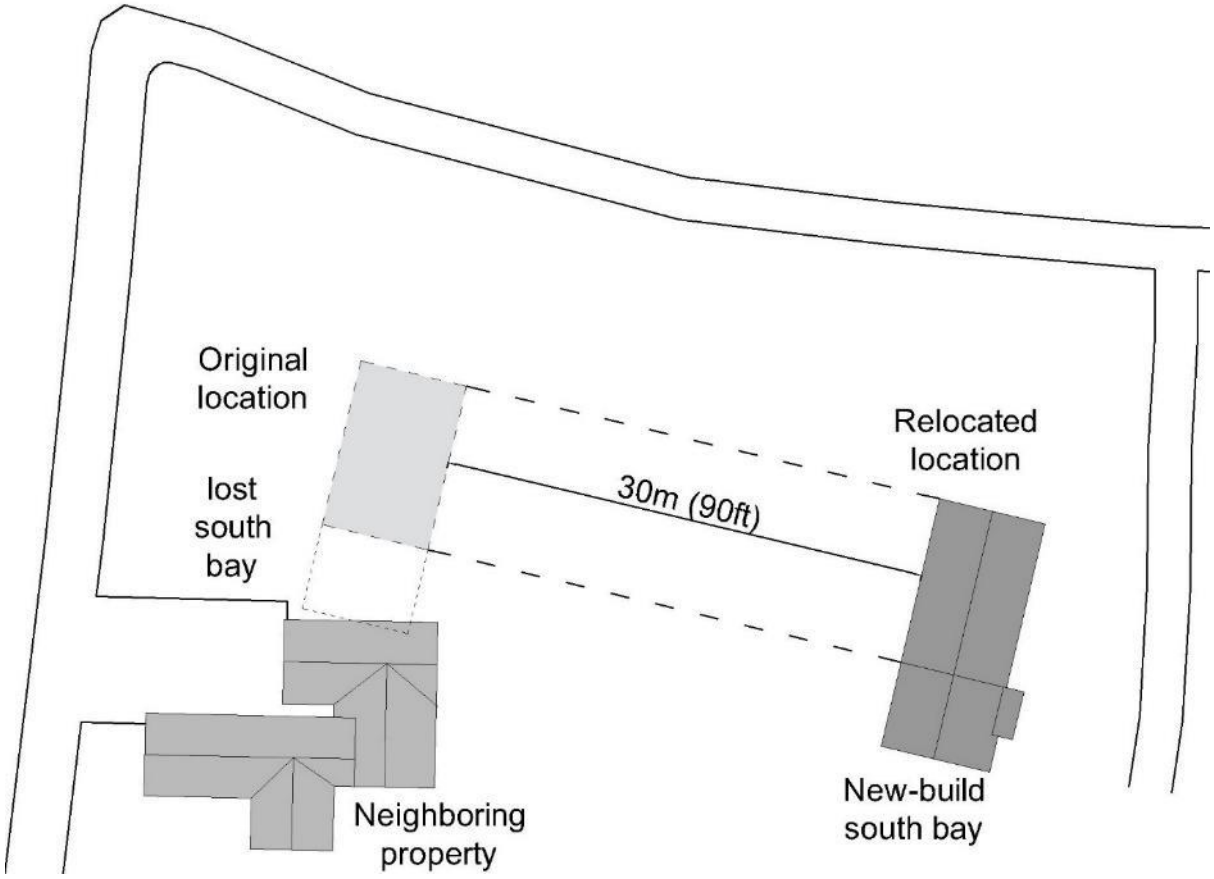


Figure 323Hacton Cruck site plan showing original and relocated sites. Source: (Author's own based on Google Earth, 2015)

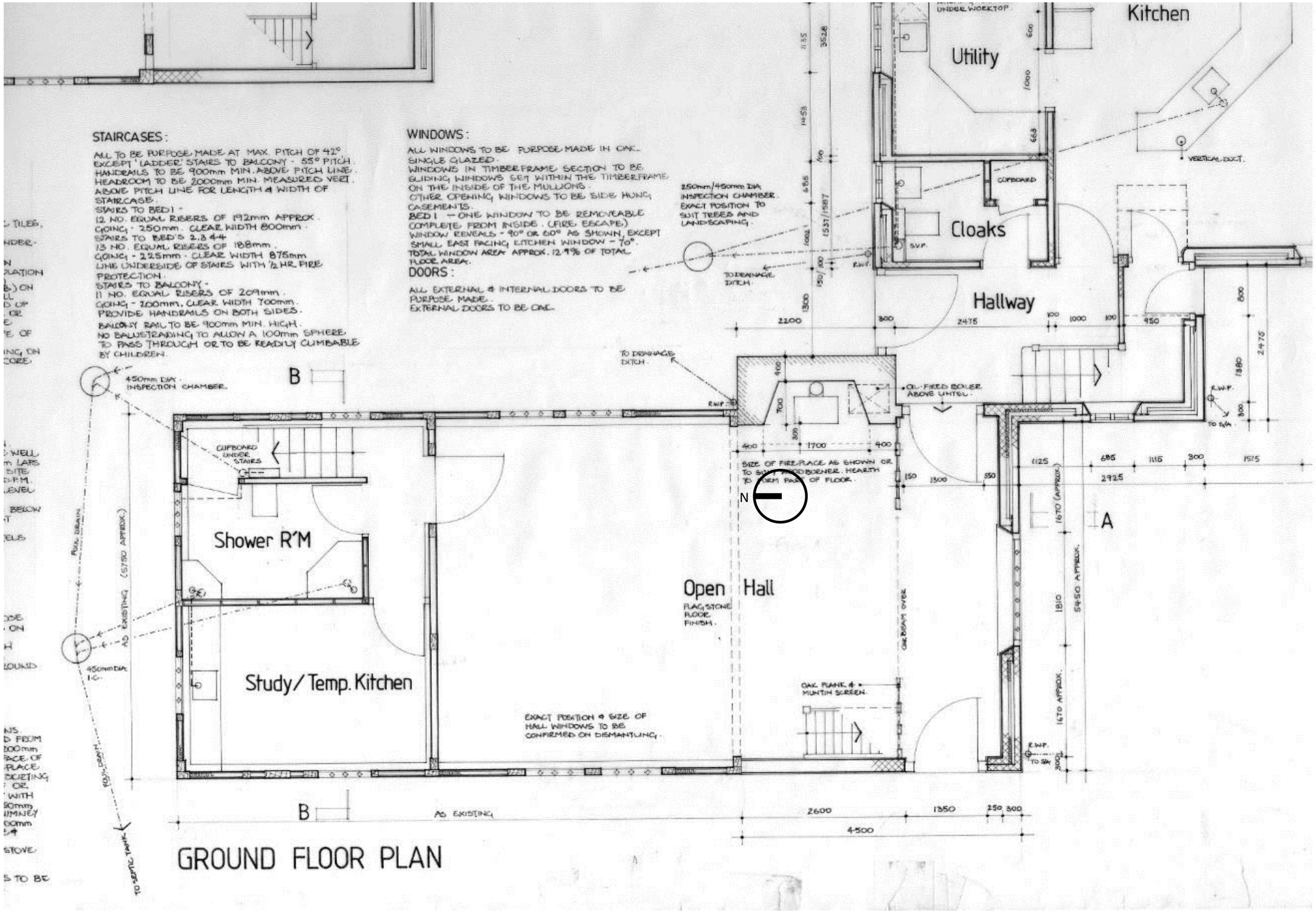


Figure 324 Hacton Cruck ground floor plan. Note that new-build to southeast has not been constructed to date. Source: (Jacqueline Demaus Architect, 2001)

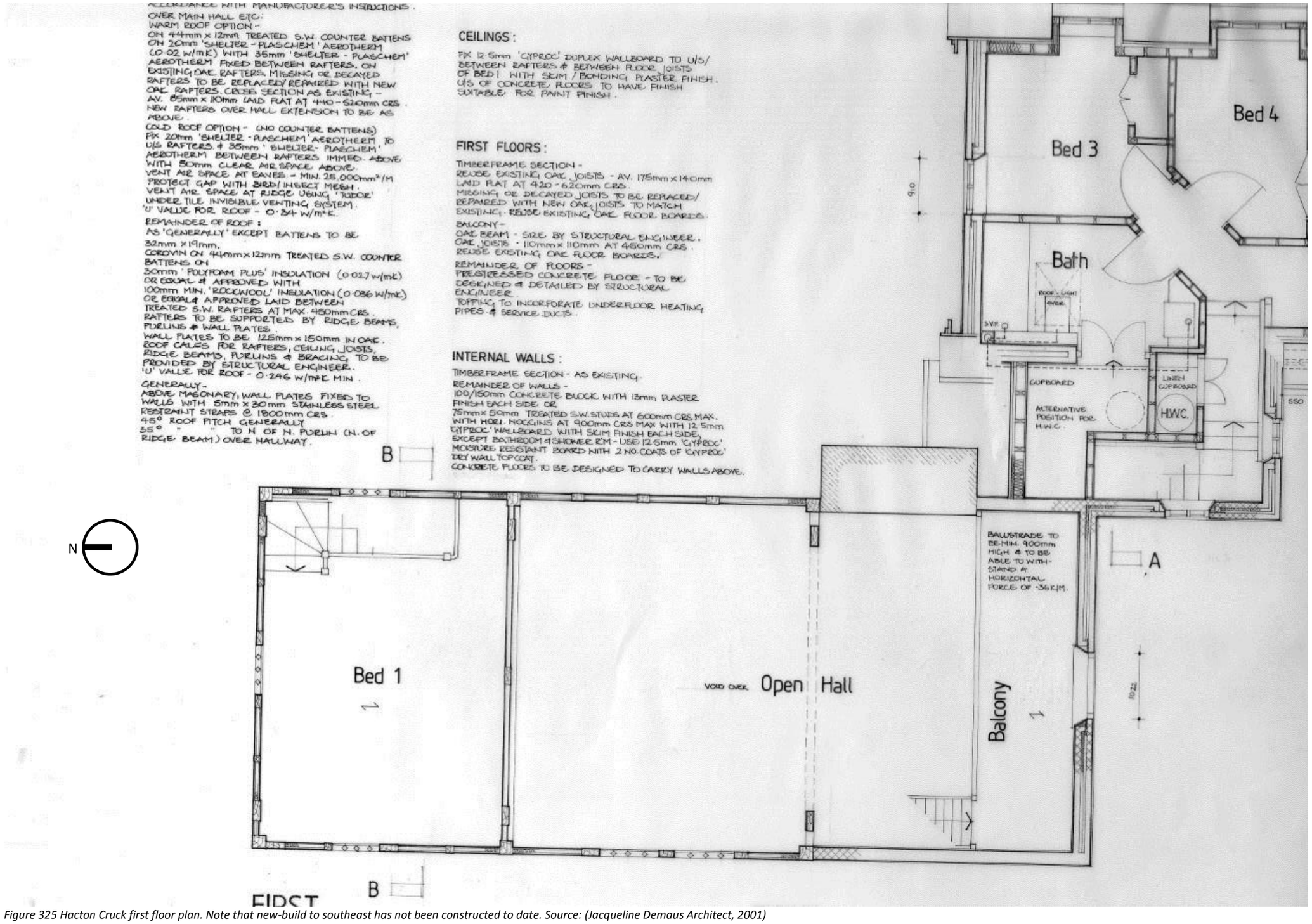


Figure 325 Hacton Cruck first floor plan. Note that new-build to southeast has not been constructed to date. Source: (Jacqueline Demaus Architect, 2001)

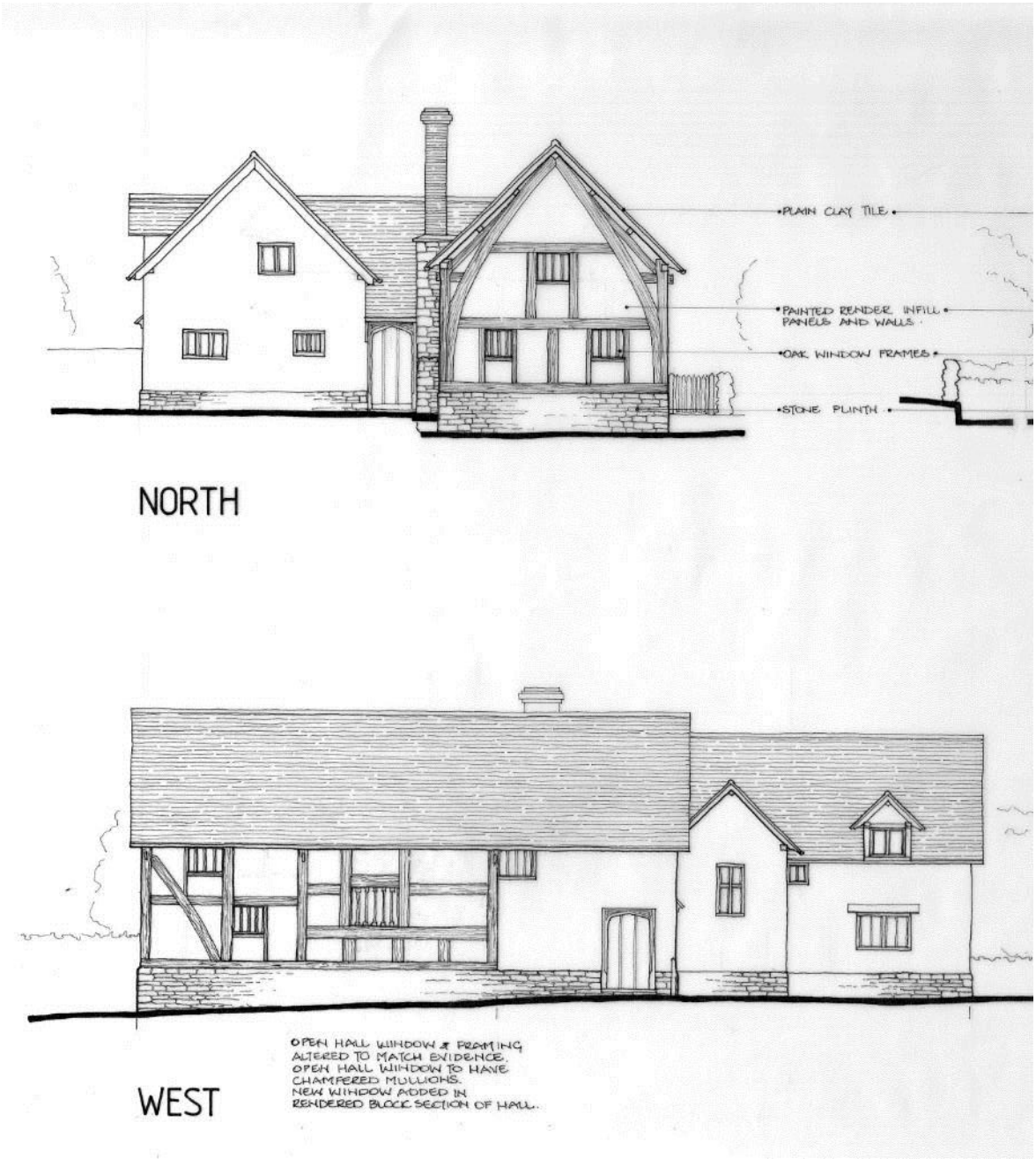


Figure 326 Hacton Cruck North and West Elevations. Note that new-build to southeast has not been constructed to date. Source: (Jacqueline Demaus Architect, 2001)

Figure 327 Hacton Cruck East and South Elevations. Note that new-build to southeast has not been constructed to date. Source: (Jacqueline Demaus Architect, 2001)

Figure 328 Hacton Cruck, longitudinal section through laser scan Source: (Author's own, 2016)

Figure 329 Hacton Cruck, perspective of longitudinal section through laser scan Source: (Author's own, 2016)

Figure 330 Hacton Cruck, cross section through laser scan Source: (Author's own, 2016)

Figure 331 Hacton Cruck, perspective of cross section through laser scan Source: (Author's own, 2016)

Appendix C2

Plans, Elevations and Sections of The Oaks, Brockhampton

Address: Near, A44, Worcester, Herefordshire WR6 5UQ, UK

Grid Reference: SO 70101 55469

Designation list entry number: 1082342

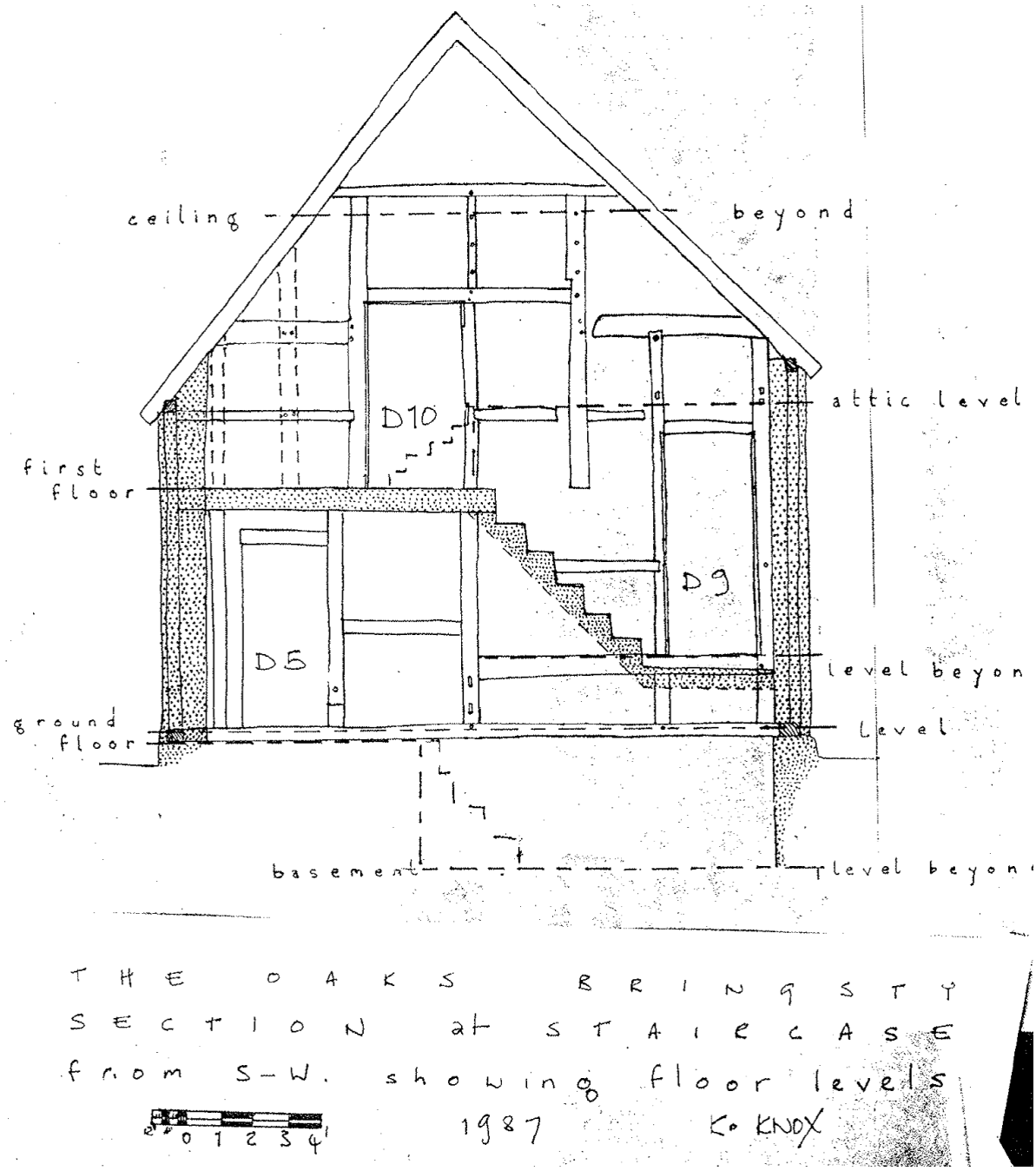


Figure 332 The Oaks, Bromyard. Cross section through staircase. Source: (National Trust, Knox, 1987)

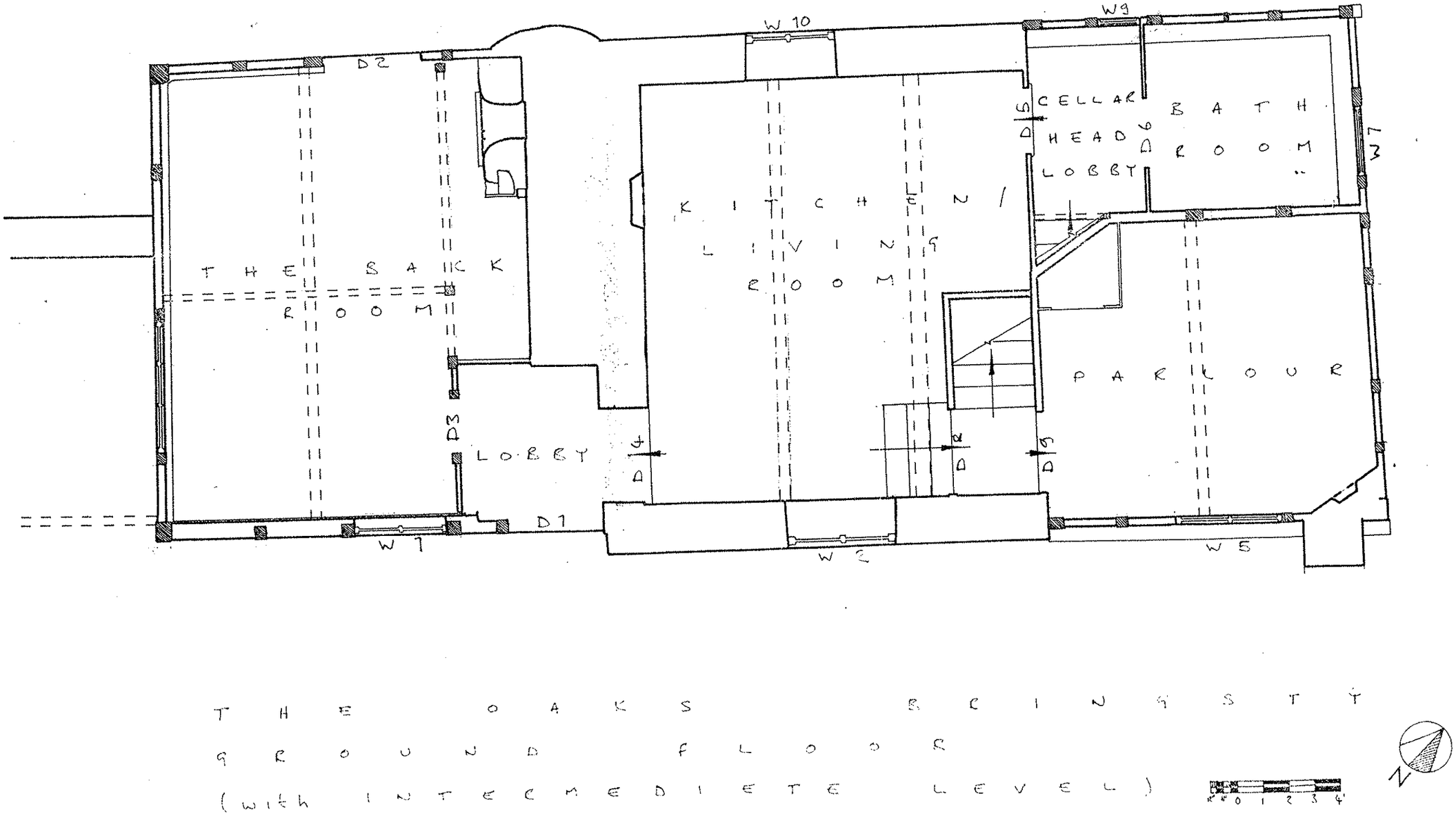


Figure 333 The Oaks, Bromyard. Ground floor plan, pre-retrofit. Source: (National Trust, Knox, 1987)

Figure 334 The Oaks, Bromyard. First floor plan (above) and semi basement plan (below), pre-retrofit. Source: (National Trust, Knox, 1987)

Appendix C3

Plans, Elevations and Sections of The Old Mayor's Parlour and No.25 Church Street

Address: 24 & 25 Church Street, Hereford, Herefordshire, HR1 2LR, UK

Grid Reference: SO 50983 39895

Designation list entry number: 1280302

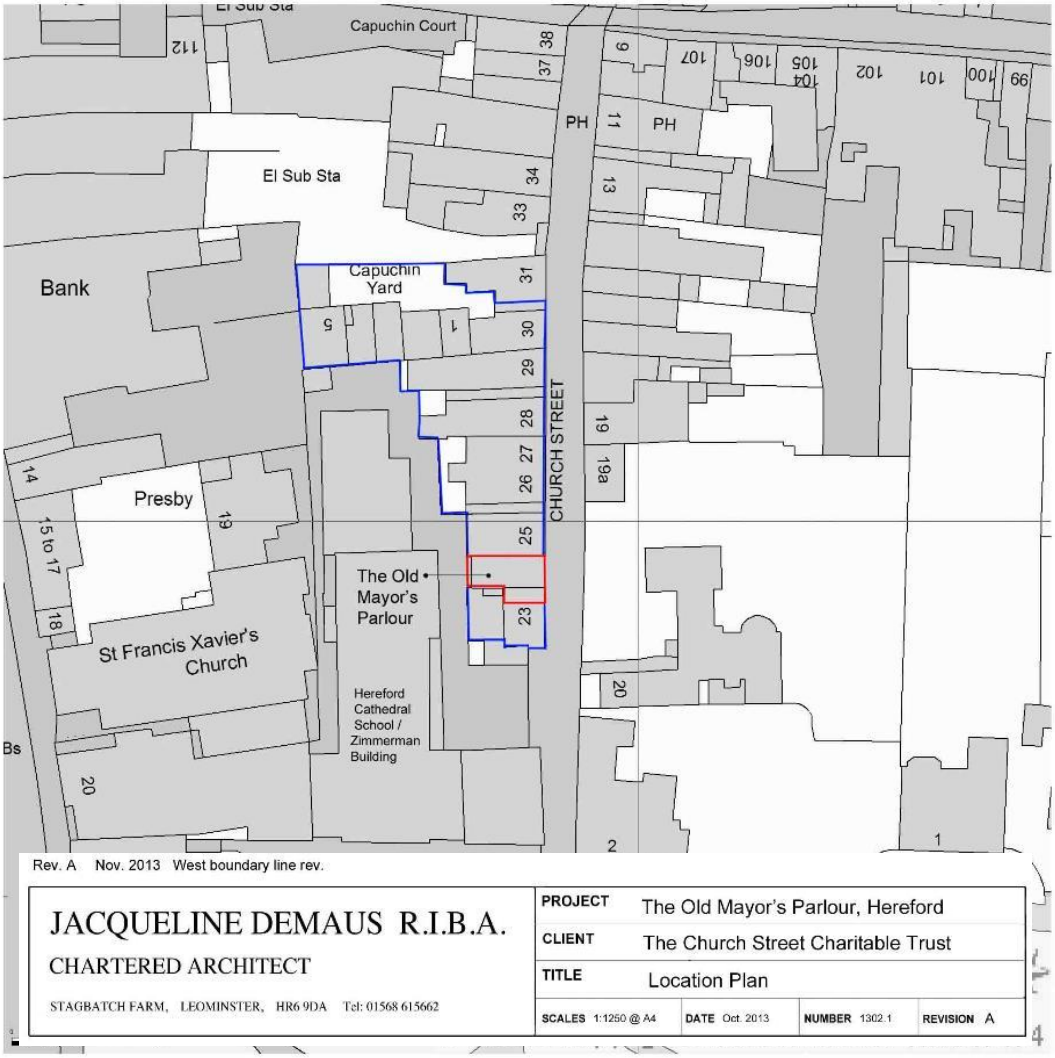


Figure 335. Old Mayor's Parlour and No.25 Church Street. Site location plan. Source: (Jaqueline Demaus Architect, 2013)

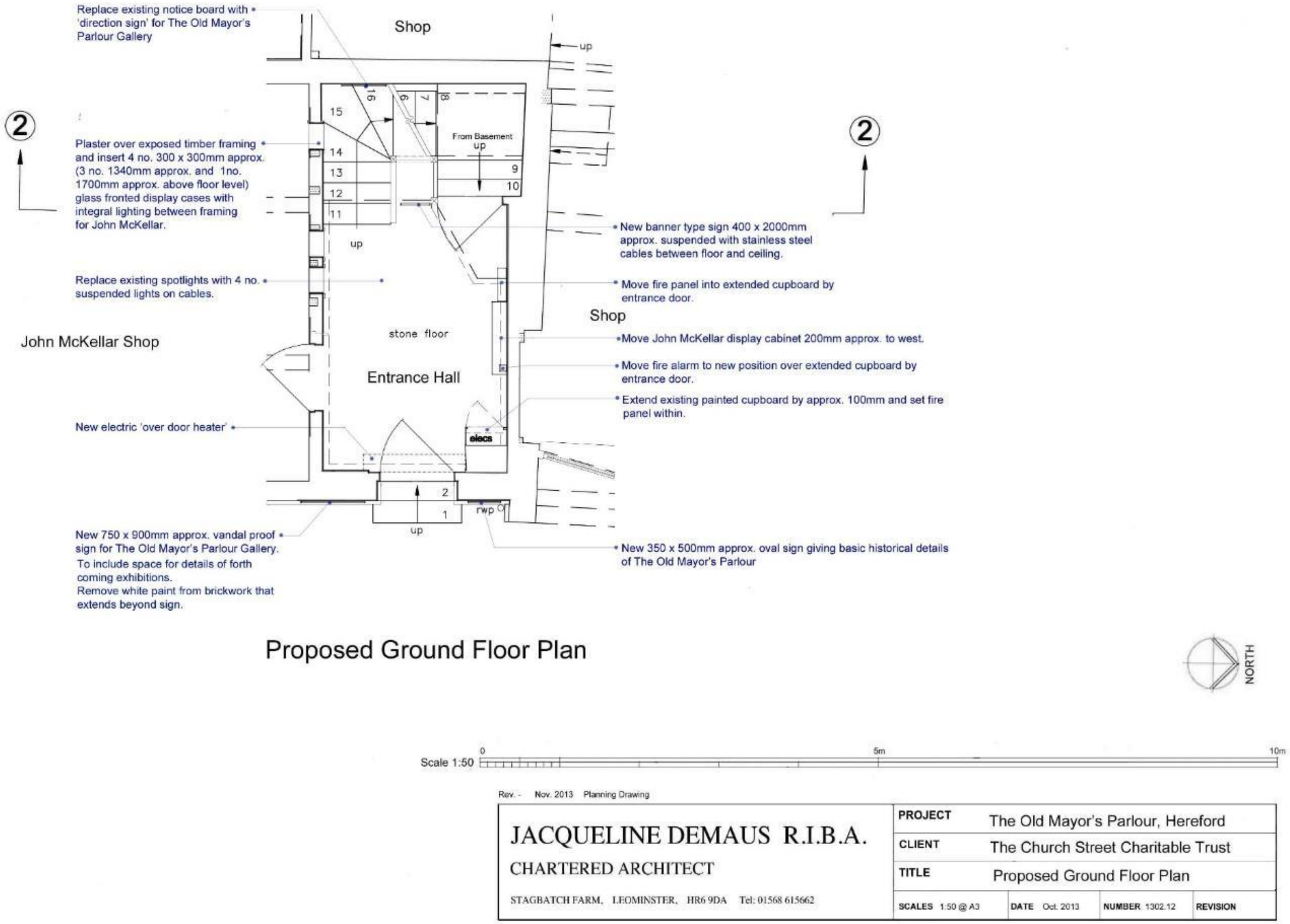


Figure 336 Old Mayor's Parlour. Ground floor plan, post-retrofit. Source: (Jaqueline Demaus Architect, 2013)

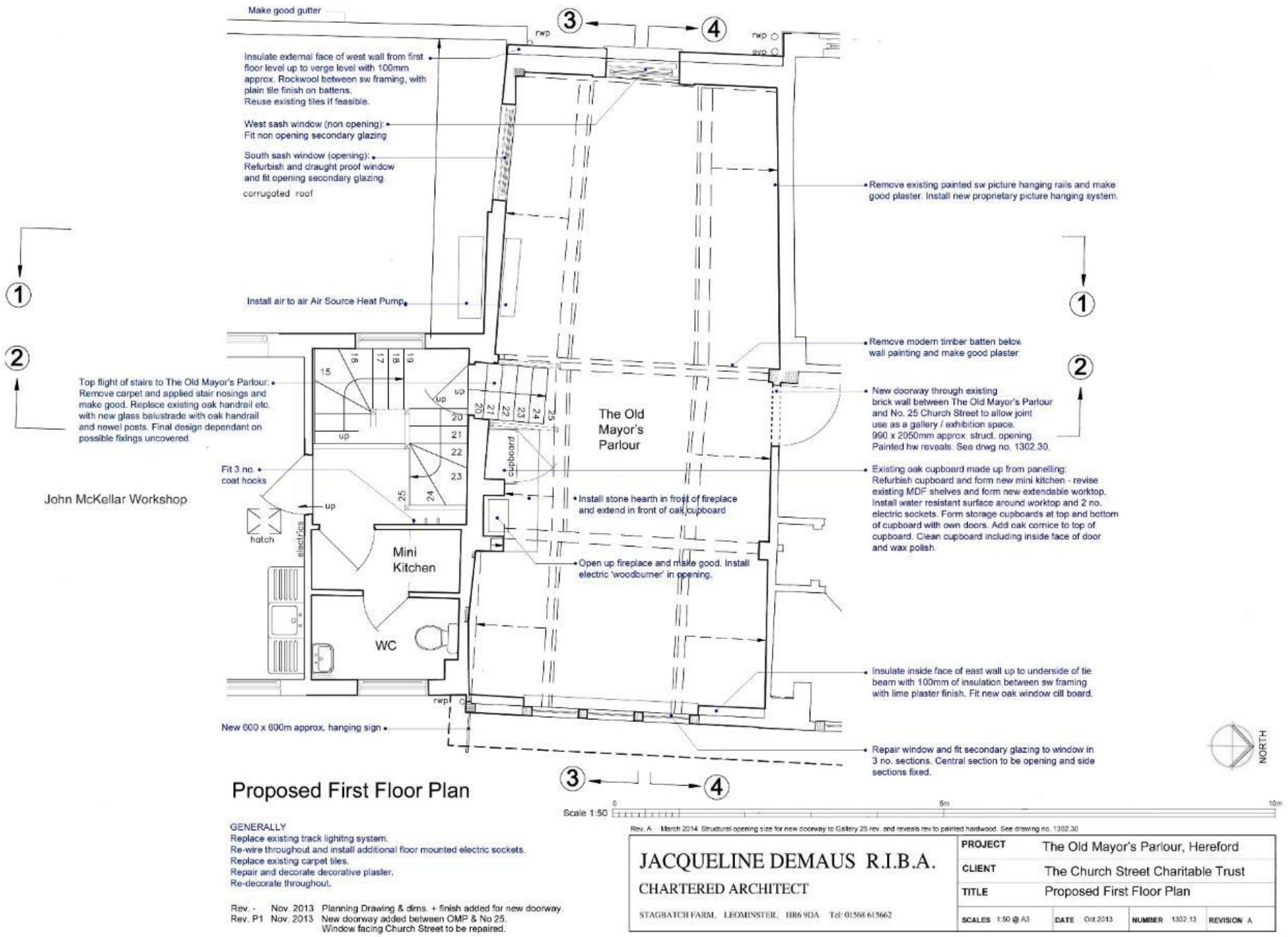


Figure 337 Old Mayor's Parlour. Ground floor plan, post-retrofit. Source: (Jaqueline Demaus Architect, 2013)

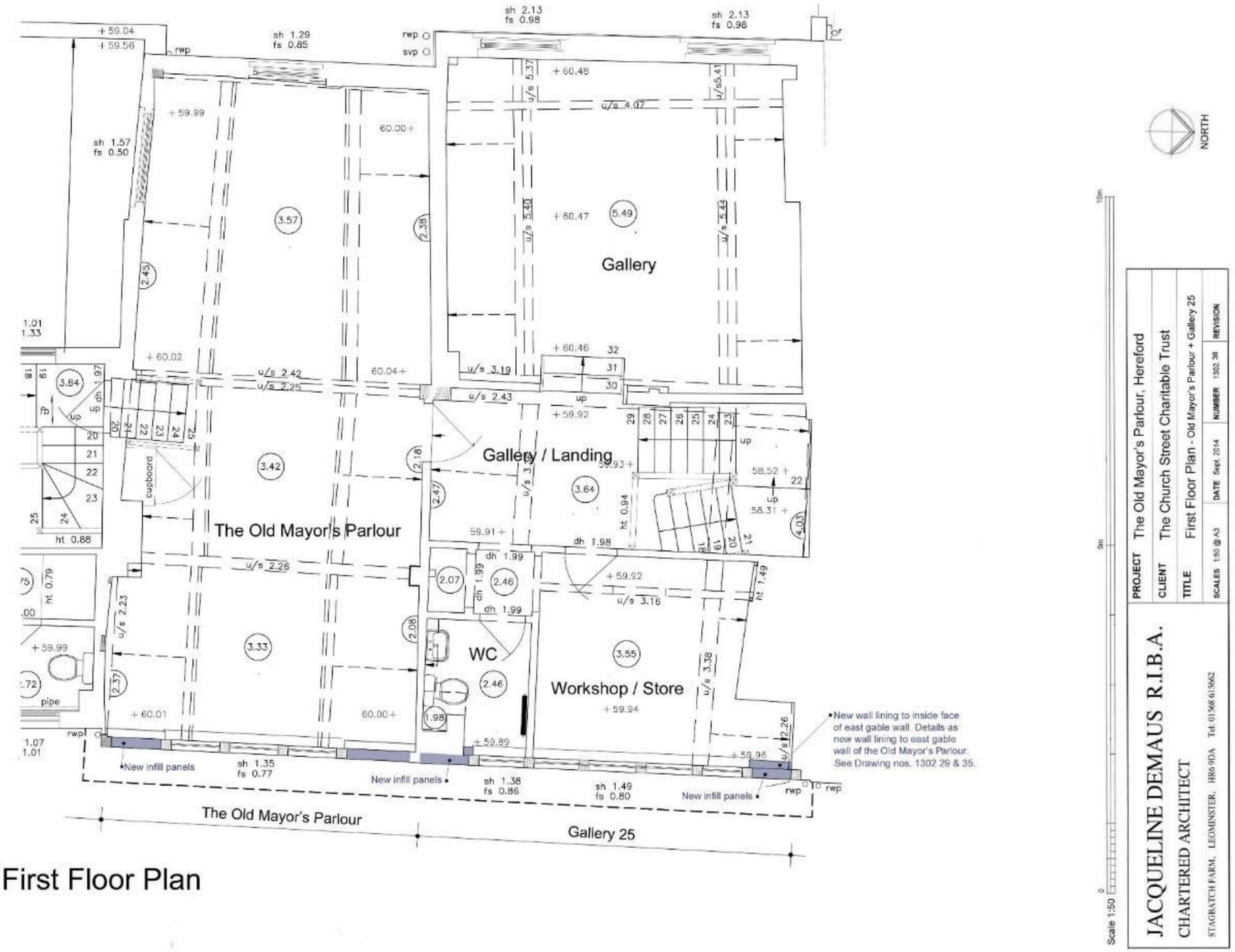


Figure 338 Old Mayor's Parlour and No.25 Church Street. Fround floor plan, post-retrofit. Source: (Jaqueline Demaus Architect, 2014)

Proposed Church Street / West Elevation

Figure 339 Old Mayor's Parlour and No.25 Chruch Street. East Elevation (labelled incorrectly on drawing), post-retrofit. Source: (Jaqueline Demaus Architect, 2013)

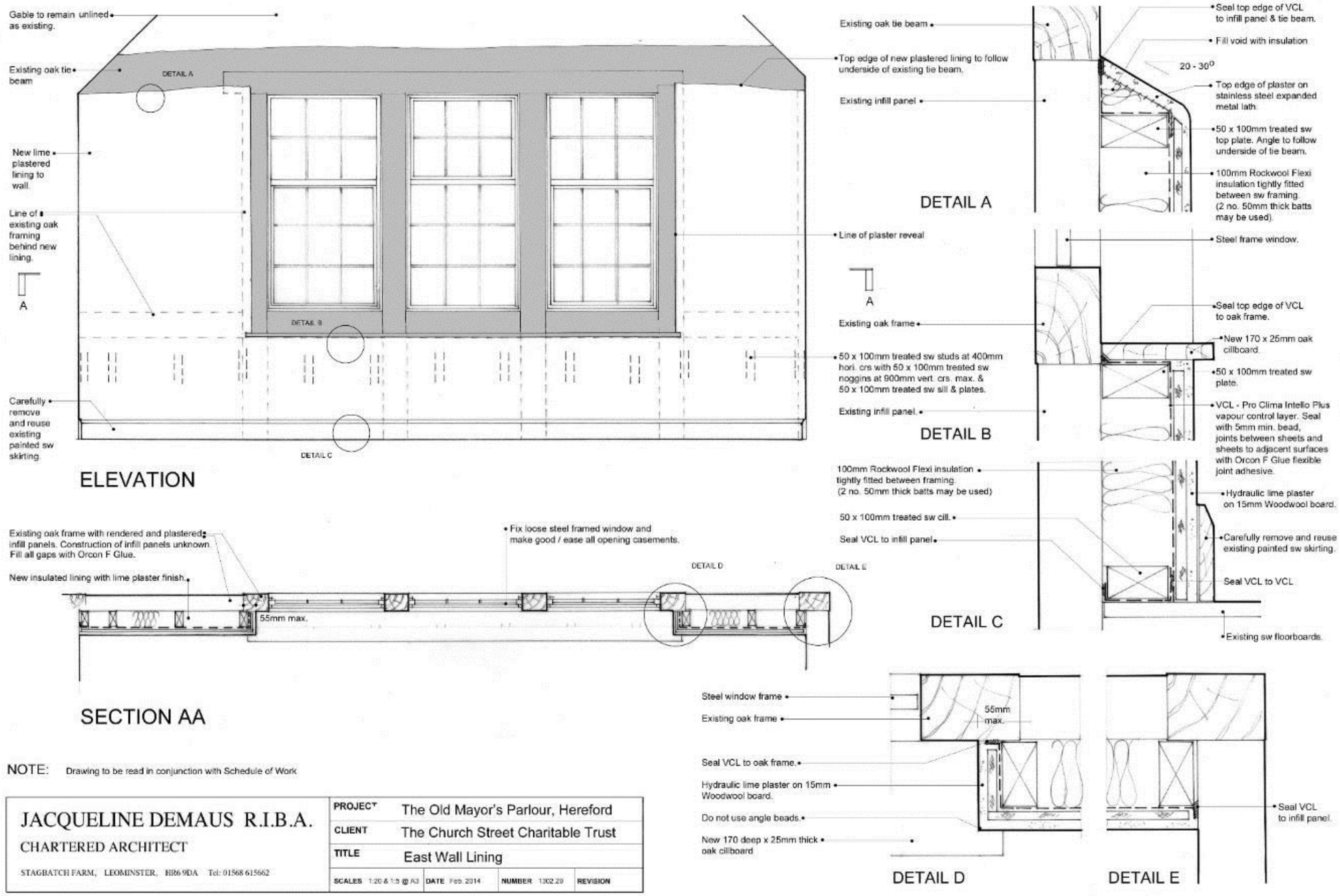
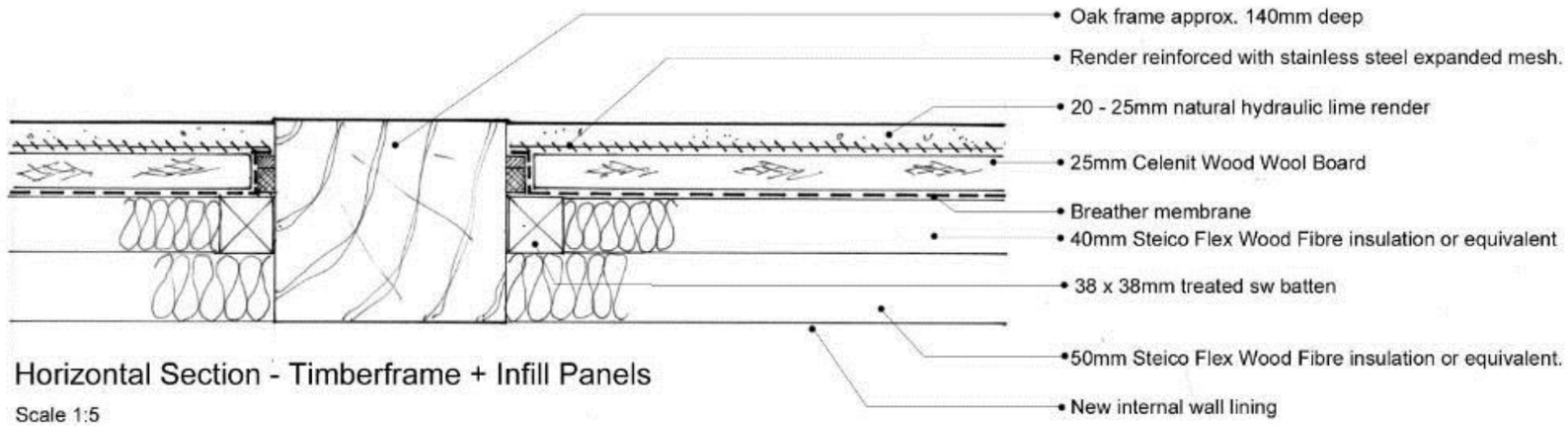
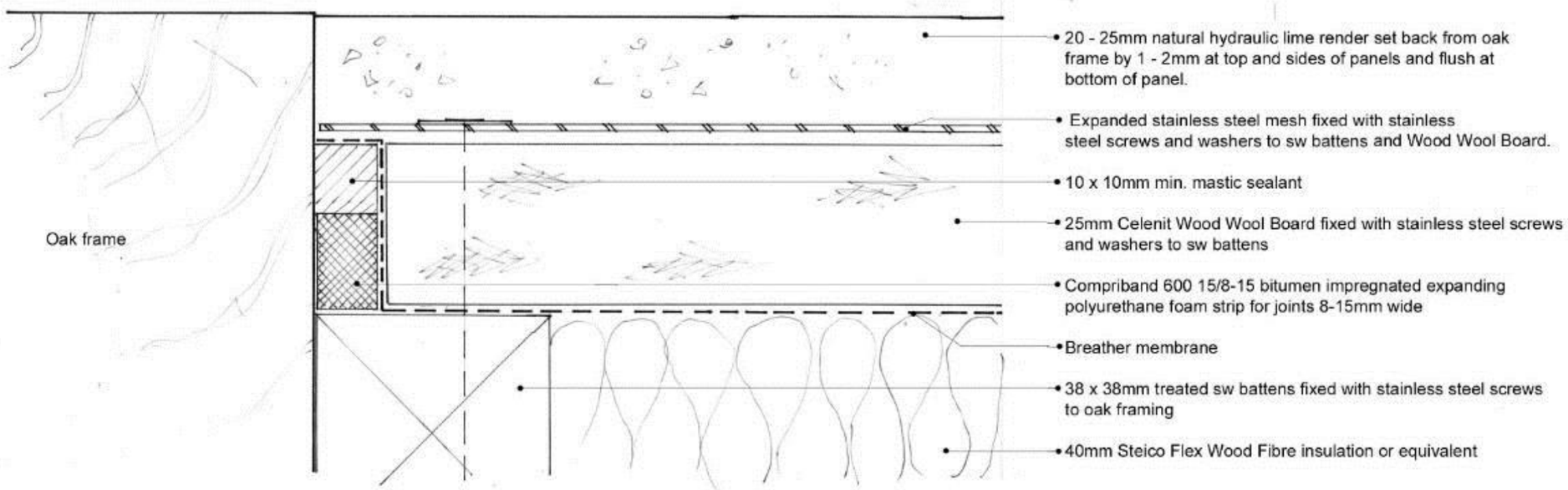


Figure 340 Old Mayor's Parlour. Details for internal lining to first floor. Source: (Jaqueline Demaus Architect, 2014)



Horizontal Section - Timberframe + Infill Panels

Scale 1:5



Horizontal Section - Infill Panel Detail

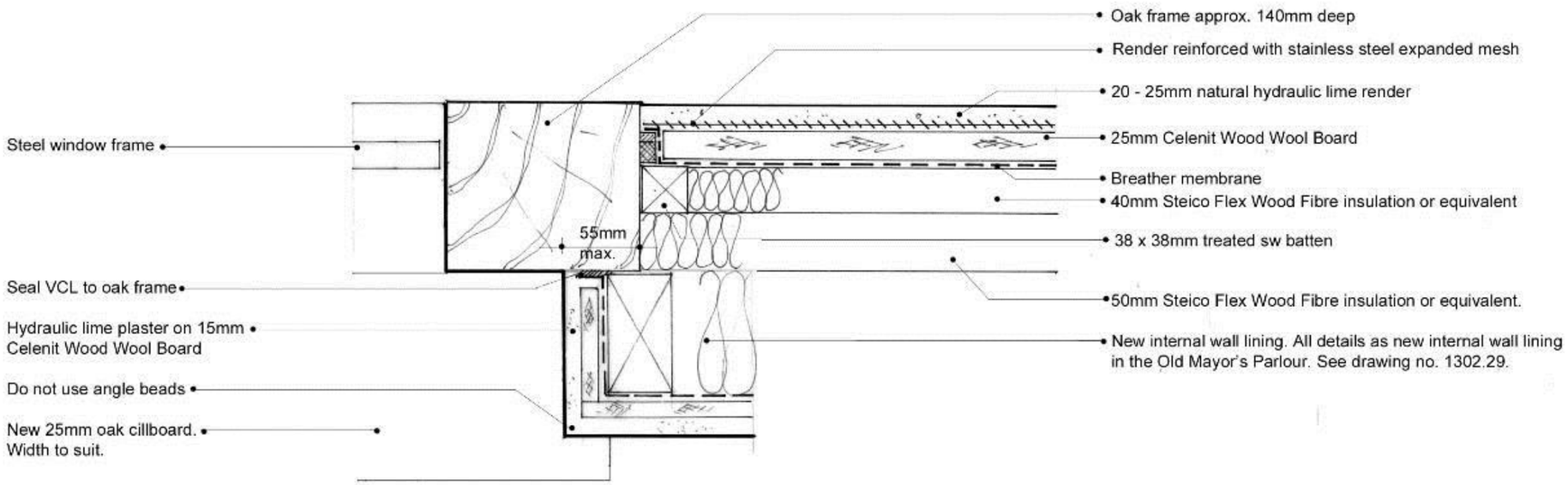
Scale 1:1

JACQUELINE DEMAUS R.I.B.A. CHARTERED ARCHITECT STAGBATCH FARM, LEOMINSTER, HR6 9DA Tel: 01568 615662	PROJECT	The Old Mayor's Parlour, Hereford		
	CLIENT	The Church Street Charitable Trust		
	TITLE	Proposed Infill Panel Detail - OMP		
	SCALES 1:1 & 1:5 @ A4	DATE Sept. 2014	NUMBER 1302.34	REVISION A

Note: Infill panel detail based on non-traditional infill panel detail recommended by English Heritage in 'Practical Building Conservation Timber'

Rev. A: OMP added to title block.
Stainless steel mesh to cover whole of panel.

Figure 341 Old Mayor's Parlour. Replacement panel infill detail. Source: (Jaqueline Demaus Architect, 2014)



Horizontal Section - Timberframe + New Infill Panels + New Internal Wall Lining.

Scale 1:5

JACQUELINE DEMAUS R.I.B.A. CHARTERED ARCHITECT STAGBATCH FARM, LEOMINSTER, HR6 9DA Tel: 01568 615662	PROJECT	The Old Mayor's Parlour, Hereford		
	CLIENT	The Church Street Charitable Trust		
	TITLE	Proposed Infill Panel + Lining Detail - Gallery 25		
	SCALES 1:5 @ A4	DATE Sept. 2014	NUMBER 1302.35	REVISION

Note: Infill panel detail based on non-traditional infill panel detail recommended by English Heritage in 'Practical Building Conservation Timber'

Drawing to be read in conjunction with drawing nos. 1302.29 & 1302.34A

Figure 342 Old Mayor's Parlour. Replacement panel infill detail showing internal lining. Source: (Jaqueline Demaus Architect, 2014)

Appendix C4

Plans, and laser scan of Nos.25-27 Church Street

Address: 25 & 27 Church Street, Saffron Walden, Essex, UK

Grid Reference: TL 53797 38574

Designation list entry number: 1196155

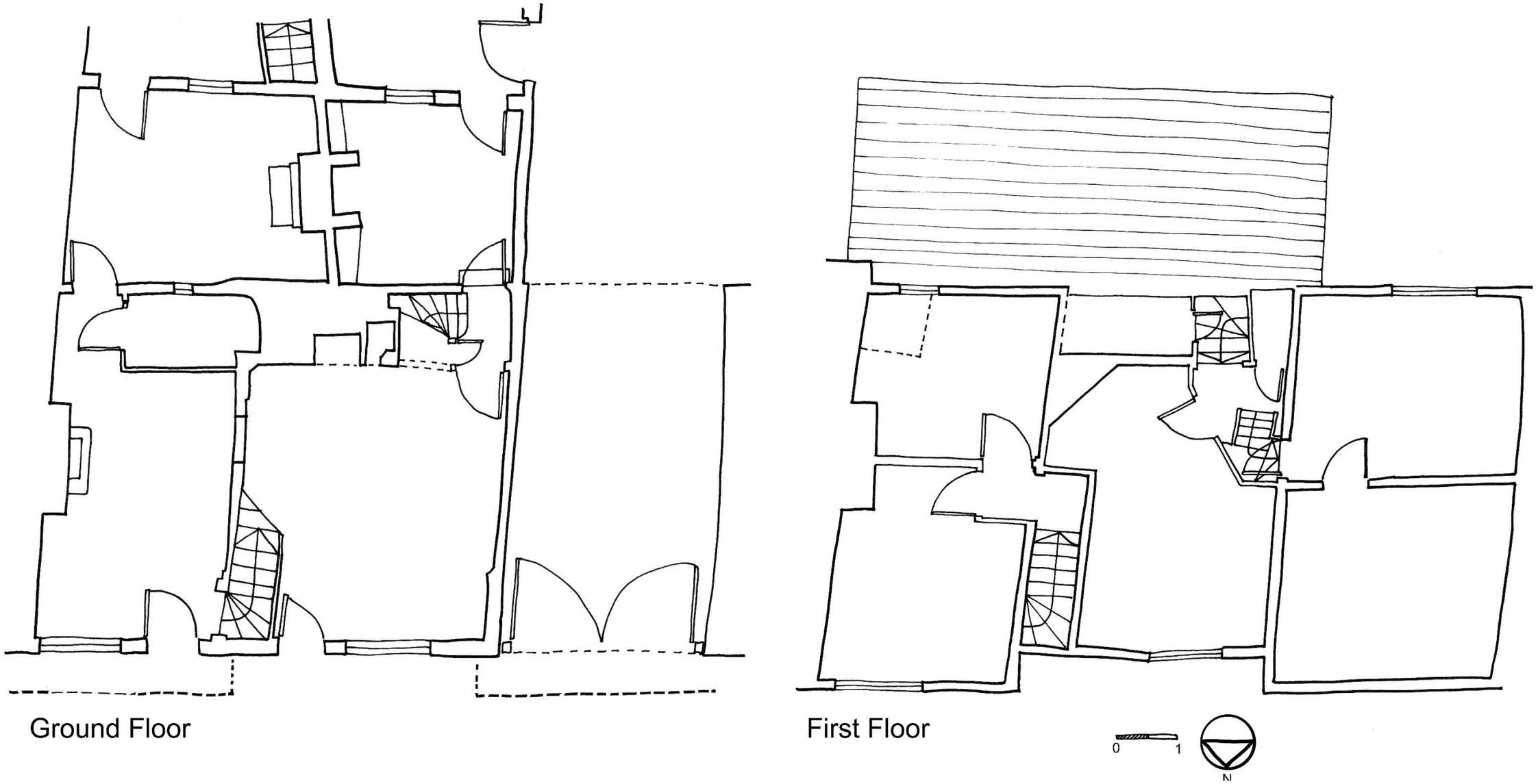


Figure 343. Nos. 25 & 27 Church Street, Saffron Walden, Essex, plans. Source: (Author's own based on drawings by (Kent, 2015)

Figure 344. Nos 25 & 27 Church Street, Saffron Walden, Essex, laser scan of north façade. Source: (Author's own, 2017

Appendix C5

Plans, and Section of Old Stokes Farm, Battisford

Address: Straight Road, Battisford, Stowmarket, IP14 2NB

Grid Reference: TM 02797 53850

Designation list entry number: 1032955

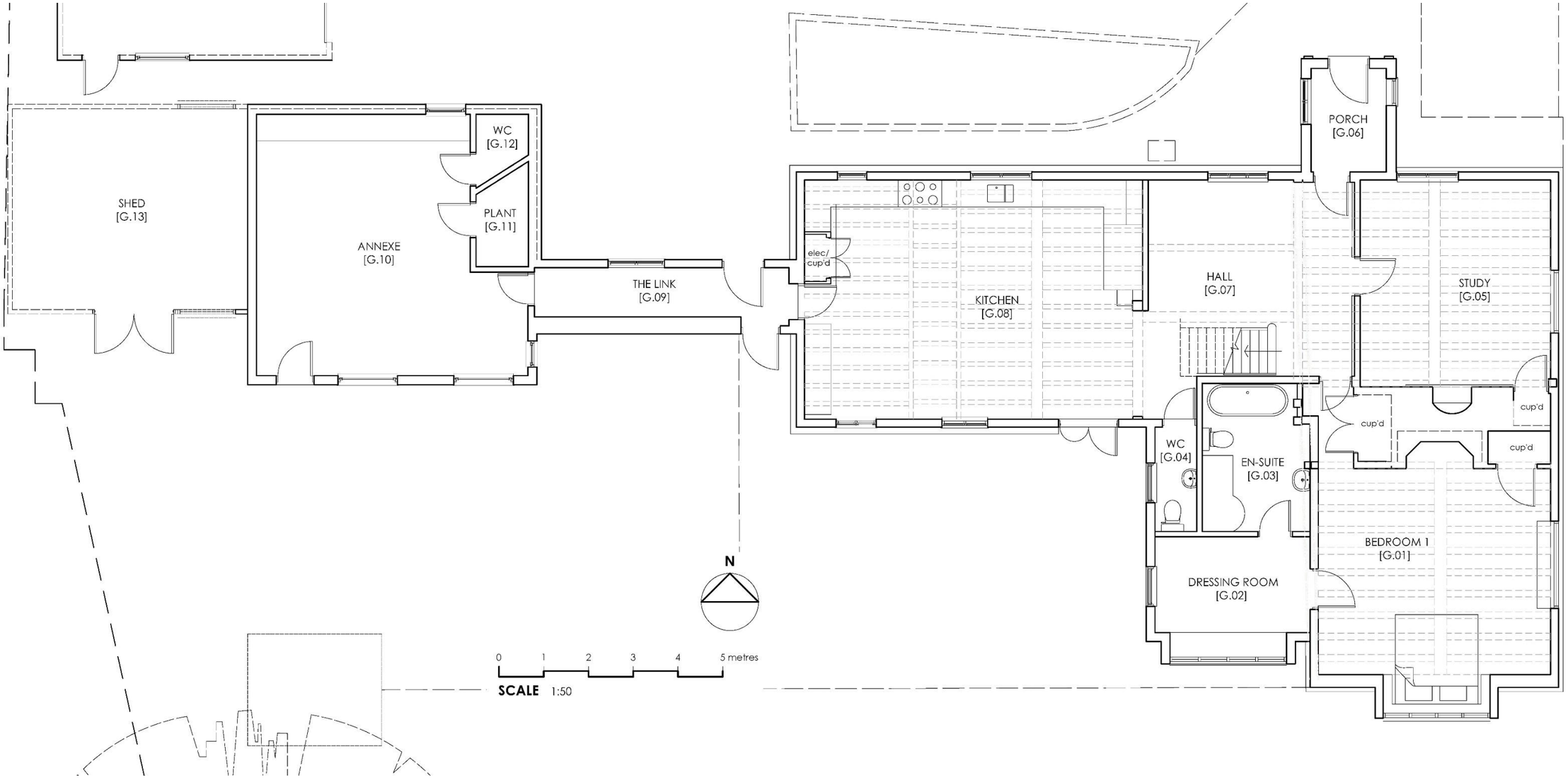


Figure 345. Ground floor Plan. Old Stokes Farm, Battisford, Suffolk. Source: (Andrew Faulkner Associates Ltd, 2016)

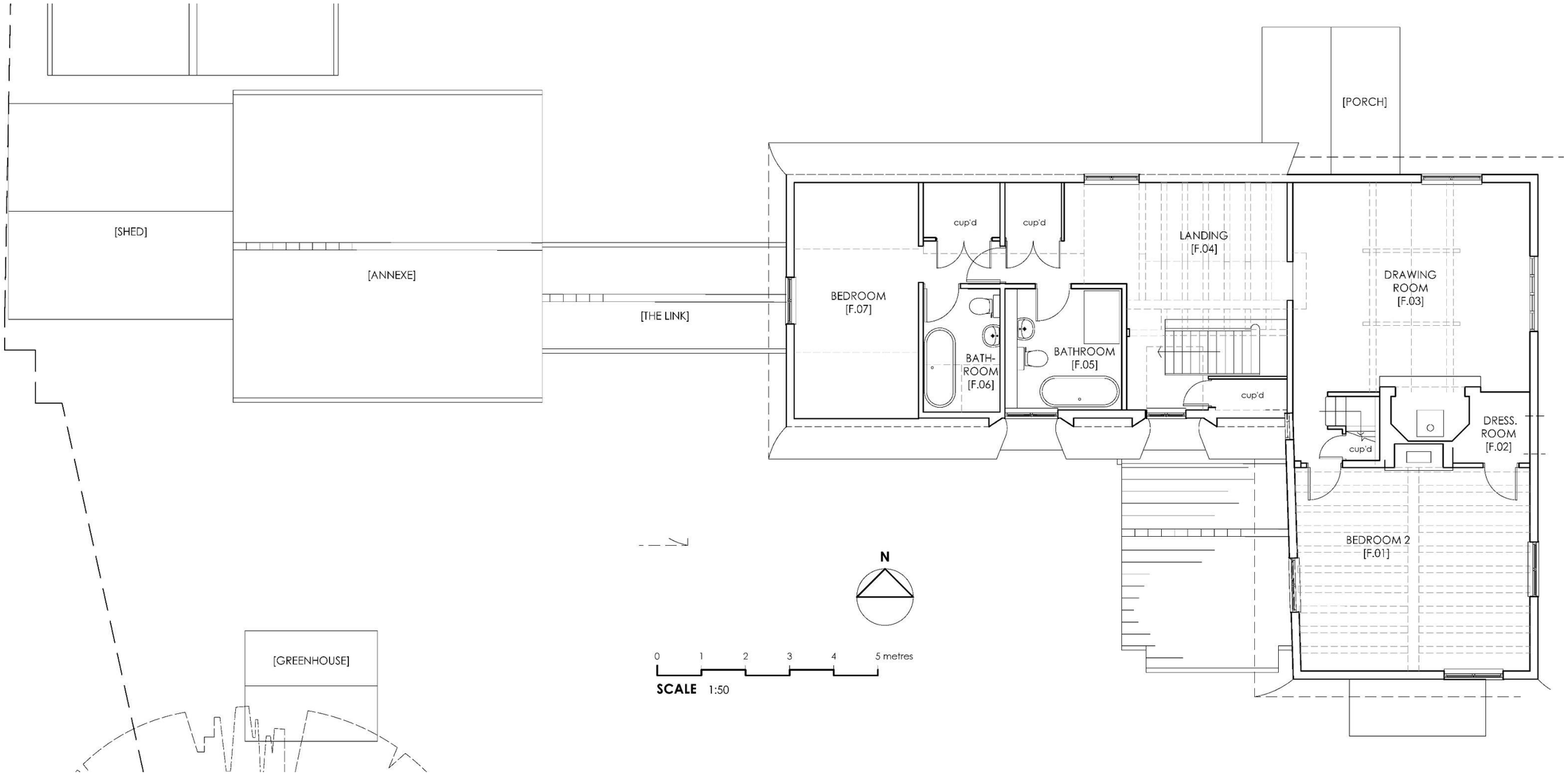


Figure 346. First floor Plan. Old Stokes Farm, Battisford, Suffolk. Source: (Andrew Faulkner Associates Ltd, 2016)

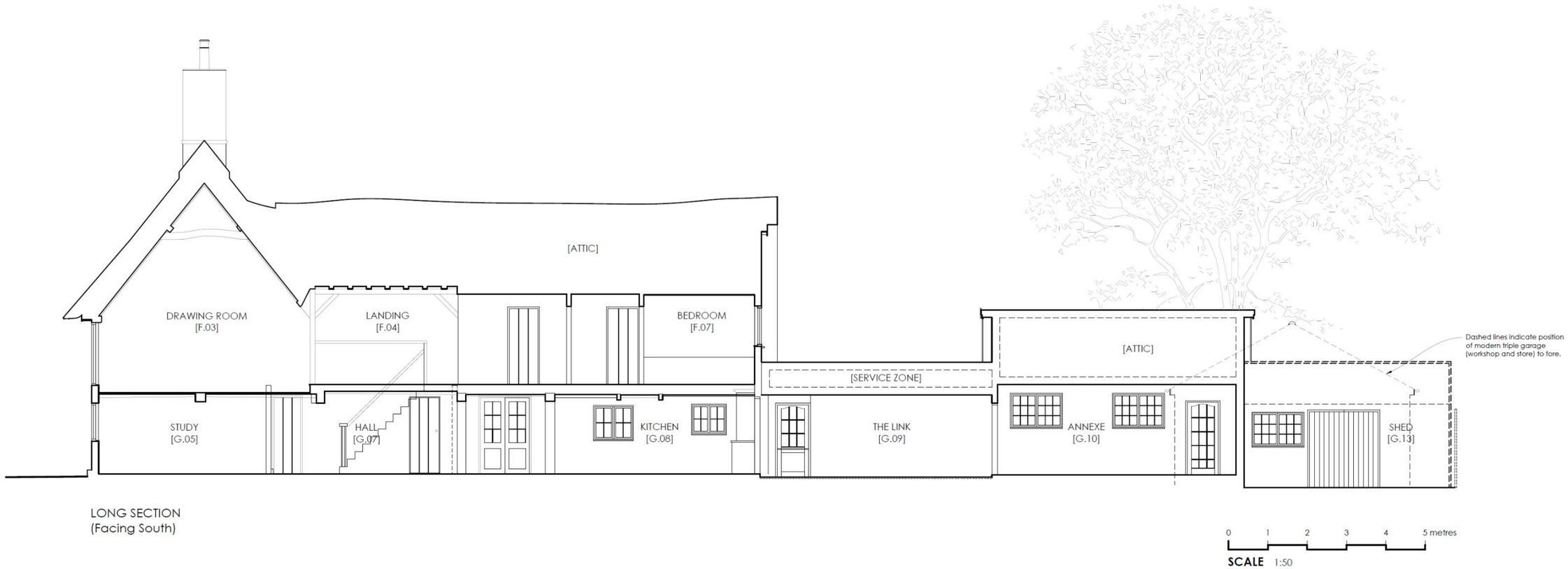


Figure 347. Long section. Old Stokes Farm, Battisford, Suffolk. Source: (Andrew Faulkner Associates Ltd, 2016)

APPENDIX D

Detailed methodology for Pressure Testing Calculations

There follows a description of the use of the methodology defined by BS EN ISO 9972:2015 (British Standards Institution, 2015b), to calculate the air permeability index ($m^3/h/m^2$), the air change rate at 50 Pascal (/hr) and under normal unpressurised conditions, and the effective leakage area.

Firstly the fan pressure readings (ΔP_{Fan}) are converted into an airflow rate (q_r) using the following equation:

$$Q_r = a\ (\Delta P_{Fan})^b x\ cf \qquad (2)$$

Where :

q_r is the fan airflow rate
ΔP_{Fan} is the fan pressure readings
a is the manufacturers coefficient dependant on use of blanking plates or free fan
b is the manufacturers exponent dependant on use of blanking plates or free fan
cf is the conversion factor to convert ft^3/m to m^3/s = 0.000471946667

Once converted, these fan airflow rates (q_r) are corrected to what the BS terms a measured airflow rate (q_m) to allow for the barometric pressure and temperature at the time of measurement. This correction takes place using the following formula:

$$q_m = q_r \left(\frac{\rho_e}{\rho_0}\right) \qquad (3)$$

Where

q_m is the measured airflow rate
ρ_e is the external air density (kg/m^3)
ρ_o is the air density (kg/m^3) at standard conditions (20°C and 1.01325 x 10^5 Pa.)

The air density (kg/m^3) at standard conditions (ρ_o) is taken to be 1200 kg/m^3 and the external air density (ρ_e) is calculated:

$$\rho_e = \left(\frac{293.15\rho_o}{101325}\right)\left(\frac{\rho_{bar}}{T_e}\right) \tag{4}$$

Where
ρ_{bar} is the average barometric pressure at time of monitoring
T_e is the absolute average external dry bulb air temperature at time of monitoring in Kelvin (K)

The measured airflow rates (q_m) then undergo a further conversion to airflow rates through the building envelope (q_{env}). This conversion takes into account the specific internal and external air densities encountered at the time of measurement. To avoid the measuring of air densities, an approximation is made using the measured dry bulb air temperatures.

$$q_{env} = q_m \left(\frac{\rho_{int}}{\rho_e}\right) \approx q_m \left(\frac{T_e}{T_{int}}\right) \tag{5}$$

Where:
ρ_{int} is the internal air density (kg/m^3)
ρ_e is the external air density (kg/m^3)
T_{int} is the internal air absolute temperature (K)
T_e is the external air absolute temperature (K)

These airflow rates through the building envelope (q_{env}) are then plotted against the measured building pressure difference (ΔP). The resulting graph should show a smooth curve.

To enable the calculation of flow rates at other building pressure differences, this curve must be extrapolated. The equation of this curve can be represented as:

$$q_{env} = C_{env} (\Delta P)^n \tag{6}$$

Where:
C_{env} is the airflow coefficient
ΔP is the building pressure difference
n is the airflow exponent

Due to the difficulty of fitting a curve to the plotted measurements, it is easier to plot the logarithm of the airflow rate through the building envelope (q_{env}) and the building pressure difference (ΔP) and then fit a linear equation of:

$$\log_e(q_{env}) = n \times \log_e(\Delta P) + \log_e(C) \quad (7)$$

As all linear equations follow the form $y = mx + b$ where b is the intercept and m is the gradient, the airflow coefficient (C_{env}) will therefore be the intercept, and the airflow exponent (n) the gradient of the best fit line through the plotted logarithms of the data. The coefficient of determination (R^2) of this best fit line gives the reliability of the fit. This value should be as close to 1 as possible. Erroneous readings distorting the graph may need to be deleted to achieve this.

Once calculated, the air leakage coefficient (C_L) is obtained by correcting the airflow coefficient (C_{env}) to standard conditions. These are defined by the standard as 20°C and 1.013 x 10^5 Pa. The formula for this correction for depressurization is:

$$C_L = C_{env} \left(\frac{\rho_e}{\rho_0}\right)^{1-n} \approx C_{env} \left(\frac{T_o}{T_e}\right)^{1-n} \quad (8)$$

Where
ρ_o is the air density at standard conditions (kg/m^3)
T_o is the air absolute temperature at standard conditions (K)

The air leakage rate (q_{pr}) at the reference pressure difference (ΔP_r) is determined using the following formula:

$$q_{pr} = C_L (\Delta P_r)^n \quad (9)$$

The air leakage rate is normally quoted for a reference pressure difference of 50 Pa. To express this in m^3/h the result must be multiplied by 3600. Using this figure, the following derived quantities can then be calculated:

Air change rate at reference pressure difference

This is normally calculated for a pressure difference of 50 Pa. To calculate, the previously calculated air leakage rate at 50 Pa., is divided by the internal volume of the building.

$$n_{pr} = \frac{q_{pr}}{V} \tag{10}$$

Where
n_{pr} is the air change rate a reference pressure difference
V is the volume of the building calculated as previously described

Equation 10 can also be used to calculate the air change rate under normal unpressurised conditions.

Effective leakage area

The effective leakage area ELA_{Epr} at a given pressure difference can be calculated following formula 11. This is usually calculated for a reference pressure difference of 10 Pa:

$$ELA_{Epr} = \left(\frac{\rho_o}{2}\right)^{0.5} (\Delta P_r)^{n-0.5} \tag{11}$$

Where
ELA_{EPr} is the effective leakage area at the reference pressure difference
ρ_o is the is the air density at standard conditions (kg/m^3)
ΔP is the building reference pressure difference
n is the airflow exponent

Air permeability index

Finally, the air permeability index or specific leakage rate at 50 Pa (q_{E50}) is calculated using formula 12. The air permeability index is measured in $m^3/h/m^2$

$$q_{E50} = \frac{q_{50}}{A_E} \tag{12}$$

Where

q_{E50} is the air permeability index or specific leakage rate at 50 Pa.

q_{50} is the air leakage rate at 50 Pa

A_E is the internal surface area of the building, calculated as previously described.

In order to comply with UK building regulations part L, buildings must have an air permeability index <10 $m^3/h/m^2$ (HM Government, 2016c).

APPENDIX E

Results of Timber surface Moisture Measurements

7.7	8.1	9.3	12.6	9.2
7.725		9.75		8.8
7.75		10.2		8.6
7.775		10.9		7.9
7.8	8.4	11.6	11	9
8.3		11.5		9.4
8.4		16.2		9.2
9.5		12.2		15.7
9.7	9.6	9	10.8	11.3

Figure 348. Surface moisture content (%) of timbers of north-west wall of living room, The Oaks. As measured 18/11/2016. Source: (Author's own, 2016)

9.2	9	7.7	8.2	8	9.5	9.65	9.8	9.7	8.4	8.6
9.2		8.4		9.4		10.4		8.2		8.4
8.6		8.6		9.8		10.3		9.1		8.2
8.9		11.1		9.5		9.7		10.6		8.1
12.6	9.1	10.3	8.9	8.1	7.6	14.4	9.6	11.7	9.6	8
13.1		8.5		10.1		12.6		8.1		8.1
11.1		11.2		8.5		12.2		10.4		8.2
12.8		10.9		8.2		10.1		13.9		8.95
8.2	9.4	9.3	8.2	9	7.8	7.9	9.5	10.4	10.9	9.7

Figure 349. Surface moisture content (%) of timbers of south-west wall of living room, The Oaks. As measured 18/11/2016. Source: (Author's own, 2016)

10.4	8.4	10.4	12.5	12.2
	8.975		11.15	
	9.55		9.8	
	10.125		9.15	
7.8	10.7	10.3	8.5	12.6
	9.4		8.75	
	8.1		9	
	8.1		9.8	
8.2	8.1	10.1	10.6	8.4

Key (%)
48
42
36
30
24
18
12
6
0

Figure 350. Surface moisture content (%) of timbers of south-east wall of living room, The Oaks. As measured 18/11/2016. Source: (Author's own, 2016)

8.1	9.6	10.8	12.4	12.4
6.4		11.05		9.9
8.2		11.3		10.7
8.6		12.25		10.4
8.1	10.2	13.2	8	10.8
9.6		12.3		11.7
9		16.3		13.1
11.2		13		16.4
10.8	11.2	10.2	11.5	11.1

Figure 351. Surface moisture content (%) of timbers of north-west wall of living room, The Oaks. As measured 28/07/2017. Source: (Author's own, 2017)

9.4	10.3	9.2	10.2	10.3	12.6	11.2	12.1	12.8	9.2	8.1
10.4		9.6		10.5		11.3		11		8.25
11.5		10.4		10.7		12.3		10.5		8.4
11.5		11.3		10.6		11.2		10.4		9.2
12.2	11.4	11.8	10.4	10.7	10.8	14.3	13.2	12.1	11.6	10
10.1		10.6		14.6		15.6		12.1		8.4
10.5		11.4		9.5		13.4		12.8		6.8
10		10.4		9		12		13.8		7.6
9.8	12.2	10.9	10.3	9.2	11.4	11	12.2	11.6	9.6	8.4

Figure 352. Surface moisture content (%) of timbers of south-west wall of living room, The Oaks. As measured 28/07/2017. Source: (Author's own, 2017)

12.3	8.7	11.4	13.7	14
	9.825		12.65	
	10.95		11.6	
	12.075		11.2	
11.8	13.2	11.2	10.8	12.5
	11.7		11.75	
	10.2		12.7	
	10.7		12.3	
11.2	11.2	11.6	11.9	9.5

Key (%)
48
42
36
30
24
18
12
6
0

Figure 353. Surface moisture content (%) of timbers of south-east wall of living room, The Oaks. As measured 28/07/2017. Source: (Author's own, 2017)

Within cupboard not surveyed	14.4	10.7	11.5	12.3	14.9	17.5	11.6
		11.3				11	
		10.1				8.9	
		10.6				9	
	15.5	9.5	10.25	11	10.6	10.2	11.9
		11.5				9.7	
		16.4				14.7	
		35.7				25.8	
	21.6	21.6	28.5	36.3	31.4	27.9	16.8

Figure 354. Surface moisture content (%) of timbers of north-east wall of bathroom, The Oaks. As measured 18/11/2016. Source: (Author's own, 2016)

9.2				10.8		7.5
9.5	8.3	7.1	8.95	10.8		9
9				10.05		9.25
8.55			9.3	9.3	12.3	9.5
8.55				8.2		11.3
8.1				7.1		13.1
8.75				8.5		14
8.75				8.5		14.9
9.4	13.95	18.5	14.2	9.9	13.2	16.5

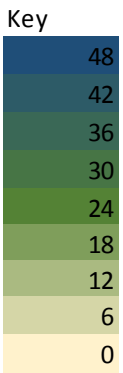


Figure 355. Surface moisture content (%) of timbers of south-east wall of bathroom, The Oaks. As measured 18/11/2016. Source: (Author's own, 2016)

	19.5		16.6		19.1		
	25.3		16		18.2		
	32.9		30.3		39.6		
45	45	48	48	48	48	48	48

Figure 356. Surface moisture content (%) of timbers of south-west wall of cellar, The Oaks. As measured 18/11/2016. Source: (Author's own, 2016)

17.5				23.4		
21.2				26.5		
39.6				43.1		
45.6	46.1	46.8	48	48	47.4	48

Figure 357. Surface moisture content (%) of timbers of north-west wall of cellar, The Oaks. As measured 18/11/2016. Source: (Author's own, 2016)

9.4	9.3	12	15.7	19.4	20.35	21.3	26.7
8.75		9.5				11	
8.1		12.1				8.3	
9.92		20.8				11.9	
11.73	18.3	11.5	12.25	13	12	11	14
8.8		8.6				12	
9.95		16.2				20.9	
11.1		26.4				27.5	
17.85	24.6	23	31.1	30.4	34.8	30.1	21.2

Figure 358. Surface moisture content (%) of timbers of north-east wall of bathroom, The Oaks. As measured 28/07/2017. Source: (Author's own, 2017)

10.5				11.7		11.6
12.5	11.45	10.4	11.05	11.7		10.3
10.6				13.05		8.9
10.65			21.3	14.4	13.6	7.5
10.65				11.3		10.35
10.7				8.2		13.2
10.5				12.45		14.6
10.5				12.45		16
10.3	13.4	16.5	16.6	16.7	25.5	16.1

Key (%)
48
42
36
30
24
18
12
6
0

Figure 359. Surface moisture content (%) of timbers of south-east wall of bathroom, The Oaks. As measured 28/07/2017. Source: (Author's own, 2017)

	19.1		15.4		17.6		
	24.5		15.8		16.9		
	27.8		25.1		33.6		
39.1	38.3	38	38.9	38.1	39	40.6	39.3

Figure 360. Surface moisture content (%) of timbers of south-west wall of cellar, The Oaks. As measured 28/07/2017. Source: (Author's own, 2017)

17.2				21.3		
19.3				34.4		
34.8				40		
39.1	36.5	28	48	48	48	38.2

Figure 361. Surface moisture content (%) of timbers of north-west wall of cellar, The Oaks. As measured 28/07/2017. Source: (Author's own, 2017)

APPENDIX F

Thermal comfort questionnaires

Thermal comfort questionnaire

Case Study: _____

Temp (°C): RH(%):

Room: _____

Reclining □ Sitting □ Standing □ Activity:

Current activity: _____

Current clothing: _____

1. How do you currently feel?

1	2	3	4	5	6	7
Very cold	Cold	Slightly cool	**Comfortable**	Slightly warm	Hot	**Too Hot**

2. In general in winter how do you feel in the house?

1	2	3	4	5	6	7
Very cold	Cold	Slightly cool	**Comfortable**	Slightly warm	Hot	**Too Hot**

3. Are there any rooms that are particularly cold or hot in winter?

_____

4. In general in summer how do you feel in the house?

1	2	3	4	5	6	7
Very cold	Cold	Slightly cool	**Comfortable**	Slightly warm	Hot	**Too Hot**

5. Are there any rooms that are particularly cold or hot in summer?

_____

6. How do you normally dress inside the house?

Winter	Clothing	Summer
	t-shirt and shorts	
	t-shirt and light trousers	
	+thin jumper or top	
	+thick jumper	
	Coat	

7. Do you open the windows in:

Winter		Summer
	Yes	
	No	

8. If so when do you open them and for how long?

Winter		Summer
	Morning	
	Midday	
	Afternoon	
	When I'm in the room	

9. Do you feel draughts in the house?

Winter		Summer
	Yes	
	No	

10. If so are there particularly draughty locations in the house?

_____

11. Type of heating:

Central	Fuel	Distribution	Observations

Open fires	Fuel

Heaters	Fuel

Other comments:

14. Approximately when is the heating on?

	J	F	M	A	M	J	J	A	S	O	N	D
AM												
PM												
Hours												

Thermal comfort questionnaire- The Oaks

Case Study:	The Oaks
Room:	Kitchen Temp (°C): 23.7 RH(%): 52.2
Current activity:	Reclining □ Sitting □ Standing ☒ Activity:
Current clothing:	Jean and long sleeve t-shirt

1. How do you currently feel?

1	2	3	4	5	6	7
			x			
Very cold	Cold	Slightly cool	**Comfortable**	Slightly warm	Hot	**Too Hot**

2. In general in winter how do you feel in the house?

1	2	3	4	5	6	7
	x					
Very cold	Cold	Slightly cool	**Comfortable**	Slightly warm	Hot	**Too Hot**

3. Are there any rooms that are particularly cold or hot in winter?

Overall the house is cold with heating struggling to maintain a temperature of around 19°C but just put on a thick jumper. There is a general lack of radiators in the house. The sitting room is OK when the log burner is lit but the heat from this has no effect on the rest of the house. The Kitchen is the coldest room. The bathroom is OK as there are three radiators.

4. In general in summer how do you feel in the house?

1	2	3	4	5	6	7
		x	x			upstairs
Very cold	Cold	Slightly cool	**Comfortable**	Slightly warm	Hot	**Too Hot**

5. Are there any rooms that are particularly cold or hot in summer?

The upstairs is generally too hot in summer, especially the master bedroom above the kitchen which is very hot.

6. How do you normally dress inside the house?

Winter	Clothing	Summer
	t-shirt and shorts	
	t-shirt and light trousers	x
	+thin jumper or top	
x	+thick jumper	
	Coat	

7. Do you open the windows in:

Winter		Summer
x	Yes	x
	No	

8. If so when do you open them and for how long?

Winter		Summer
x	Morning	
	Midday	
	Afternoon	
x	When I'm in the room	x

Comment: There is a problem with flies and bats coming in open windows.

9. Do you feel draughts in the house?

Winter		Summer
x	Yes	Windy days
	No	

10. If so are there particularly draughty locations in the house?

The bathroom and the stairs are the draughtiest

11. Type of heating:

Central	Fuel	Distribution	Observations
x	LPG		

Open fires	Fuel

Heaters	Fuel

Other comments: The LPG is expensive but this does not influence the use of heating. In winter set to 15°C at night and when out and 21°C at other times.

14. Approximately when is the heating on?

	J	F	M	A	M	J	J	A	S	O	N	D
AM												
PM												
Hours	6-22	6-22	6-22	6-22	6-22				6-22	6-22	6-22	6-22

Heating also used in summer months if needed.

Thermal comfort questionnaire- Occupant 1-Female

Case Study:	Old Stokes Farm
Room:	**Hall** Temp (°C): **18.8** RH(%): **50.4**
Current activity:	Reclining ☒ Sitting □ Standing □ Activity:
Current clothing:	**Thin fleece, T-shirt and Jeans**

1. How do you currently feel?

1	2	3	4	5	6	7
			x			
Very cold	Cold	Slightly cool	**Comfortable**	Slightly warm	Hot	**Too Hot**

2. In general in winter how do you feel in the house?

	1	2	3	4	5	6	7
Upstairs		**x**					
Down				x	Study		
	Very cold	Cold	Slightly cool	**Comfortable**	Slightly warm	Hot	**Too Hot**

3. Are there any rooms that are particularly cold or hot in winter?

The study is the hottest through preference. The bedroom is cooler with windows open even in winter. Downstairs has the perfect temperature.

4. In general in summer how do you feel in the house?

	1	2	3	4	5	6	7
Upstairs				**x**			
Down					x		
	Very cold	Cold	Slightly cool	**Comfortable**	Slightly warm	Hot	**Too Hot**

5. Are there any rooms that are particularly cold or hot in summer?

The downstairs is warmer as the underfloor heating stays on

6. How do you normally dress inside the house?

Winter	Clothing	Summer
	t-shirt and shorts	**x**
	t-shirt and light trousers	
x	+thin jumper or top	
	+thick jumper	
	Coat	

7. Do you open the windows in:

Winter		Summer
x	Yes	x
	No	

The windows in the bedroom and study are open most of the year.

8. If so when do you open them and for how long?

Winter		Summer
	Morning	x
	Midday	x
	Afternoon	x
	When I'm in the room	

The opening of windows is governed more by the need for fresh air rather than temperature regulation

9. Do you feel draughts in the house?

Winter		Summer
x	Yes	x
	No	

10. If so are there particularly draughty locations in the house?

In the hallway

11. Type of heating:

Central	Fuel	Distribution	Observations
Ground source		Underfloor (downstairs)	Lovely temperature, best they have experienced

Open fires	Fuel
Every day	Logs

Heaters	Fuel
Guest room	Electric

Other comments:

The log burner in the drawing room is lit everyday even in summer.

14. Approximately when is the heating on?

	J	F	M	A	M	J	J	A	S	O	N	D
AM												
PM												
Hours	24	24	24	24	24			24	24	24	24	24

Thermal comfort questionnaire- Occupant 2-Male

Case Study:	Old Stokes Farm
Room:	Outside Temp (°C): RH(%):
Current activity:	Reclining ☐ Sitting ☒ Standing ☐ Activity:
Current clothing:	T-shirt and light trousers

1. How do you currently feel?

1	2	3	4	5	6	7
			x			
Very cold	Cold	Slightly cool	**Comfortable**	Slightly warm	Hot	**Too Hot**

2. In general in winter how do you feel in the house?

	1	2	3	4	5	6	7
Upstairs			**X (attic)**				
Down				x			
	Very cold	Cold	Slightly cool	**Comfortable**	Slightly warm	Hot	**Too Hot**

3. Are there any rooms that are particularly cold or hot in winter?

The annex is cold.

4. In general in summer how do you feel in the house?

	1	2	3	4	5	6	7
Upstairs				**x**			
Down				x			
	Very cold	Cold	Slightly cool	**Comfortable**	Slightly warm	Hot	**Too Hot**

5. Are there any rooms that are particularly cold or hot in summer?

No

6. How do you normally dress inside the house?

Winter	Clothing	Summer
	t-shirt and shorts	**x**
x	t-shirt and light trousers	
	+thin jumper or top	
	+thick jumper	
	Coat	

7. Do you open the windows in:

Winter		Summer
x	Yes	x
	No	

The windows in the bedroom and study are open most of the year.

8. If so when do you open them and for how long?

Winter		Summer
	Morning	x
	Midday	x
	Afternoon	x
	When I'm in the room	

The opening of windows is governed more by the need for fresh air rather than temperature regulation

9. Do you feel draughts in the house?

Winter		Summer
	Yes	
x	No	x

10. If so are there particularly draughty locations in the house?

In the hallway

APPENDIX G

Materials used for DesignBuilder® Simulations

Table 36 Construction elements for Hacton Cruck. All values stated are taken from DesignBuilder database unless otherwise noted.

Construction Element	**Materials (outer to inner)**	**Thickness (mm)**	**Coefficient of thermal conductivity (W/mK)**	**U-Value (W/m^2K)**
Ground floor	Expanded Clay	254	0.1	0.287
	Limecrete	152	0.257†	
	Lime Screed	76	0.8	
	Sandstone Flags	76	1.83	
Internal Floors	Suspended timber	N/A	N/A	N/A
Lath and Plaster panels	Original lime plaster on oak lath	100	N/A	2.21*
Wattle-and-daub panels	New clay daub split oak lath	100	N/A	2.88*
Insulated panels	Lime plaster on expanded metal lath and Triiso multi-foil insulation in cavity	100	N/A	0.66*
Oak frame	Solid oak frame	100	0.19	1.248
Uninsulated block walls	Lime render	12	0.8	1.619
	Medium density concrete block	215	0.51	
	Lime plaster	9	0.7	
Insulated block wall	Lime render	12	0.8	0.364
	Medium density concrete block	100	0.51	
	Air cavity	50	N/A	
	Rigid Polyurethane insulation	50	0.28	
	Medium density concrete block	100	0.51	
	Lime plaster	9	0.7	
Uninsulated stone wall				
Windows	Single glazed 3mm in metal framed			
External Doors				
Interior Partitions	Lath and plaster & Plasterboard	N/A	N/A	N/A
Thatched roof	Thatch	210	0.07‡	0.318

† Ty Mawr Lime (Gervis and Gervis, 2014)
* Measured U-value. See section
‡ Historic Scotland Report (Baker, 2011)

Table 37 Construction elements for The Oaks. All values stated are taken from DesignBuilder database unless otherwise noted.

Construction Element	Materials (outer to inner)	Thickness (mm)	Coefficient of thermal conductivity (W/mK)	U-Value (W/m²K)
Basement floor	Cast concrete	100	0.13	2.378
	Concrete Screed	50	0.41	
Ground floor	Cast concrete	100	0.13	1.935 1.423 (lounge)
	Concrete Screed	50	0.41	
	Vinyl on ply	9	0.8	
	Polypropylene Carpet on underlay (lounge only)	14	0.6	
Internal Floors	Suspended timber	N/A	N/A	N/A
Wattle-and-daub panels	Original clay daub on wattle.	100	0.364*	2.249
Uninsulated concrete block panels	Lime render	12	0.8	1.619
	Medium density concrete block	100	0.51	
	Lime plaster	9	0.7	
Oak frame	Solid oak frame	100	0.19	1.248
Stone Wall	Lime render	12	0.8	2.077
	limestone masonry 6% lime mortar bridging	410	1.5	
	Lime plaster	9	0.7	
Windows Pre-retrofit	Single glazed 3mm in timber frame	3	N/A	3.835
Windows Post-retrofit	Single glazed 3mm in timber frame	3	N/A	2.788
	Air gap	200		
	Single glazed 3mm	3		
External Doors				
Internal Partitions	Timber stud and plasterboard	100	N/A	N/A
	Solid stone (lounge-kitchen)	500	N/A	N/A
Uninhabited pitched roof Pre-retrofit	Assumption 1 Uninsulated Slate roof	N/A	N/A	2.3‡
	Assumption 2 1983-1990 (band G) Slate roof	N/A	N/A	0.4‡
Uninhabited pitched roof Post-retrofit	mineral wool above and over joists at ceiling level	270	0.036	0.14
Inhabited pitched roof Pre-retrofit	Assumption 1 Uninsulated Slate roof	N/A	N/A	2.3‡
	Assumption 2 1983-1990 (band G) Slate roof	N/A	N/A	0.5‡
Inhabited pitched roof Post-retrofit	Celotex PIR insulation board between rafters 5% bridging	80	0.022	0.25
Flat roof Pre-retrofit	Assumption 1 Uninsulated Slate roof	N/A	N/A	2.3‡
	Assumption 2 1983-1990 (band G) Slate roof	N/A	N/A	0.4‡

Table 37 (cont.) Construction elements for The Oaks. All values stated are taken from DesignBuilder database unless otherwise noted

Construction Element	**Materials (outer to inner)**	**Thickness (mm)**	**Coefficient of thermal conductivity (W/mK)**	**U-Value (W/m²K)**
Flat roof Post-retrofit	Celotex PIR insulation board between rafters 5% bridging	80	0.022	0.25

* SPAB U-value report (Rye et al., 2012b)
‡ Guidance for SAP 2012 (BRE, 2014)

Table 38 Construction elements for The Old Mayor's Parlour. All values stated are taken from DesignBuilder database unless otherwise noted.

Construction Element	Materials (outer to inner)	Thickness (mm)	Coefficient of thermal conductivity (W/mK)	U-Value (W/m²K)
Floor	Suspended timber	N/A	Assumed to be adiabatic	N/A
Oak frame	Solid oak frame	140	0.19	1.103
Oak frame with polyisocyanurate internal lining	Solid oak frame	140	0.19	0.228
	Rigid polyisocyanurate foam	100	0.030	
	Woodwool board	15	0.11	
	Lime plaster	12	0.8	
Uninsulated block infill	Lime render	12	0.8	2.124
	Medium density concrete block	140	0.51	
	Lime plaster	9	0.7	
Wood fibre insulated infill (unlined)	Lime render	12	0.8	0.319
	Woodwool board	25	0.11	
	Steico flex Wood fibre insulation	90	0.35†	
	Woodwool board	15	0.11	
	Lime plaster	9	0.7	
Wood fibre insulated infill With polyisocyanurate internal lining	Lime render	12	0.8	0.110*
	Woodwool board	25	0.11	
	Steico flex Wood fibre insulation	90	0.038†	
	Rigid polyisocyanurate foam	100	0.030	
	Woodwool board	15	0.11	
	Lime plaster	12	0.8	
Uninsulated tile hung block wall	Clay tiles	30	1.0	1.502
	Air space	40	N/A	
	Medium density concrete block	140	0.51	
	Lime plaster	9	0.7	
Uninsulated tile hung oak frame	Clay tiles	30	1.0	0.886
	Air space	40	N/A	
	Oak frame	140	0.19	
	Lime plaster	9	0.7	
Insulated tile hung block wall	Clay tiles	30	1.0	0.557
	Air space	40	N/A	
	TLX Gold Multi foil	33	0.039‡	
	Air space	20	N/A	
	Plywood	12	0.12	
	Medium density concrete block	140	0.51	
	Lime plaster	9	0.7	

Table 38 (cont.) Construction elements for The Old Mayor's Parlour. All values stated are taken from DesignBuilder database unless otherwise noted.

Insulated tile hung oak frame	Clay tiles	30	1.0	0.463
	Air space	40	N/A	
	TLX Gold Multi foil	33	0.039‡	
	Air space	20	N/A	
	Oak Frame	140	0.19	
	Lime plaster	9	0.7	
Windows East Façade	Single glazed 3mm in metal framed			
Windows West Façade	Single Glazed 3mm in timber frame			
External Doors	Solid Oak			
Sloping roof Uninsulated	Clay Tile	25	1.0	2.696
	Bitumen felt	0.5	0.19	
	Rafters (92% air gap)	20	0.13	
	Lime plaster	18 (average)	0.7	
Sloping roof (roof space) Uninsulated	Clay Tile	25	1.0	2.897
	Bitumen felt	0.5	0.19	
	Rafters (92% gap)	20	0.13	
Ceiling Uninsulated	Rafters (92% air gap)	20	0.13	2.112
	Lime plaster	18 (average)	0.7	
Sloping roof Insulated	Clay Tile	25	1.0	1.345
	Bitumen felt	0.5	0.19	
	Wood fibre insulation 8% bridging	20	0.038	
	Lime plaster	18 (average)	0.7	
Ceiling Insulated	Wood fibre insulation 8% bridging	20	0.13	1.372
	Lime plaster	18 (average)	0.7	

† Steico Technical Information (Steico, 2016)
* Measured U-value. See 9.4.1
‡ TLX Gold (Gold, 2015)

Table 39 Construction elements for 25-27 Church Street. All values stated are taken from DesignBuilder database unless otherwise noted.

Construction Element	Materials (outer to inner)	Thickness (mm)	Coefficient of thermal conductivity (W/mK)	U-Value (W/m²K)
Floor	Oak beams	150	0.19	1.571
	Oak floor boards	15	0.19	
Oak frame with unknown infill external pargeting and internal lime plaster	Lime pargeting	Varies	unknown	1.05*
	Solid oak frame	100	0.19	
	Varies- Wattle and daub, brick nogging	100	unknown	
	Lime plaster	20	0.8	
Oak frame with brick underbuilding	Lime render	20		1.670
	Brick	225	0.770	
	Solid oak frame 20%		0.19	
	Dense Plaster	13	0.570	
Brick walls	Brick	225	0.770	2.062
	Dense Plaster	13	0.570	
Insulation opt.1 All walls plus	Wood fibre insulation	25	0.038†	Pargeted - 0.614 Brick – 0.864 Nogging – 0.774
	Lime plaster	12	0.8	
Insulation opt.2 All walls plus	Wood fibre insulation	50	0.038†	Pargeted - 0.437 Brick – 0.55 Nogging – 0.511
	Lime plaster	12	0.8	
Insulation opt.3 All walls plus	Wood fibre insulation	100	0.038†	Pargeted - 0.278 Brick – 0.319 Nogging – 0.305
	Lime plaster	12	0.8	
Windows	Single glazed 6mm in timber frame			
External Doors	Solid Oak			
Clay tiled roof	Clay tiles	5	1.00	0.201
	Solid oak frame (20%)	150	0.19	
	Lime plaster	12	0.7	
Ceiling uninsulated	Mineral wool batts insulation 8% bridging	200	0.038	1.597
	Lime plaster	12	0.7	

* Measured U-value. See 9.5.1

† Steico Technical Information (Steico, 2016)

Table 40 Construction elements for Old Stokes Farm. All values stated are taken from DesignBuilder database unless otherwise noted.

Construction Element	Materials (outer to inner)	Thickness (mm)	Coefficient of thermal conductivity (W/mK)	U-Value (W/m^{2}K)
Floor	Cast Concrete	150	0.13	2.602
	Honed sandstone flags	76	1.83	
Oak Frame	Cement Render	20	1.00	1.396
	Solid oak frame	100	0.19	
Polyisocyanurate infill and cement render	Cement render	20	1.00	1.8* (calculated 0.921)
	Rigid polyisocyanurate foam board (bridged by oak 34%)	80	0.019	
	Gypsum Plasterboard	12	0.8	
Lath and plaster infill and lime render	Lime render	20	0.8	2.104
	Lath and plaster	100	0.468†	
Windows (general)	Double glazed 3mm clear with 13mm air gap	NA	NA	2.716
Windows (feature windows to East)	Single glazed 6mm in timber frame	NA	NA	5.778
External Doors	Solid Oak			
Thatched roof (roof space) Unoccupied	Thatch	210	0.07‡	0.318
Sloping roof Occupied	Thatch	210	0.07‡	0.201
Sloping roof Occupied	Mineral wool batts (bridged by oak 20%)	100	0.038	0.201
	Solid oak frame (20%)	150	0.19	
	Gypsum Plasterboard (bridged by oak 34%)	12	0.8	
Ceiling Insulated	Mineral wool batts insulation 8% bridging	200	0.038	1.338
Ceiling Insulated	Gypsum plasterboard	12	0.16	1.338

* Measured U-value. See 9.6.1
† Calculated from measured U-value at Hacton Cruck. See 9.2.1
‡ Historic Scotland Report (Baker, 2011)

APPENDIX H

Materials used for WUFI® Simulations

Table 41. Materials used in WUFI simulations

Detail code	Source	Material	WUFI Material	Database
S1a	SPAB[1] fig.12	Wattle and Daub.	Mud Plaster	MASEA
		Lime plaster	Lime Plaster (stucco)	Fraunhofer
S1b	SPAB[1] fig.12	Foil backing	Vapour barrier (sd=1500m)	Fraunhofer
		Plasterboard	Gypsum board	Fraunhofer
S2	SPAB[1] fig.13	Glasswool	Mineral wool	Fraunhofer
S3	SPAB[1] fig.14	Wood wool	Wood wool board	Fraunhofer
		Vapour barrier	PVC roof membrane	Fraunhofer
		Wood fibre insulation	Wood fibre insulation board	Fraunhofer
S4	SPAB[1] fig.17	Extruded Polyurethane	PU (heat cond. 0.025 W/mK	Fraunhofer
		Vapour barrier	Vapour barrier (sd=1500)	Fraunhofer
		Gypsum plaster	Interior Plaster (gypsum plaster)	Fraunhofer
S5	SPAB[1] fig.18	Half brick nogging	Brick (old)	North America
		Expanded Polystyrene Insulation	Expanded Polystyrene Insulation	North America
E1a	EH-1[2] pg325	Vapour barrier	Weather Resistive Barrier (sd=0,1m)	Fraunhofer
		Breather Membrane	ISOVER Vario Extrasafe	Fraunhofer
E2	EH-2[3] Fig.18	Historic infill retained	Mud Plaster	MASEA
		Breather Membrane	Weather Resistive Barrier (sd=0,1m)	Fraunhofer
E3	EH-2[3] Fig.19	Plasterboard	Gypsum board	Fraunhofer
HC1	Stanwix & Sparrow[4]	Hemp lime.	Hemp lime	A. Evrard[6]
T1a	Tŷ-Mawr[5]	Cork board	Cork (heat cond. 0.04 W/mK	Frauhofer

1 SPAB (Reid, 1989)
2 EH-1 (McCaig and Ridout, 2012)
3 EH-2 (Ogley, 2010, Historic England, 2016)
4 (Stanwix and Sparrow, 2014)
5 Tŷ-Mawr- developed by author
6. (Evrard, 2008)

APPENDIX I

Publications

- Whitman, C.J. and Prizeman, O. 2016 **U-value Monitoring of Infill Panels of a Fifteenth-century Dwelling in Herefordshire, UK**. *APT Bulletin*, Volume XLVII No.4 p.6-13 (*winner of the APTi Oliver Torrey Fuller Award for the most outstanding article demonstrating technical excellence and innovation in preservation practice*.)

- Whitman, C.J., Prizeman, O., Walker, P. and Gwilliam, J. **Improving the Energy Performance of Historic Timber-Framed Buildings in the UK**. 33rd Passive and Low Energy Architecture, PLEA 2017, Edinburgh, UK.

- Whitman, C.J., Prizeman, O. and Walker, P. **Interstitial Hygrothermal Conditions of Low Carbon Retrofitting Details for Historic Timber-Framed Buildings in UK.** 31st Passive and Low Energy Architecture, PLEA 2015, Bologna, Italy

U-value Monitoring of Infill Panels of a Fifteenth-century Dwelling in Herefordshire, UK

Christopher J. Whitman
Oriel Prizeman

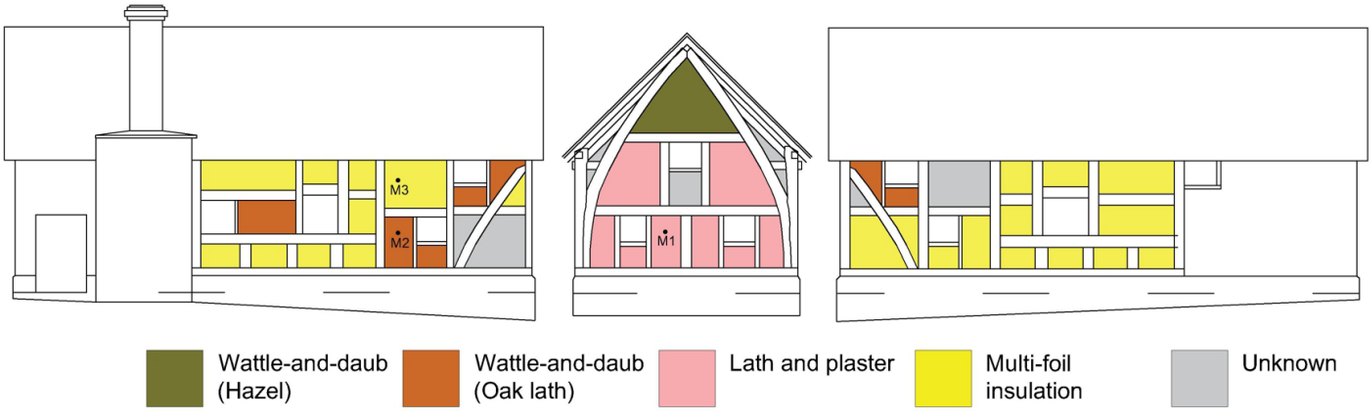


Fig. 1. Hacton Cruck Hall, east, north, and west elevations showing panel infill materials, 2015. All images by the authors, unless otherwise noted.

Monitoring timber-framed buildings reveals the importance of a holistic approach when considering their retrofit.

With dwellings now responsible for 37 percent of the final energy use in the UK, the demands placed on the performance of domestic building envelopes are increasing.[1] Centuries-old walls of heritage buildings are now the focus of energy retrofits that aim to reduce greenhouse-gas emissions, lower energy bills, and improve hygrothermal comfort. Understandably, research in the UK to date has focused on the retrofit of solid masonry construction, which accounts for 93 percent of the pre-1850 building stock in England.[2] However, retrofits in the UK are also being undertaken on some of the 66,000 pre-1850 timber-framed buildings, but with only limited knowledge of the impact of the applied solutions. In order to ensure their preservation, it is essential to understand the thermal performance of the constituent elements of these buildings and the potential impact of introducing new materials. Failure to do so could result in increased risk of interstitial condensation, raised moisture levels, and irreversible damage to the historic fabric through fungal or insect attack.

This paper presents the results of in situ U-value (thermal transmittance) monitoring of three infill panels of differing ages and material assemblies at a fifteenth-century cruck hall in the Wye Valley in Herefordshire in the English West Midlands. The property, once derelict, has been restored in stages over the past 15 years by its owner and now provides holiday accommodation (Fig. 1). Three types of panels were monitored: one original oak-lath and lime-plaster panel, one replacement wattle-and-daub panel (earth render on timber lath), and one new panel with modern multi-foil insulation consisting of reflective foils separated by polyester fleece. The multi-foil insulation is held in place between vertical timber staves within a void finished internally and externally with lime plaster on expanded metal lath. Figure 1 shows the location of each

panel type and the monitoring points M1, M2, and M3. Twenty-two percent of the infill panels are original oak lath and lime plaster; 18 percent are wattle and daub; 46 percent are insulated; and 14 percent are of unknown construction. All panels are visually identical and in good condition. Thermography and pressure testing were also conducted to complement the in situ U-value monitoring. This monitoring forms part of an ongoing PhD research project into the low-carbon retrofitting of historic timber-framed buildings in the UK.

Cruck Construction

Evidence of cruck construction can be found in the British Isles dating from at least the twelfth century; it is argued by some to have pre-Roman origins.[3] The technique utilizes pairs of massive, book-matched timber members cut from the same tree, which rise from low within the external walls to the apex of the roof.[4] Most of the roof loads are carried by these principal members; the walls are secondary elements whose principal role is to enclose the internal space, providing shelter from the elements. The material used in the walls to create this enclosure varies according to geographical region (Fig. 2) with traditional materials including stone, brick, timber frame, and cob. The variation in infill material is most probably due to the influences of climate and availability of local materials. The distribution of external wall materials illustrated in Figure 2 clearly shows the limestone belt, running diagonally from the southwest, that divides the forests of central and southeast England. The preference for stone or brick walls in the west and north of the country could also be due to the harsher climates of these areas.

Hacton Cruck Hall, Preston-on-Wye

Hacton Cruck was constructed as a three-bay, single-hall dwelling in the late-fourteenth or early-fifteenth century.[5] The property was divided into two separate dwellings sometime during the eighteenth or nineteenth century but lay uninhabited and abandoned for much of the twentieth century. Prior to restoration, the south bay had collapsed, and much of the remaining fabric was in a poor state of repair. Over a period of 12 years, starting in 2000, the current owner undertook a process of restoration that resulted in the building that exists today (Fig. 3).

In order to reconstruct the lost south structural bay, it was necessary to relocate the building approximately 30 meters (90 feet) to the east (Fig. 4).

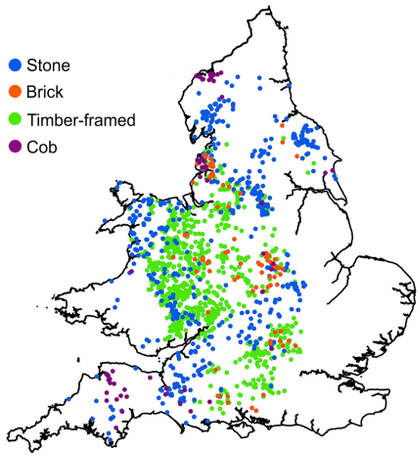


Fig. 2. Map of the UK showing distribution of surviving and demolished cruck-framed buildings according to N. W. Alcock, Cruck Construction: An Introduction and Catalogue (London: Council for British Archaeology, 1981). The map is by the authors based on the information of N.W. Alcock.

Fig. 3. Hacton Cruck Hall, Preston-on-Wye, Herefordshire, UK, built in the late-fourteenth or early-fifteenth century, east elevation looking northwest, 2015.

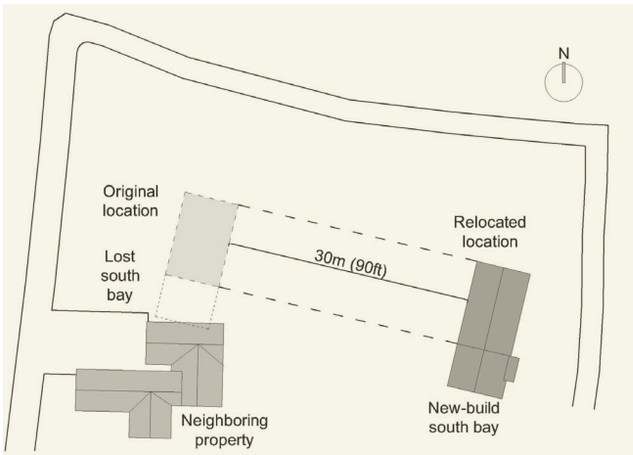


Fig. 4. Hacton Cruck Hall, site plan showing original and relocated site, 2015.

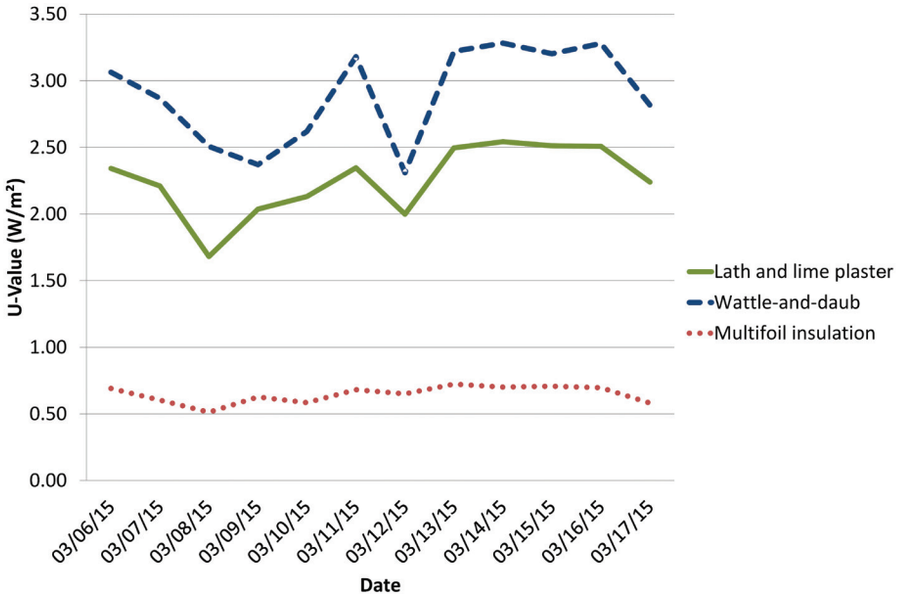


Fig. 5. Calculated U-values of three infill-wall panels measured on March 6–17, 2015.

To achieve this, the timber frame was first repaired in its original location before being hauled across flattened ground by a vintage Matador timber crane. The roof was rethatched, with the thatch being exposed internally in the two-story central bay. Although most of the original infill panels had been lost, those of the north wall survived, protected by a modern lean-to pigsty and weatherboarding above. These surviving panels consisted of lime plaster on traditional riven-oak lath. With minor repair work, all but the topmost panel were saved. Elsewhere, in order to provide improved thermal resistance, most of the new infill panels incorporated multi-foil insulation, sandwiched between finishes of lime plaster on expanded metal lath. In some parts however, the members of the external timber-frame walls were barely 76 millimeters (3 inches) wide; here, new panels of wattle and daub were installed. The presence of these three panel types in one building presented the opportunity to monitor three different constructions under the same climatic conditions. Like much of the UK, the Wye Valley has a temperate-maritime climate with warm summers and cold winters. The heating season typically lasts from November until March with no requirement for mechanical cooling during summer months.

In Situ U-value Monitoring

In order to evaluate the thermal performance of the three different types of panels, in situ U-value monitoring was undertaken during the heating season over a period of two weeks in early March 2015. The methodology employed was in accord with the British Standard BS ISO 9869-1:2014, "Thermal Insulation—Building elements—In-situ measurement of thermal resistance and thermal transmittance. Part 1: Heat flow meter method."[6] The heat flux (W/m²) through each infill panel was measured with a Huxeflux HFP01 heat-flow meter plate connected to an Eltek telemetry transmitter with inputs for voltage. The transmitter in turn relayed the data to an Eltek Squirrel data logger, with the voltage recorded at five-minute intervals. The internal ambient air temperature (˚C) directly behind each heat-flow plate was measured with an Eltek telemetry transmitter with built-in temperature and relative-humidity sensors; measurements were recorded at the same frequency as the voltage. The external ambient air temperature (˚C) was measured adjacent to the external wall surface at the points corresponding to the internal location of the heat-flow plates. The temperature was measured using thermistors connected to an Eltek telemetry transmitter with inputs for external thermistors, also transmitting to the Eltek Squirrel data logger, with readings at the same frequency of five minutes.

Using the data collected, the daily mean U-value was calculated according to the following equation:

$$\text{U–value} = \frac{\sum_n Q}{\sum_n (t_i - t_e)}$$

Where
Q = mean heat flux (W/m²)
t_i = mean internal temperature (°C)
t_e = mean external temperature (°C)

In accordance with BS ISO 9869–1:2014, only nighttime readings (from one hour after sunset until sunrise) were included in order to remove the influence of any direct solar radiation. The thermal conductance was deemed to be that recorded over a period of three subsequent nights, where a variation of no more than ±5 percent was detected in the calculated U-value. This was observed on the nights of March 13 through 16, 2015. The results obtained are presented in Figure 5 and Table 1.

The results show that the original lath and lime-plaster panel performs remarkably well with a U-value equivalent to that of a historic solid brick wall.[7] The new wattle-and-daub infill performs less well, with a U-value equivalent to that of a concrete wall 250 millimeters (10 inches) thick. The new panel with multi-foil insulation sandwiched between lime plaster on metal lath performs the best, with a U-value equivalent to that of a typical new stick-frame building insulated with 2 inches of mineral wool. The new insulated panel conducts only 28 percent of the heat when compared to the original lath-and-plaster panels.

Table1. Thermal transmittance and thermal resistance

Wall panel infill	U-value (W/m²K) (Thermal transmittance)	R-value (hr ft2 ⁰F/Btu) (Thermal resistance)
Lath and lime plaster	2.51	2.26
Wattle-and-daub	3.25	1.75
Multi-foil insulation	0.71	8.0

Table 1. Thermal transmittance and thermal resistance of wall panels calculated from data (shown in Figure 5) measured March 13-16, 2015.

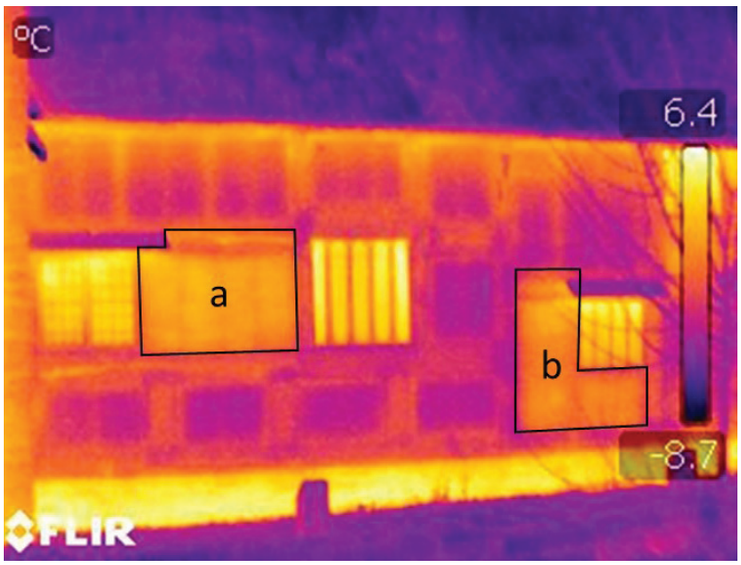
Thermography

At the end of the two-week measurement period, thermography of the property was undertaken using a FLIR thermal-imaging camera. The images were taken at 5:30 a.m., a half hour before sunrise, to ensure maximum temperature differences between the internal (15˚C, 59˚F) and external environments (1˚C, 34˚F) and to avoid any influence of direct solar radiation.[8] Additional fan heaters were used for an hour prior to taking the images to achieve this temperature difference. To further enhance the transfer of heat, the building was first pressurized for thermography of the exterior of the building, then depressurized for the thermography of the interior. This was achieved using a Minneapolis Blower Door, a standardized kit consisting of an adjustable fabric door fitted with a variable speed fan.

The images clearly show the differing thermal performance of the various infill panels, with the lighter, warmer colors indicating areas of higher heat loss. In Figure 6 two new wattle-and-daub panels can be identified in paler orange (a and b), due to their higher surface temperature. One panel is located between the two windows on the left (a), and the other is L-shaped and adjacent to the right-hand window (b). Cold-bridging (increased localized thermal transmittance) formed by the upright timber staves within the panels appears as the lighter vertical lines in the middle of each panel. The image also indicates the lack of sufficient perimeter insulation to the edge of the concrete floor slab containing underfloor heating.

While the external thermography visibly demonstrates the differing thermal performance of the infill panels (Fig. 6),

Fig. 6. Hacton Cruck Hall, thermographic image of exterior of east elevation, taken at 5:30 a.m. on March 25, 2015. Lighter colors indicate greater heat loss. New wattle-and-daub panels (a and b) show more heat transfer than surrounding panels insulated with multi-foil insulation.



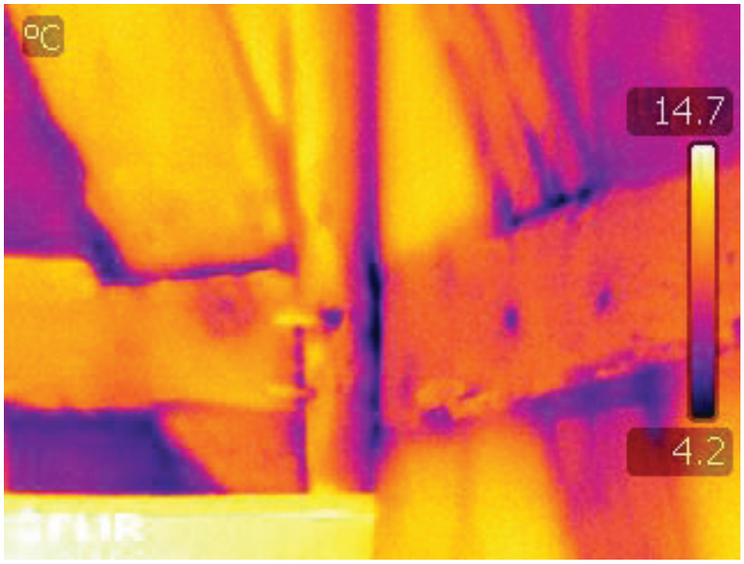


Fig. 7. Hacton Cruck Hall, thermographic image of internal northeast corner, taken at 5:45 a.m. on March 25, 2015.

the internal thermography made evident the heat loss via air infiltration through the perimeter joints between panel and frame, through the joints between timbers, and through peg holes within the timber members themselves (Fig. 7). The cold air being drawn into the depressurized building shows up as dark blue and purple in this image. Overall, the thermography begins to suggest that while the inclusion of multi-foil insulation within most of the new panels will improve their individual performance, there are other factors influencing the overall efficiency of the building as a whole. These factors became more evident in the results of the hygrothermal monitoring and pressure testing.

Hygrothermal Comfort Monitoring

In order to assess the current hygrothermal-comfort conditions (temperature and relative humidity) achieved within the house, TinyTag hygrothermal sensors were mounted in four internal locations and one external location protected from precipitation and direct solar radiation in order to monitor ambient air temperature (˚C) and relative-humidity percentage. Although the ISO 7726 recommends that sensors be located at specific heights within the center of the space being monitored, this arrangement was not possible since the property is a holiday rental and there was concern over potential visual intrusion and the risk of interference from guests. It was therefore necessary to locate the sensors discreetly within the four rooms. While this arrangement reduced the accuracy of the readings, it was only by doing so that continual monitoring could occur. Monitoring took place over the period of one year, from March 2015 until March 2016.

The results of this monitoring are presented in Figures 8 and 9. They show the hygrothermal comfort as defined by Baruch Givoni for those days when the house was occupied, according to the visitors' book.[9] The results show that the warmest room in the house is the ground-floor bathroom, which has only one external wall, original lath-and-plaster infill, and underfloor heating. However, due to high relative humidity, this

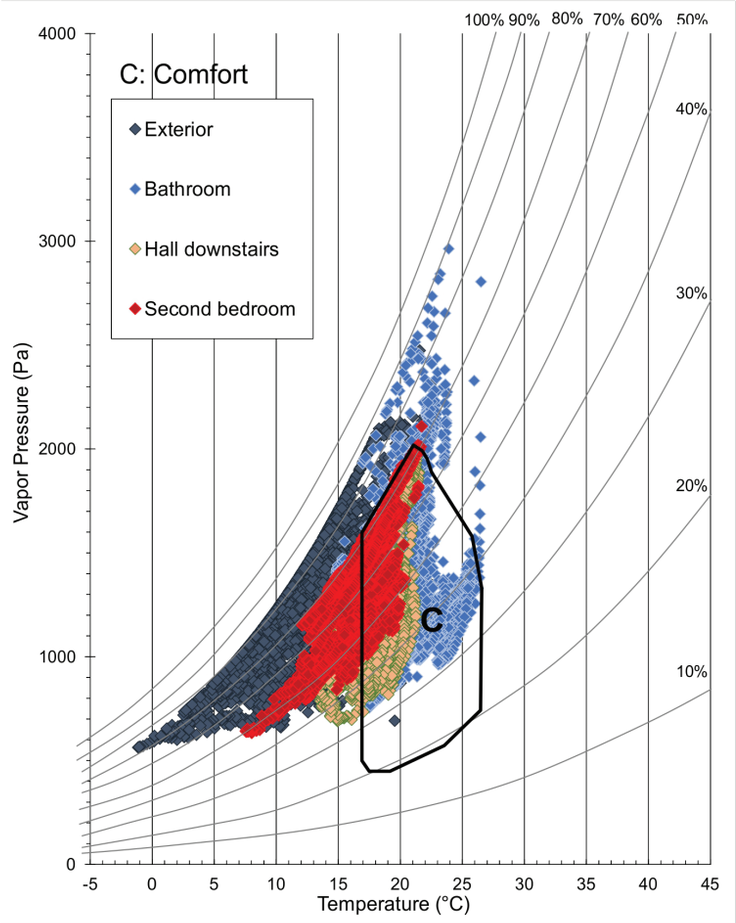


Fig. 8. Psychrometric chart created according to Baruch Givoni showing hygrothermal comfort at Hacton Cruck Hall during occupied days between March and November, 2015.

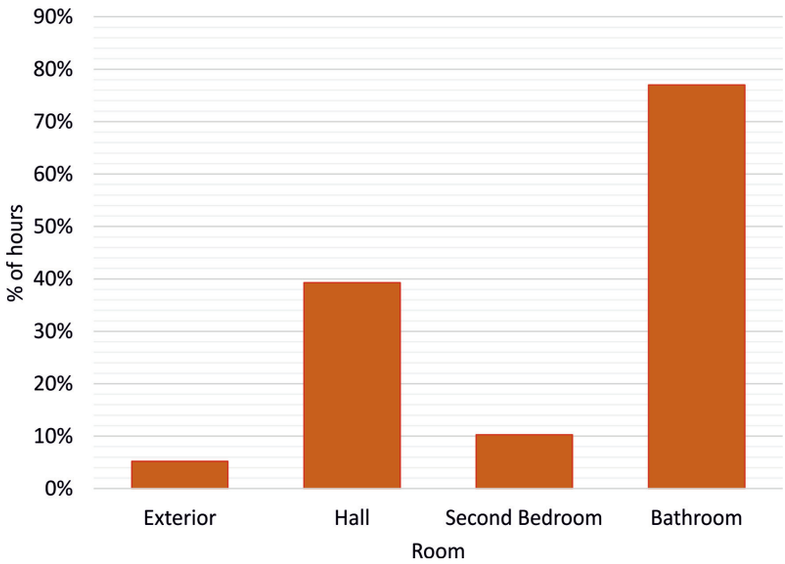


Fig. 9. Percentage of occupied hours where hygrothermal comfort was achieved at Hacton Cruck Hall between March and November, 2015.

room achieves acceptable comfort conditions only 77 percent of the time. The main, double-height hall achieves comfort conditions 39 percent of the time. In part this may be due to the volume of the space and the possible stratification of temperature, with heat rising. The infill panels of the exterior walls of this room are predominantly new insulated panels, with only 9 percent new wattle and daub. The measurements suggest that the least comfortable room is the second bedroom, located on the ground floor, which achieves comfort conditions a mere 10 percent of the time, even though 62 percent of its external infill panels are insulated and 38 percent are original lath and lime plaster. It should be noted that the effects of radiant temperature are not taken into account in these measurements.

Pressure Testing

As previously mentioned, a Minneapolis Blower Door was used to both pressurize and depressurize the building while undertaking the thermography. The same equipment was also used to undertake depressurizing to measure the air-permeability index ($m^3/hr/m^2$) and air-change rate of the house. The methodology, as prescribed by the British Standard BS EN ISO 9972:2015, is to seal all vents, drains, and fireplaces and to depressurize the building to over 50 pascals, taking readings of fan pressure and building pressure on the way up and on the way down, to afterwards calculate the air-change rate at 50 pascals.[10]

In the case of Hacton Cruck, on the first attempt on March 25, 2015, it was difficult to achieve even 4 pascals even with the fan on full power, with no blanking plate, and with all vents, drains, and fireplaces sealed. While limited in number, the readings taken would suggest that the house had an air-permeability index of 154 $m^3/hr/m^2$, an air-change rate at 50 pascals of 130 changes per hour, an estimated unpressurized air-change rate of 6.5 air changes per hour, and an effective open area of 32.6 square meters. To put this in context, 32.6 square meters is the equivalent of 19 open doors, and according to UK building regulations, new-build dwellings must achieve an air-permeability index of no more than 10 $m^3/hr/m^2$. One area responsible for these high infiltration rates has already been identified, that of the junctions between panels and timber and between those timbers themselves. However, a much more significant element contributing to this lack of air-tightness is the unlined thatched roof (Fig. 10). Thermography of this element clearly showed the difference between the unlined and the lime-plastered roofs at either end of the building.

In late October 2015 the owner of Hacton Cruck decided to improve the air-tightness of the building by lime plastering, or "torching," the central section of the ceiling. The lime-plaster finish was applied to the entire underside of the thatch except to a central square, which was left untorched to represent the original presence of a smoke hole before the construction of a chimney. The plaster was not continued right up to the ridge beam but stopped short to allow some air movement to aid in drying the external thatch. Following the completion of this work, the pressure testing was repeated. This time a maximum pressure of 11 pascals was achieved. While not the 50 pascals required by the official methodology, it was an improvement. The increased pressure allowed for more readings to be taken, leading to a greater reliability of the results. These showed an air-permeability index of 80 $m^3/hr/m^2$, an air-change rate at 50 pascals of 68 changes per hour, an estimated unpressurized air-change rate of 3.4 air changes per hour, and an effective open area of 15.8 square meters. Even with the uncertainty about the accuracy of the original measurements due to the limited readings, the results of the second pres-

Fig. 10. Hacton Cruck Hall, interior view of central hall with bedroom beyond showing unlined thatch roof, 2015.

sure test show a marked improvement of approximately 50 percent.

Visitors' Perceptions and Comments

Empirical data can provide only a partial indication of the building's performance, with most measurements being only a snapshot, both in time and of one specific parameter. In order to gain a greater understanding of the comfort perceived by occupants, it is necessary to obtain the opinion of the building's users. Since Hacton Cruck is a holiday-rental property, the visitors' book provided valuable insight into guests' perceptions. Of the 135 guests who had written in the book between the opening in August 2011 and March 2016, a total of 15 percent had commented on the house being cold and drafty, and 5 percent had commented on its being warm. The other 80 percent made no mention of thermal comfort within the house, commenting instead on their delight of staying in a fourteenth-century cruck hall and the quality of the restoration work. Some of the comments concerning comfort, however, included such statements as "The authentic indoor weather provided proper gusts of wind, rather than the mere drafts of other old homes" and "far less [chilly] than one might expect from a 500-year-old medieval hall!" It is also interesting to note that a number of comments stated that the second ground-floor bedroom was the warmest. These comments are in contrast to the empirical data, which shows this room to be the coldest. Possible explanations include the radiant underfloor heating, as neither radiant nor globe temperature was monitored, and reduced drafts, as this room is on the ground floor and therefore not open to the thatched roof. These are, however, only hypotheses and require further investigation.

Conclusions and Areas for Further Study

This study demonstrates just some of the complexities inherent in the retrofit of historic timber-frame buildings. Specific results show that the existing lath-and-lime plaster has a U-value of 2.5W/m^{2}K, that the new wattle and daub has a U-value of 3.3W/m^{2}K, and that a modern infill with multi-foil insulation has a U-value of 0.7W/m^{2}K, thereby allowing transmittance of only 28 percent of the heat through the historic lath-and-lime plaster panel. This analysis clearly illustrates that the inclusion of modern insulation materials within replacement infill panels can significantly improve the thermal performance of these building elements. The question, however, still remains as to whether the introduction of these materials could have unintentional negative impacts on the surrounding historic fabric through an increase in moisture content in the panel and through the creation of interstitial-hygrothermal conditions favorable to fungi or insects. As part of the wider PhD research studying the low-carbon retrofitting of historic timber-framed buildings, digital simulation of similar infill panels has been conducted, and physicals test cells are to be built, thanks to the support of the Association for Preservation Technology's Martin Weaver Scholarship.[11]

At the same time, both the thermography and pressure testing have highlighted the need for a whole-building approach when considering any energy retrofits, whether it be to contemporary or historic buildings. The initial pressure testing suggested an estimated 6.5 air changes per hour at atmospheric pressure, with an effective open area of 32.6 square meters, due to the poor airtightness of joints and the unlined thatched roof. Following the lime-plastering of the thatched roof, the subsequent pressure test showed a substantial improvement with a reduction to an estimated 3.4 air changes per hour at atmospheric pressure and an effective open area of 15.8 square meters, a reduction of approximately 50 percent. This improvement in airtightness is undeniably a step in the right direction; however, even at this reduced rate, these air changes greatly reduce any positive impact that the improved thermal transmittance of the walls might have on internal hygrothermal-comfort conditions. Research and practice concerned with improving both the energy performance and internal comfort of historic buildings must therefore look at strategies for all aspects of a building's performance and not concentrate on only individual elements.

The work by others at Hacton Cruck has saved a building that was largely ignored in the twentieth century and enabled visitors to experience the pleasure of staying in a fourteenth-century home. It is hoped that the research presented here and the owners' continuing commitment to the conservation of the building will allow the enjoyment of this building and others like it to continue for centuries to come.

Acknowledgements

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Notes

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INTERSTITIAL HYGROTHERMAL CONDITIONS OF LOW CARBON RETROFITTING DETAILS FOR HISTORIC TIMBER-FRAMED BUILDINGS IN UK.

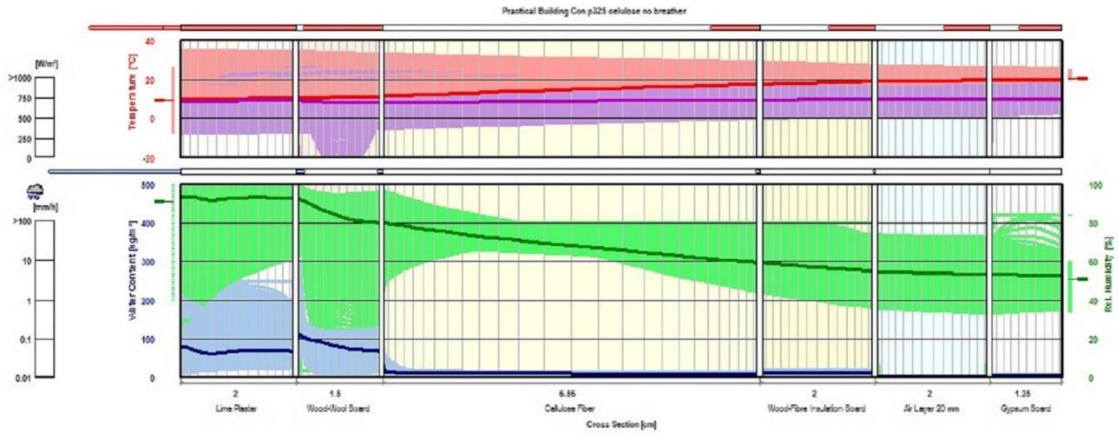

Fig 1: WUFI Pro5 simulation of English Heritage replacement infill detail.

Research summary

Heritage buildings have often been considered off-limits when considering energy refurbishment projects, however rising energy prices and stricter legislation for public buildings mean that they can no longer be ignored (Todorović, 2012). In the case of historic properties refurbishment is a complex issue, involving aesthetic considerations in addition to technical issues (English Heritage, 2012). The hygrothermal behaviour of wall build-ups of traditional materials must also be fully understood in order to avoid problems of interstitial moisture, long term decay and overheating. Research in this area to date has focused on solid-walled masonry construction (Gandhi, Jiang , & Tweed, 2012; Mohammadpourkarbasi & Sharples, 2013; Scott & Rye, 2014) however little work has been conducted on historic timber-framed construction, the subject of the research presented in this paper. Whilst representing only a small percentage of the UK pre-1919 housing stock (approximately 66,000 in England (Nicol, Beer, & Scott, 2014); 1,200 in Wales and almost non-existent in Scotland (Naismith, 1985) and Northern Ireland (Gailey, 1984)), many historic timber-framed buildings have stood for hundreds of years and form an important element of UK heritage. Inappropriate introduction of thermal insulation can cause unintentional negative impacts, including increased moisture content and interstitial condensation leading to the deterioration of the built fabric. Using WUFI Pro5 transient heat and moisture simulation software, the interstitial temperature, humidity and moisture conditions within traditional and retrofitted wall build-ups have been simulated. This paper presents the results of these simulations which would initially suggest that current proposed retrofit details do not pose a serious threat to timber-framed buildings. Further simulation, experimental and building monitoring, is however required and this is planned as part of this on-going research programme.
Keywords: Timber-framed, interstitial, hygrothermal, retrofit, simulation, UK

1. Introduction

In 2008 the UK government committed itself to reducing national greenhouse gas emissions by at least 80% by 2050, taking 1990 emissions as a base line ("Climate Change Act," 2008). In 2013, buildings were responsible for 37% of these emissions (Commitee on Climate Change, 2014) and it has been estimated that 70% of the current UK housing stock will still be in use in 2050 (Lowe, 2007). When the embodied energy of these existing buildings is added to the social, environmental, economic and cultural impact of their replacement it becomes clear that their refurbishment is the preferable solution (Power, 2008). This is even more so when considering heritage buildings, however, their refurbishment is a challenging issue, involving aesthetic and philosophical considerations in addition to complex technical issues (English Heritage, 2012). For this reason heritage buildings have until recently not been considered candidates for energy retrofitting, however, rising energy prices and stricter legislation for public buildings means that they can no longer be ignored (Todorović, 2012). One technical issue is the hygrothermal behaviour of wall build-ups in buildings of traditional materials. This must be fully understood in order to avoid problems of interstitial moisture, long term decay and overheating. Research to date has focused on solid-walled masonry construction (Gandhi et al., 2012; Mohammadpourkarbasi & Sharples, 2013; Scott & Rye, 2014) however little work has been conducted on timber-framed construction. This research therefore aims to explore this previously under-researched area, starting with the digital simulation of interstitial hygrothermal conditions.

1.1 History of Timber-framed buildings in UK

Timber construction can be traced back to the earliest British dwellings (Prizeman, 1975) where central poles supported a basket like structure of branches and twigs, often with a covering of turf. Following improved felling methods, construction in solid logs became possible in the Bronze Age. The only surviving example of this construction can be seen at the church of St Andrews, Greensted, Essex (Prizeman, 1975). As timber became less plentiful, methods requiring less timber were developed in the form of the timber frame. The earliest surviving timber framed building dates from the 13th Century (Harris, 2010). Building in timber framed continued as a common construction method until the late 18th early 19th Century (Harris, 2010). The size of the timbers varied according to the size of structure and the available local timber. The infill of the frames consisted of oak laths and plaster, stone slabs, fired brick or woven timber plastered with an earthen render, known as wattle and daub. One of the earliest examples of the use of wattle and daub in Britain can be found at an Iron Age settlement in Glastonbury (Davey, 1961). In Roman times, Vitruvius bemoaned the use of this material. In his second book, chapter VIII paragraph 20, he writes; “As for “wattle and daub” I could wish that it had never been invented. …it is made to catch fire, like torches. And, in the stucco covering, too, it makes cracks from the inside by the arrangement of its studs and girts. For these swell with moisture as they are daubed, and then contract as they dry, and, by their shrinking, cause the solid stucco to split.” (Vitruvius & Morgan, 1960). Despite these problems, examples of timber-framed buildings with wattle and daub infill can still be found to this day.

1.2 Timber-framed buildings in UK today

Today it is estimated that there are around 66,000 timber-framed buildings in England (Nicol et al., 2014) and around 1,200 in Wales (Smith, 1988). The building typology is however almost non-existent in Scotland (Naismith, 1985) and Northern Ireland (Gailey, 1984) although it was once common to these parts being referred to by the Venerable Bede in his *Historia Ecclesiastica III, xxv,* as *Mos Scotorum* or the "Scottish Manner" (Bede & Giles, 1843).

1.3 Low Carbon Retrofitting of historic timber-framed buildings

As with the conservation of all historic buildings, great care must be taken to minimize the loss of original fabric. In addition to the timber, this may include original infill material and finishes, including in some cases wall paintings. The Society for the Protection of Ancient Buildings (SPAB) advises that where more than 50% of the panel is in sound condition, repair or part renewal should be undertaken (Reid, 1989). This is followed by the caveat that on-site examination by an expert should always be sought.

Where complete renewal of the panel infill is required due to extensive damage, decay, repair of surrounding timbers or the removal of inappropriate modern materials, then there opens up the opportunity of retrofitting an alternative with a lower thermal transmittance (U-Value). Advice as to possible replacement details is given by English Heritage (McCaig & Ridout, 2012; Ogley, 2010) and SPAB (Reid, 1989). The general consensus in the conservation of historic building envelopes, is the need for the constructions to allow the movement of moisture or "breathe" (Hughes, 1986). It is therefore surprising that Reid's SPAB technical pamphlet includes details with vapour barriers, closed cell foam insulation and cement render. For this reason the pamphlet is currently in the process of being revised. Where the replacement of the infill material is deemed to be an unacceptable loss of historic fabric, English Heritage proposes the alternative of internal insulation (Ogley, 2010).

1.4 Potential risks of retrofitting

The inappropriate introduction of thermal insulation could potentially cause unintentional negative impacts, including increased moisture content and interstitial condensation leading to the deterioration of the built fabric. The two biggest threats to timber-framed construction are insect infestation and fungal decay, of which, the susceptibility to both increases as the moisture content of the timber rises. The threshold hygrothermal conditions for common insects and fungi are listed in Table 1.

Table 1 Hygrothermal conditions for common UK biological timber threats (McCaig & Ridout, 2012).

	Biological threat	**Moisture content (%)**	**Temp (˚C)**
Beetles	Powderpost (*Lycus linearis Goeze & Lyctus brunneus*)	8-25	26
	House Longhorn (*Hylotrupesw bajulus*)	15-25	20-30
	Furniture or "Woodworm" (*Anobium punctatum*)	>12	22
	Deathwatch (*Xestobium rufovillosum*)	>15	>10
Fungi	Dry Rot (*Serpula lacrymans)*	>25	17-23
	Oak Rot (*Donkioporia expansa*)	>28	5-40
	Cellar Rot (*Coniophora puteana*)	>25	20-32

2. Research objectives

This research aims to study the hygrothermal performance of details for replacement infill panel currently proposed by heritage bodies, in addition to a further 3 details developed by the authors in collaboration with Tŷ-Mawr Lime Ltd. By doing so it is hoped to evaluate the risk of unintentional negative impacts on the historic fabric. This paper presents the results

of the digital simulation of interstitial hygrothermal conditions of each of these details. Further simulation and physical monitoring are planned as part of this ongoing research programme.

3. Methodology

A total of 13 retrofit details were studied (Table 2). A thickness of 115mm was assumed for the timber-frame in each detail.

Table 2. List of reviewed details

Code	Source	Description	U-Value (W/m²K)
S1a	SPAB fig.12	Wattle and Daub + internal and external lime plaster.	2.83
S1b	SPAB fig.12	As S1a but with foil backed plasterboard in place of internal lime plaster	2.53
S2	SPAB fig.13	60mm glass wool + lime plaster on expanded metal lathe.	0.67
S3	SPAB fig.14	Lime render, 50mm wood wool, 25mm glass wool, vapour barrier (VB), 25mm wood-fibre, internal skim coat.	0.63
S4	SPAB fig.17	Lime render, 50mm wood wool, 25mm extruded polyurethane, VB, internal gypsum plaster.	0.62
S5	SPAB fig.18	Half brick nogging, 12.5mm EPS + Internal lime plaster.	1.14
E1a	EH-1* pg325	Lime render, 15mm wood wool, Breather membrane (BM), 54mm cellulose fibre, 20mm wood-fibre board, VB, service void + plasterboard.	0.42
E1b	EH-1* pg325	As E1a but with no BM or VB	0.42
E2	EH-2ǂ Fig.18	Historic infill retained, BM, 50mm wood-fibre to inside face + lime plaster.	0.64
E3	EH-2ǂ Fig.19	As E2 but with 20mm air-gap in place of BM + plasterboard	0.59
T1	Tŷ-Mawr	115mm hemp lime + internal and external lime plaster.	0.84
T2a	Tŷ-Mawr	2x40mm cork board + internal and external lime plaster.	0.48
T2b	Tŷ-Mawr	As T2 but with 2mm lime plaster between cork boards.	0.48

*EH-1 (McCaig & Ridout, 2012)
ǂ EH-2 (Ogley, 2010)

Of these 5 were taken from the SPAB Technical Pamphlet "Panel infilling to timber-framed buildings" (Reid, 1989), 1 from English Heritage's book "Timber" from their series "Practical Building Conservation" (McCaig & Ridout, 2012), 2 from English Heritage's pamphlet "Insulating timber-framed walls" in their "Energy Efficiency in Historic Buildings" series (Ogley, 2010) and a final 3 details developed by the authors in collaboration with the supplier of ecological building materials Tŷ-Mawr Lime Ltd. Eleven of the details are for replacement infill panels, whilst the remaining two are for internal insulation as suggested by English Heritage (Ogley, 2010).

3.1 Simulation with WUFI Pro5

The 13 details were simulated with WUFI (*Wärme und Feuchte Instationär*) Pro5 transient heat and moisture simulation software developed by the Fraunhofer Institute. A weather file for Hereford, UK, created with Meteonorm software, was used for the external climate, with the internal climate being calculated according to BS EN 15026:2007 as recommended by the European SUSREF guidelines for modelling refurbishment of external walls (Peuhkuri et al., 2011). An orientation of 45˚ (South West) was chosen to simulate maximum effect of wind driven rain. All material data was taken from the existing software databases, except for hemp-lime which was supplied by A. Evrard (Evrard, 2008). The simulations were set to run from 1st October for a period of three years.

3.1.1 Risk of interstitial condensation

Following the simulations the interstitial temperatures and dew-point temperatures were compared to identify if temperatures drop below dew-point thereby producing the potential risk of interstitial condensation.

3.1.2 Review of total water content

The total water content of each construction was reviewed. The period taken for annual moisture equilibrium to be achieved, i.e. for built-in construction moisture to dry-out, was calculated. This was done by comparing the first and second year results and identifying the point when the difference between the two is less than 0.1kg/m^2. The results are presented in Fig 2. The total water content for the second year of simulation, i.e. once annual moisture equilibrium has been attained, is presented in Fig 3.

3.1.3 Risk of biological attack

The hygrothermal conditions in each layer were then compared against the criteria presented in Table 1, to assess the potential risk of biological attack of timber in contact with the layer. For this analysis the initial drying period was ignored. For those constructions with drying periods longer than a month, the risk during this period was reviewed separately.

To convert the gravimetric moisture content (%) quoted in Table 1, to gravimetric water content (kg/m^3) produced by the simulation, the following formulae were used:

$$u = \frac{M_w}{M_t} \quad \text{and} \quad M_t = M_w + M_{dry}$$

Where:

u = Gravimetric moisture content (%)
M_w = Gravimetric water content (kg/m^3)
M_{dry} = Dry density of timber (kg/m^3)

Giving $$M_w = \frac{M_{dry} \text{ x } u}{1-u}$$

As the majority of UK timber-framed buildings are primarily constructed of oak, a dry density of 720kg/m^3 was used (TRADA, 2015).

4. Results and analysis

4.1.1 Risk of Interstitial Condensation

The results of the simulations would suggest that none of the proposed constructions had the risk of interstitial condensation. At times the interstitial temperature did drop close to the dew-point but at no time did it drop below.

4.1.2 Total Water Content

4.1.2.1 Drying time

The time taken to reach annual moisture equilibrium is presented Fig 2. This shows that the wattle and daub (S1a&b) and the hemp-lime (T1) have the longest drying times, the hemp lime (T1) taking 118 days, almost 4 months. When the start date of the simulation was moved from 1st October to 1st June this reduced the drying times by 63% for S1a, 50% for S1b and 54% for T1.

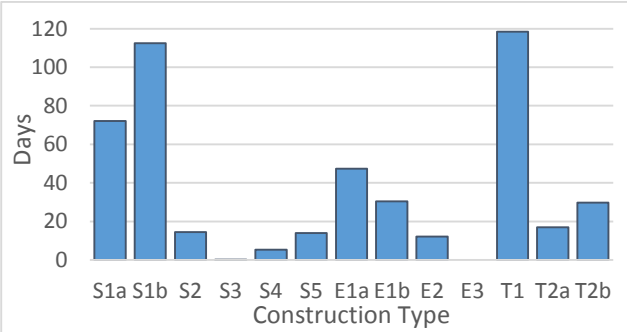

Fig 2: Drying period for constructions.

4.1.1.2 Total Water in 2nd Year

The total water content for the second year of simulation, once annual moisture equilibrium has been attained, are presented in Fig 3. This shows that the two internally insulated details as proposed by English Heritage (E2 & E3) have higher total water contents for approximately half the year. Additional simulations showed that total water content increases with insulation thickness. This is due to the cooling of the external wattle and daub reducing its ability to dry out.

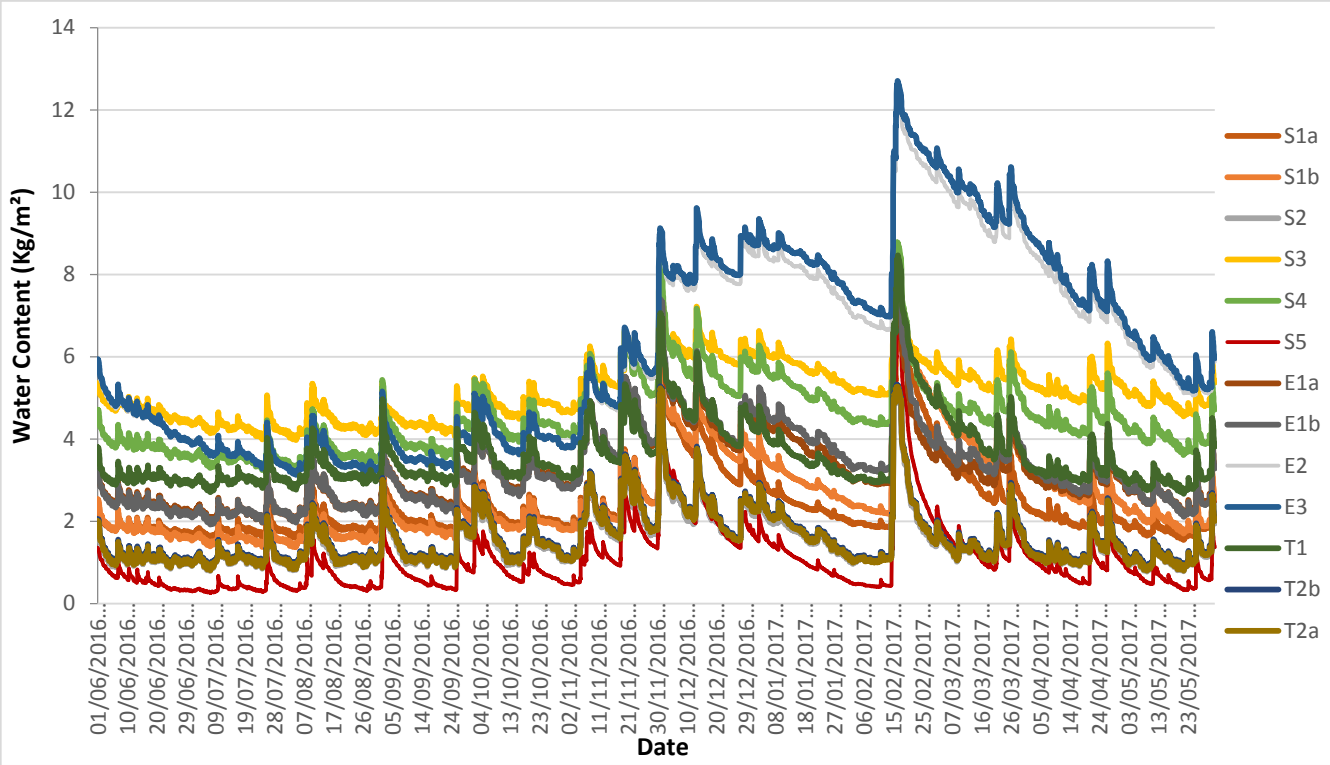

Fig 3: Total water content of constructions in second year of simulation.

No potential threat of interstitial condensation was identified by these additional simulations. Even when internal insulation was increased to 200mm there remained a difference between temperature and dew-point of +0.25˚C.

The second highest total water content was seen in the SPAB details with artificial insulation used in conjunction with wood-wool and vapour barriers (S3 & S4). Interestingly the hemp-lime construction (T1), once it has dried, has a similar total water content to the English Heritage replacement infill details (E1a&b).

There is conflicting results with regards to the inclusion of membranes in the build-up. In the case of E1a&b the introduction of internal vapour barrier and external breather membrane (E1) results in marginally lower water content during winter months. However, the introduction of a vapour barrier on the inside of a traditional wattle and daub wall (S1b) has the inverse effect, with higher water content in winter. The four details with the lowest total water content are the SPAB detail with glass fibre, metal lathe and lime plaster (S2), the two cork details (T2a&b) and the SPAB detail for insulating retained brick nogging (S5). The latter being the lowest. The addition of 2mm of lime mortar between the cork layers in T2b made negligible difference, with an increase of 0.05kg/m^2 total moisture content.

That brick infill has the least total water content would appear to go against anecdotal evidence that suggests that brick nogging is a poor infill material, holding damp and promoting decay (Harris, 2010; Reid, 1989). This highlights the fact that the simulation is only concentrating on the moisture moving between, and held within, the homogenous, continuous layers of the infill materials. It is not reflecting the moisture movement and accumulation that could occur at the junction with the timber frame, nor what occurs when layers are heterogeneous and non-continuous as in the case of the brickwork.

4.1.3 Risk of Biological Attack

The comparison of the simulated interstitial hygrothermal conditions and the conditions favourable for the growth of fungi and infestation by insects (Table 1) suggests that the only potential threat would be from the Death Watch Beetle (*Xestobium rufovillosum*). Given that this beetle can only infest sapwood and wood already modified by fungi (McCaig & Ridout, 2012), the threat is minimal. However the number of hours per year that favourable conditions exist is presented in Fig 4.

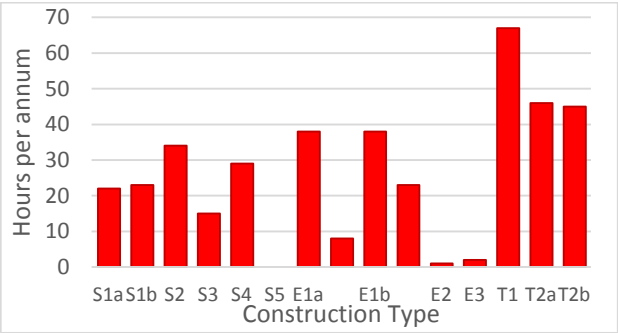

Fig 4 Presence of hygrothermal conditions favourable for Death Watch Beetle infestation.

The construction with the greatest potential risk of attack is the hemp-lime (T1) with 67 hours per annum of favourable conditions in the external lime plaster layer. These hours are spread over 15 instances, the duration of which range from 1 to 14 hours, with an average duration of 4.5 hours. During the separately studied drying period an instance of prolonged favourable hygrothermal conditions lasting 39 hours was identified.

The cork board details (T2a&b) have the second highest potential risk of attack with 46 and 45 hours respectively, spread over 10 instances, with a 4.6 hour average duration. In the case of the English Heritage replacement infill details (E1a&b) the potential risk spreads from the external render, into the underlying wood-wool board. Detail E1a with an external breather membrane has 8hrs of favourable conditions within this secondary layer, whilst that without a membrane (E1b) has three times this with 23hrs spread over 5 instances with a duration ranging from 2 to 9 hours.

5. Future Implementation

It is important to stress, as previously mentioned, that the simulations presented in this paper represent the moisture movement between idealized, homogenous, continuous layers of the infill materials. They do not reflect the moisture movement and potential accumulation at the junction with the timber frame, nor the reality of heterogeneous and non-continuous layers present in actual constructions. For this reason simulation with WUFI 2D-3 and physical monitoring is essential. It is hoped that this further research will enable the production of best practice details.

6. Conclusions

The initial results of the simulations have not identified any proposed infill details that create hygrothermal conditions that pose a major threat to the surrounding timber-framed construction. Within the details studied there was a wide range of resulting total water contents, however these did not necessarily translate into conditions favourable for biological attack. Care should be taken with the use of internal insulation due to the resulting higher total water content and increased risk of intestinal condensation. As would be expected, techniques with high built-in moisture, (wattle and daub and hemp-lime) have long drying periods. Care should therefore be taken as to the timing such work.

As previously mentioned further research is required and is planned as part of this ongoing research.

7. Acknowledgments

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Design to Thrive

Improving the Energy Performance of Historic Timber-Framed Buildings in the UK.

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Abstract: As we aim to improve the performance of our existing building stock, both to reduce carbon emissions and to improve occupant comfort, even timber-framed buildings that have stood for hundreds of years are now the focus of energy retrofits. This paper presents a review of the energy retrofit of three historic, half-timbered buildings in Herefordshire, UK. Using u-value and airtightness data measured in situ, dynamic energy simulations using DesignBuilder have been undertaken to assess the effectiveness of each of the applied retrofit strategies. These strategies include the installation of secondary glazing, plastering of thatched roofing, increased loft insulation and complete replacement of infill panels. Initial results suggest that strategies that result in improved airtightness have the highest impact on energy demand, whilst intrusive interventions within the timber-frame itself have limited positive impact.

Keywords: Energy Retrofit, Historic buildings, Timber-frame, Energy Simulation

Introduction

Although in the UK historic and traditional buildings are exempt from full compliance with the energy efficiency requirements of the building regulations (HM Government, 2016, Scottish Government, 2016), they must still aim to "improve energy efficiency as far as is reasonably practicable" (HM Government, 2016). Historic England states that "an informed approach can achieve significant energy efficiency improvements" (English Heritage., 2012), although these need not reach Building Regulation standards. As such, the level of intervention often remains at the discretion of the building owner and their professional advisors, in discussion with the local conservation officer. This paper reviews three historic timber-framed case studies where differing approaches have been taken. Dynamic building energy simulation has been used to evaluate the decisions taken and compare them to possible alternative scenarios. By doing so conclusions can be drawn as to the effectiveness of each approach and the consequence of this on the retrofit of the UK's 68,000 historic timber-framed buildings (Historic England., 2014, RCAHMW, 2014) and historic and traditional buildings in general. The research in this paper forms part of an ongoing research programme.

Case Studies

The three case study buildings presented in this paper are, Hacton Cruck (Figure 1), a mediaeval peasant hall, now let as holiday accommodation; The Oaks (Figure 2), an estate cottage built over three centuries, now owned by the National Trust and let as a single-family residence; and The Old Mayor's Parlour (Figure 3), a gallery space, managed by a charitable trust, whose origins date back to the 14th century. As such, the case studies represent a variety of ownership models, tenancies and uses. Hacton Cruck and The Old Mayor's Parlour have undergone substantial retrofits and display a variety of different panel infills, both old and new. The work on these properties was designed and overseen by a local, sole practitioner architect. In contrast, The Oaks has had minor retrofit interventions with no change to the existing wall construction, and the works were specified by the estate surveyor in line with the National Trust's environmental standards. The construction work at The Oaks was undertaken by a small building contractor; at The Old Mayor's Parlour by a conservation contractor; and at Hacton Cruck by the building owner in collaboration with professional conservation contractors.

Figure 1 Hacton Cruck, Preston-on-Wye Figure 2 The Oaks, Brockhampton and Figure 3 The Old Mayor's Parlour Hereford. Source: (Author's own, 2015)

Location

All three case studies are all located in the county of Herefordshire, in the English West Midlands, on the border with Wales. Hacton Cruck is situated in the west of the county, The Oaks in the northeast and The Old Mayor's Parlour in the heart of Hereford, the county town, which lies at the centre of the county (latitude 52.06, longitude -2.72). The predominant panel infill materials of the region are brick (47%), plaster (44%) and wattle and daub (8%) (Figure 4). 16% of the buildings with modern infill materials also lie within the county boundaries.

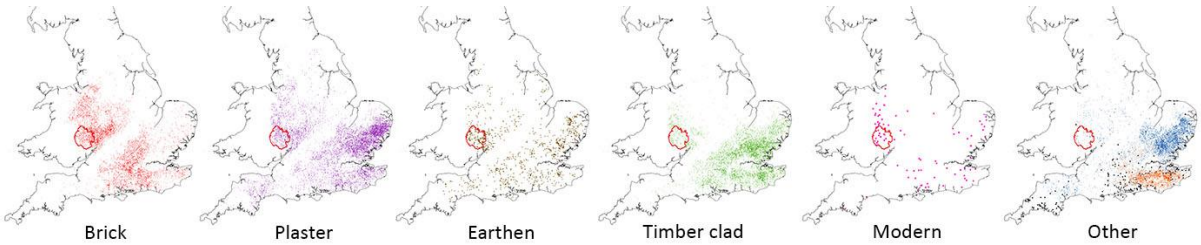

Figure 4 Distribution of timber-framed panel infill materials, with Herefordshire highlighted in red. Source: (Author's own based on data from (Historic England., 2014, RCAHMW, 2014))

Hacton Cruck Hall, Preston-on-Wye, Herefordshire

Hacton Cruck is a 15th century cruck hall in the Wye Valley, Herefordshire, UK (NGR SO 38783 41829). For much of the 20th century it lay abandoned and derelict, yet from 2000 until 2012

it was restored by its owner and now provides holiday accommodation. The renovation involved three different approaches to wall infill panels. On the northern elevation the surviving oak lath and lime plaster panels were retained and repaired. Elsewhere the original infill had been lost and new panels were installed. For most of these it was decided to improve the thermal efficiency by introducing a modern multi-foil insulation, consisting of reflective foils separated by polyester fleece. The foil is held by upright staves within a void and is finished internally and externally with lime plaster on expanded metal lath. In a few locations the thickness of the wall was insufficient for this construction. Led by a desire to experiment with traditional building techniques, the owner decided to recreate wattle and daub for these few panels. The distribution of these panels is shown in Figure 5.

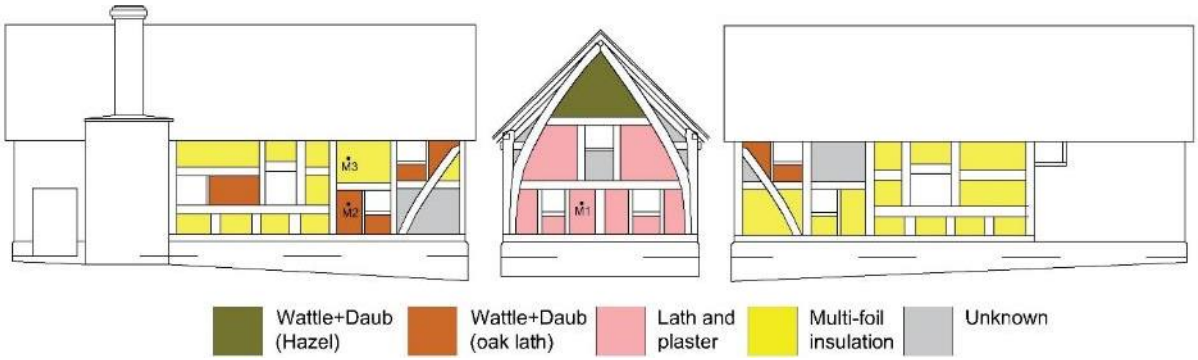

Figure 5 Hacton Cruck. Diagram showing location of each infill panel type. Source: (Author's own, 2016)

The building was completed with a new thatched roof using reed from the Tay Estuary and Sedge, for the ridge, from the Norfolk Broads (Williams, 2011). From 2012 until 2015 the central bay of the hall was left with no internal finish to the underside of the thatch. Following pressure testing by the authors in 2015 it was decided to torch (lime-plaster) the underside of this central section.

In situ measurements

In situ u-value monitoring using Hukseflux HFP01™ heat flow plates, thermistors and an Eltek™ Squirrel data logger, and pressure testing using a Minneapolis Blower door, were undertaken in 2015 (Whitman and Prizeman, 2016). A summary of the results are shown in Table 1.

Table 1. Results of in situ monitoring at Hacton Cruck, March & November 2015

U-value		
Material	**Measured U-value (W/m²K)**	**Calculated U-value (W/m²K)**
Repaired original lath and plaster	2.51	2.40
New Wattle and daub	3.25	2.99
Lime plastered Multi-foil insulation	0.71	0.41
UK building regulations Part L1B	-	0.70†
Airtightness	**Air changes per hour @50 Pa**	**Air permeability @50 Pa (m³/(h·m²)**
Pre-torching	130	154
Post-torching	68	80
UK Building Regulations Part L1A	-	5*

† U-value for existing building with change of use. In this case from farm building back to house

* An air permeability index is stated only for new constructions

The Oaks, Brockhampton Estate, Bromyard, Herefordshire

The Oaks (NGR: SO 70112 55441), is a National Trust let property on their Brockhampton Estate. The small, two bedroom, timber-framed cottage has sections dating from the 16th, 17th and 19th Centuries (Coope, 2015). In February 2015 The National Trust launched a new

set of environmental standards specifically for their let estate. These standards aim to ensure that their housing is healthy and affordable to heat, has a lower environmental impact, and achieves an Energy Performance Certificate (EPC) of E or above (National Trust, 2015). In line with this policy, in the summer of 2015 The Oaks had secondary glazing installed and the roof insulated. No interventions were made to the walls, although thermography indicated that most infills were of modern concrete block with only a few surviving in wattle and daub.

In situ measurements

Pressure testing using the same Minneapolis Blower Door was undertaken in June 2015 prior to the retrofit and in November 2015 following its completion. The results are presented in Table 2.

Table 2 Results of in situ monitoring at The Oaks, June & November 2015

Airtightness	Air changes per hour @50 Pa	Air permeability @50 Pa ($m^3/(h{\cdot}m^2)$)
Pre-retrofit	16.5	17.8
Post-retrofit	10.8	11.7
UK Building Regulations Part L1A	-	5*

* An air permeability index is stated only for new constructions

The Old Mayor's Parlour, Church Street, Hereford

The Old Mayor's Parlour, 24 Church Street, Hereford is a gallery space owned by the Church Street Charitable Trust, along with the adjacent property, 25 Church Street (NGR SO 50981 39895). The original description by The Royal Commission on Historical Monuments (RCHM, 1931) records the building as probably built early in the 16th century but with a stone-built cellar under the north part of the building, containing 15th century doorways. The gallery is located on the first floor and is access via an unheated semi-external staircase. The east façade onto Church Street is timber-framed at first floor with underbuilding and 20th century shopfronts. The west façade is tile-hung timber-frame with modern concrete block infill. The most recent refurbishment work was carried out in two phases. The first phase consisted of internally lining the east wall, thereby removing the cold-bridge formed by the timber frame. Originally, it was not intended to replace the infill panels, however, during this first phase of work it was discovered that the infill was of very loose concrete blockwork (Demaus, 2015). A second phase of refurbishment, was therefore undertaken to replace the concrete block infill from the timber-framed east façade and replaced with wood-fibre insulation using the detail published by Historic England (McCaig and Ridout, 2012) (Figure 6). In addition a multi-foil insulation was installed between the tile-hanging and the concrete block of the west façade. No work was undertaken to the roof due to the elaborate 17th century plaster ceiling.

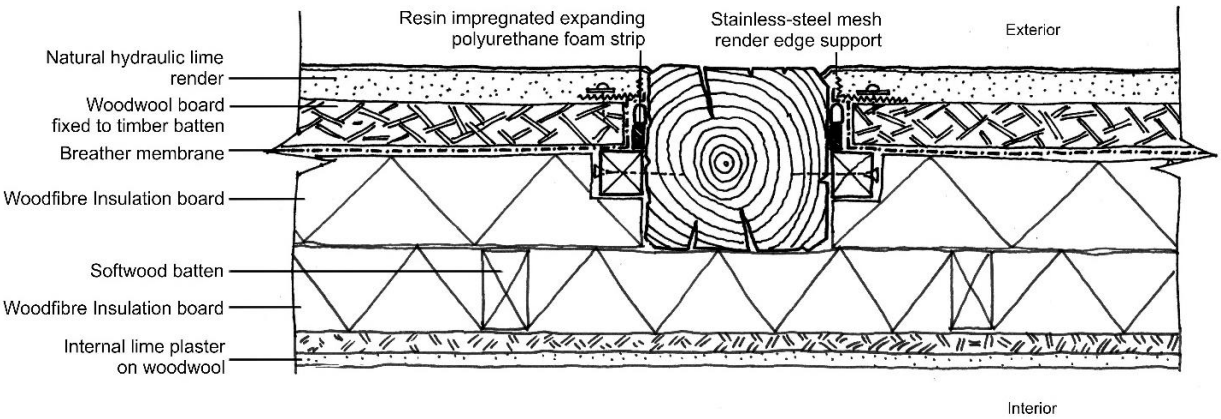

Figure 6 Replacement panel infill detail with internal lining. Source: (Author's own based on (Demaus, 2015) adaption of Historic England detail (McCaig and Ridout, 2012))

In situ measurements

In February 2016 in situ u-value monitoring of the new infill panels and internal lining of the east façade and pressure testing were undertaken using the same previously detailed equipment. The results are presented in Table 3.

Table 3 Results of in situ monitoring at The Old Mayor's Parlour, March 2016

U-value		
Material	**Measured U-value (W/m^2K)**	**Calculated U-value (W/m^2K)**
Historic England detail with woodfibre	0.13	0.13
UK building regulations Part L2B	-	0.28
Airtightness	**Air changes per hour @50 Pa**	**Air permeability @50 Pa ($m^3/(h{\cdot}m^2)$)**
Old Mayor's Parlour	22.5	17.6
UK building regulations Part L2A	-	5

† U-value for replacement thermal element (wall) for an existing non-residential building

* An air permeability index is stated only for new constructions

Energy Simulation

Methodology

The simulations presented in this paper were undertaken using the software DesignBuilder Version 4.2.0.54. This software provides the graphical interface for the dynamic simulation engine EnergyPlus DLL v8.1.0.009 (Design Builder, 2014), a building energy simulation software developed by the University of Illinois and the University of California, for the Office of Building Technology of the Department of Energy of the United States of America (US Department of Energy, 2016 p3).

For the building thermal zone calculation, EnergyPlus uses a heat balance model based on the assumption that the air in each building zone is homogenous with no stratification of temperature (Crawley et al., 2001 p323). As such there is no requirement for the height of differential wall materials to be accurately modelled. The complicated timber-frame was therefore simplified to block sub-surfaces, the area of which accurately represents the area of timber-frame, if not its precise location and configuration (Figure 7).

Figure 7. DesignBuilder models of (from left) Hacton Cruck, The Oaks and The Old Mayor's Parlour. Source: (Author's own, 2017)

Climate Conditions and Weather Files

Like the majority of the UK, Herefordshire is located in a temperate maritime climate with warm summers and cold winters. The climate is classified under the Köppen-Geiger climate classification system as Cfb (C-Warm temperate, f-fully humid, b-warm summers) (Kottek et al., 2006). Average climatic data for the West Midlands, the larger region in which Hereford is located, are presented in Figure 8. The heating season typically lasts from November until March with no requirement for mechanical cooling during summer months. Meteonorm version 6.1 was used to create weather files for each site using the time period 1996-2005.

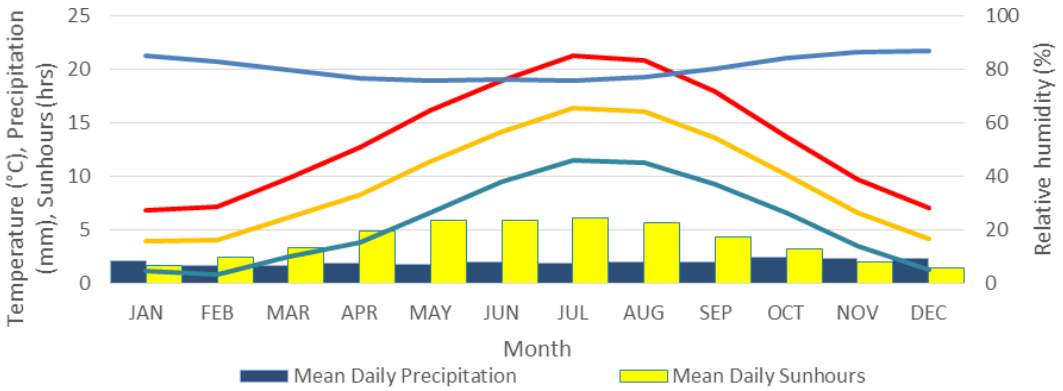

Figure 8 Climatic data for the West Midlands, UK 1981-2010. Source: (Met Office, 2016)

Hacton Cruck

Four scenarios of infill panels were simulated. The first imagined that all original lath and plaster panels had survived; the second imagined that all panels had been replaced with new wattle and daub; the third that all had been replaced with the new multi-foil panels; and the fourth simulated the as built situation with a mixture of all three panel types. The measured u-vales were used for each panel type. These four scenarios were simulated with both the pre- and post-torching air-change-rates and a third hypothetical air-change-rate of 0.5 ac/h@50Pa.

The Oaks

The two retrofit actions (secondary glazing and roof insulation) were simulated separately. In addition two hypothetical retrofit actions were modelled the first replacing all concrete block infill panels with woodfibre insulation and the second replacing all infill panels, including historic wattle and daub with woodfibre. Scenarios with combinations of all retrofit actions, both real and hypothetical, were also simulated.

The Old Mayor's Parlour

As with The Oaks, each retrofit action was simulated separately, in addition to the hypothetical actions of insulating the roof and installing secondary glazing. Again scenarios combining retrofit actions were also simulated. As the gallery is located on the first floor between adjacent buildings, these and the ground floor were modelled as adiabatic volumes.

Results, Analysis and Discussion

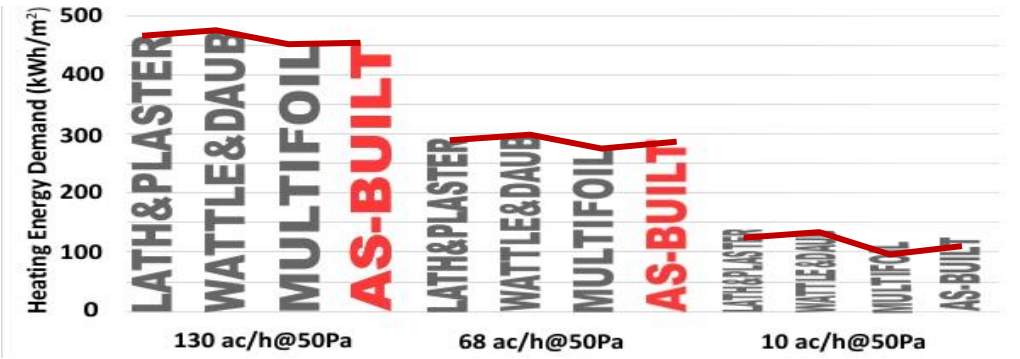

Figure 9. Simulated Heating Energy Demand (kWh/m²) for Hacton Cruck. Hypothetical scenarios in grey

Figure 9 clearly shows that the performance of the infill panels has little effect on the heating energy demand with a variation of only +4% and -0.01% when compared to the current

situation. It is however the simple act of torching the underside of the thatched roof, thereby improving the airtightness, which sees a 36% reduction. If further work, such as improving the joints between panel and timber-frame and plugging post-holes, was undertaken to improve the airtightness to a hypothetical 10ac/h@50Pa then a reduction of 72% could be achieved. Whilst for this specific property no historic fabric was lost in the upgrading of the infill panels, the results of these simulations should have significant weighting in the planning of future retrofits of historic timber-framed buildings.

At The Oaks (Figure 10 left) it can be seen that just the installation of secondary glazing is more effective (10% reduction) than replacing all the infill panels (9% reduction). Whilst it can be argued that secondary glazing is visually intrusive it is however a fully reversible retrofit action and does not result in the loss of historic fabric. The insulating of the roof is the retrofit action with the greatest individual benefit (25% reduction) which when combined with the secondary glazing results in an overall reduction of 34% and is the solution that was applied in reality. With the disruption involved it is questionable whether the additional 11% reduction, achievable by replacing infill panels, would ever be justifiable. Whilst the increase in airtightness resulting from the installation of the secondary glazing is beneficial with regards to energy efficiency, there could be some issues concerning increased internal moisture levels. Initial testing has shown an increase in the surface moisture content of the exposed timber-frame, however further monitoring is ongoing to establish if this is a seasonal variation or a result of the retrofit and further research into this area is ongoing.

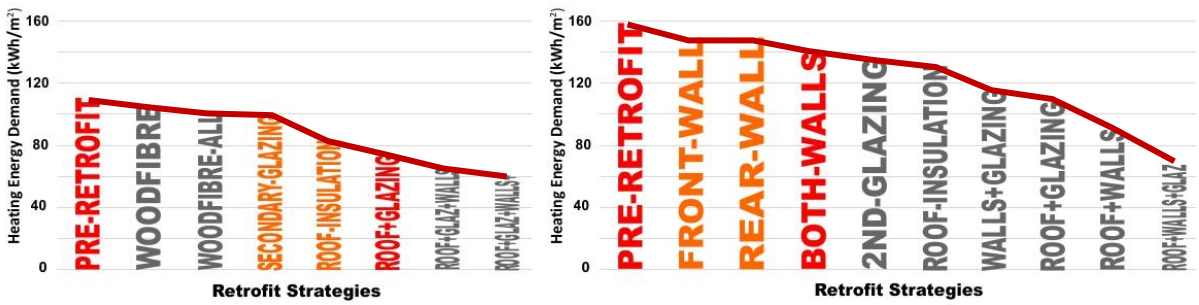

Figure 10. Simulated Heating Energy Demand (kWh/m^2) for The Oaks (left) and The Old Mayor's Parlour (right) Hypothetical scenarios in grey, individual retrofit actions in orange and as-built in red

At the Old Mayor's Parlour it was however only the upgrading of the walls that was undertaken, resulting in just a 6% reduction for each wall and a combined reduction of 12%, even with the avoidance of cold-bridging. It is interesting to note that, assuming secondary glazing would achieve a similar increase in airtightness as seen at the oaks, secondary glazing alone could potentially achieve a reduction of 15%. The introduction of 200mm woodfibre insulation to the roof could potentially have achieved a 17% reduction alone, or 42% when combined with the walls, and 58% combined with walls and secondary glazing. It is however understandable the architect's reluctance to intervene in the roof given the historic value of the 17th century plastered ceiling, however thermography has identified a marked difference in surface temperature between insulated walls and uninsulated ceiling. Potentially this could lead to increased condensation on the ceiling. Intervening in the walls with their poor quality modern infill and avoiding work to the historic fabric of the ceiling would appear a sensible conservation approach, however if humidity within the room is not carefully controlled this decision may have detrimental consequences. Internal hygrothermal monitoring by the authors is ongoing at this property.

Conclusion

The results of these simulations and associated in situ monitoring have highlighted that apparently small measures such as plastering ceilings and installing secondary glazing can have the most significant impact on reducing the heating demand of historic timber-framed buildings. It is interesting to note that the property with the least intervention and the highest achieved reduction in heating demand was the property owned by National Trust. It is perhaps not surprising that an organisation with a large property portfolio of historic buildings should achieve the best balance between intervention, outlay and payback.

In all the cases it was shown that improving the thermal performance of the walls did not dramatically improve the building's thermal performance. Whilst no historic fabric was lost in these case studies, this may not be the case in the retrofit of other historic timber-framed buildings. Care must be taken not to create large discrepancies in internal surface temperatures that in turn could put at risk uninsulated historic building fabric, however simple monitoring and simulation such as that presented in this paper could have aided in the correct selection of retrofit strategies and avoid the unnecessary loss of historic fabric.

Given the relatively small number of timber-framed buildings in the UK (68,000) these energy retrofits are more important with regards to the ongoing use and survival of these buildings, rather than significantly reducing energy consumption at a national level.

Monitoring is ongoing at all three case studies and associated research into the interstitial hygrothermal conditions of retrofitted timber-framed walls is underway as part of the wider research programme.

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