2016

Thermography Approaches for Building Defect Detection

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http://hdl.handle.net/10026.1/4304

http://dx.doi.org/10.24382/3310

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BUILDING
PERFORMANCE
ANALYSIS
WITH
PLYMOUTH
UNIVERSITY

THERMOGRAPHY APPROACHES FOR BUILDING DEFECT DETECTION

by

MATTHEW WILLIAM FOX

A thesis submitted to Plymouth University

in partial fulfilment for the degree of

DOCTOR OF PHILOSOPHY

Environmental Building Group

July 2015

ACKNOWLEDGMENTS

This thesis would not have been possible without the support and assistance from a wide range of sources. To begin with the author would like to express sincere gratitude to my three supervisors, Professor Pieter de Wilde (Plymouth University), Professor David Coley (University of Bath) and Professor Steve Goodhew (Plymouth University). Each brought a different and fresh perspective to my work, which greatly contributed to shaping my direction, informing research processes and ultimately refining my thesis. In particular, I would like to single out Professor Pieter de Wilde, who as my director of studies provided much needed support throughout the many highs and lows that a student encounters.

This project has been funded through a European Social Fund, Combined Universities of Cornwall (ESF-CUC) studentship grant. The project reference for this is 11200NC05/CUC/Phase2. Whilst providing much needed financial support, which helped with living, equipment and training expenses this project was established to collaborate with local external business partners. I therefore extend my gratitude to both Sue Wilton (From RTP surveyors) and Denys Stephens (From DCH Group housing association), and their respective businesses for their support and commercial guidance throughout this project. As part of this connection, both business partners provided access to some of the buildings investigated during this thesis, for which I am very grateful.

I would like to thank all of the residents, who kindly permitted access to their homes. I hope that in some way my research has benefited some, by discovering previously unknown building defects.

Part of this research (walk-through thermography) coordinated with another project, funded by DECC and part of the wider ‘Cornwall Together phase 2’ project. I would therefore like to thank all those involved with this project, in particular Julie Goodhew, the project lead.

I would also like to thank the staff and fellow PhD students in the Environmental Building Group at Plymouth University. In particular university technician, Kevin Owen, who provided essential assistance with the construction of experimental equipment and Jane Campbell for editorial support. Thanks are also reserved for Lawrence Bishop, who assisted with data collection from the climate chamber, Chris Brookman (from Back to Earth) for providing free wood fibre insulation (for the hot/cold box experiments) and Vim Mistry (from Campbell Scientific) for assistance with setting up the CR1000 data logger.

Aside from academic support, I have also received great emotional support from family and friends. In particular I would like to thank my parents and brother, whom have provided countless years of support. I think they had thought my education was over when I qualified as an Architect. Thanks are also reserved for my parent-in-laws and the academic guidance they provided as University professors. Also thanks go to my brother-in-law Alastair Norton, who assisted by with computer/data-logger programming. Finally, I would like to thank my wife, Andrea for her ever-present care and support. There were countless times, when I would spend long evenings in front of the computer, leaving her to take care of the parenting duties for our one year old daughter Josephine. I hope that one day I have the opportunity to repay this support when she undertakes her own PhD.

AUTHOR'S DECLARATION

At no time during the registration for the degree of *Doctor of Philosophy* has the author been registered for any other University award without prior agreement of the Graduate Sub-Committee.

Work submitted for this research degree at the Plymouth University has not formed part of any other degree either at Plymouth University or at another establishment.

This study was financed with the aid of a European Social Fund, Combined Universities of Cornwall studentship.

Relevant scientific seminars and conferences were attended at which work was presented; several journal papers were prepared for publication; joint research was undertaken with other members of Plymouth University. This involved the author conducting ‘traditional’ thermal imaging surveys of domestic properties, providing basic training to other thermographers, analysing the data from over 100 thermal imaging surveys and documenting all findings as part of a published project report.

Published journal papers:

> Fox, M., Coley, D., Goodhew, S. & Wilde, P. d. (2014) 'Thermography methodologies for detecting energy related building defects'. *Renewable and Sustainable Energy Reviews*, 40 pp 296 - 310.

Fox, M., Coley, D., Goodhew, S. & De Wilde, P. (2015) 'Time-lapse thermography for building defect detection'. *Energy and Buildings*, 92 (0). pp 95-106.

Conference papers:

Fox, M., Coley, D., Goodhew, S. & Wilde, P. d. (2012) 'Comparing Transient Simulation with Thermography Time Series'. *Building Simulation and Optimization Conference*. Loughborough, UK: 10 - 11th September IBPSA England, pp 8.

Garmston, H., Fox, M., Pan, W. & Wilde, P. d. (2013) 'Multi-storey building retrofit with a focus on the façade selection process: a UK commercial office case study'. *29th Annual Association Of Researchers In Construction Management Conference*. Reading, UK: 2-4 September 2013, pp 81-90.

Other publications:

Goodhew, J., Fox, M., Boomsma, C., Pahl, S. & Goodhew, S. (2013) 'Thermal Imaging Cornwall 2013'. *Cornwall Together Phase II*. Plymouth: Plymouth University. 47.

Research training:

Level 1 thermography course. Provided by Norman Walker and Ray Faulkner at iRed in Emsworth, Hampshire. 23rd – 27th April 2012.

Level 2 thermography course. Provided by Ray Faulkner and Colin Pearson at iRed in Emsworth, Hampshire. 10th – 14th February 2014.

GTA and PGCAP 600 General Teaching Associates Course. Provided by Plymouth University. Undertaken from 2013 to 2014.

Thermographic surveys and presentations:

The author of this thesis has conducted a large number of thermographic surveys and provided numerous presentations on this topic in addition to the work presented in this thesis. Presentations have included an interview with BBC Radio Cornwall, and articles published in regional newspapers (Western Morning News).

Word count of main body of thesis: 66,679

Signed

Date 14/01/2016

ABSTRACT

Author: Matthew William Fox

Title of the thesis: Thermography Approaches for Building Defect Detection

Thermography is one technology, which can be used to detect thermally significant defects in buildings and is traditionally performed using a walk-through methodology. Yet because of limitations such as transient climatic changes, there is a key performance gap between image capture and interpretation. There are however new methodologies currently available, which actively address some of these limitations. By better understanding alternative methodologies, the performance gap can be reduced.

This thesis contrasts three thermography methodologies (Walk-through, time-lapse and pass-by) to learn how they deal with limitations and address specific building defects and thermal performance issues. For each approach, practical methodologies were developed and used on laboratory experiments (hot plate) and real dwelling case studies. For the real building studies, 133 dwellings located in Devon and Cornwall (South West England) were studied; this sample represents a broad spectrum of construction types and building ages.

Experiments testing these three methodologies found individual strengths and weaknesses for each approach. Whilst traditional thermography can detect multiple defects, characterisation is not always easy to achieve due to the effects of transient changes, which are largely ignored under this methodology. Time-lapse thermography allows the observation of transient changes from which more accurate assessment of defect behaviour can be gained. This is due to improved

differentiation between environmental conditions (such as cloud cover and clear sky reflections), actual material thermal behaviour and construction defects. However time-lapse thermography is slow, complex and normally only observes one view. Walk-past thermography is a much faster methodology, inspecting up to 50 dwellings per survey session. Yet this methodology misses many potential defects due to low spatial resolutions, single (external only) elevation inspection and ignoring transient climate and material changes.

The implications of these results for building surveying practice clearly indicate that for an improved defect characterisation of difficult to interpret defects such as moisture ingress, thermographers should make use of time-lapse thermography. A review of methodology practicalities illustrates how the need for improved characterisation can be balanced against time and resources when deciding upon the most suitable approach.

In order to help building managers and thermographers to decide on the most suitable thermography approach, two strategies have been developed. The first combines different thermography methodologies into a phased inspection program, where spatial and temporal resolution increase with each subsequent thermography inspection. The second provides a decision-making framework to help select the most appropriate thermography methodology for a given scenario or defect.

CONTENTS

LIST OF TABLES, FIGURES, EQUATIONS AND MOVIES

Note. All tables, figures, equations and movies in this thesis are produced by the author unless otherwise stated in the text.

Tables

Figures

Equations

Movies

The following list of movies relates to time-lapse sequences discussed in chapter 6.

These are included on an accompanying CD to this thesis.

Movie 1. Case study 1. 30-minute temporal resolution.

Movie 2. Case study 2. 20-minute temporal resolution.

Movie 3. Case study 2. 120-minute temporal resolution.

Movie 4. Case study 2. 360-minute temporal resolution.

Movie 5. Case study 3. 30-minute temporal resolution.

1.0 Introduction

1.1 Carbon Reduction Needs

In order to achieve the UK target of 80% reduction in carbon emissions on 1990 levels by 2050 (Climate Change Act 2008, 2008; DECC, 2011), new and existing building stock performance will need to be improved. Although this target is aligned more with energy performance than building defects, it can be argued that heat loss from defective building components, such as thermal bridges and draughts, relates directly to a building's overall energy performance (Lloyd et al., 2008). For instance, it is well known that building defects and component failures lead to increased energy use in buildings. This is significant, since increased energy use also equates to increased carbon emissions, depletion of natural resources, increased energy costs to residents and in some cases the potential for fuel poverty.

Space heating accounts for over 60% of domestic energy use in Britain (Palmer & Cooper, 2011) and with energy prices rising (DECC, 2013), conservation of heat can contribute to improved comfort levels, lower energy bills and fewer households experiencing fuel poverty. As such, more stringent building standards have been introduced over the past 50 years (Lowe & Bell, 1998). Part L of the England and Wales Building Regulations sets out a number of standards dealing with the conservation of fuel and power in buildings (DCLG, 2014b), including standards related to the thermal transmission of the building fabric and CO_2 emissions. While many factors are taken into consideration for the Target Emission Rate (TER) and Dwelling Emission Rate (DER), these calculations are time dependant, indicating the performance of a building for steady state conditions.

1.2 Housing Refurbishment Needs

The English context

The *English Housing Survey, Headline Report 2012-13* (2014a), presents the housing stock profile for dwellings in England. Reported on the basis of dwelling age, the data indicated that the majority of England's housing stock was built before the 1990s, as illustrated in Figure 1.

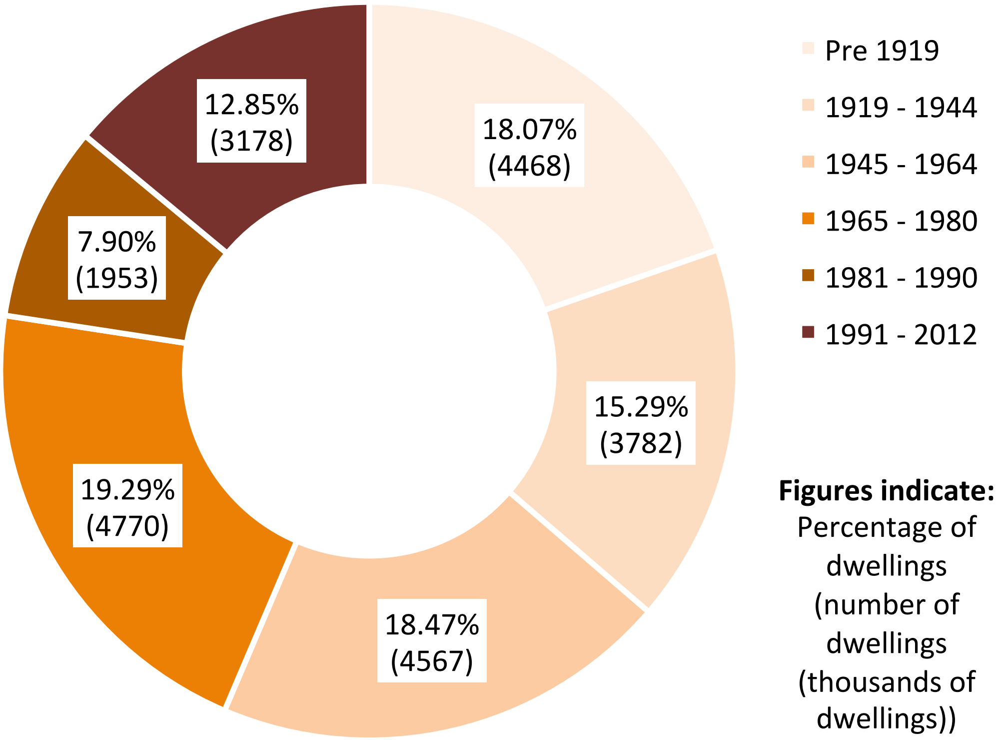


Figure 1. Housing stock profile by age (DCLG, 2014a).

Davies (2010) suggested that if the UK was to build 200,000 new houses per year, it would take 120 years to replace the existing housing stock. However, using NHBC new dwelling registration (NHBC, 2013) figures for England in 2013 (117,969 dwellings), it would take approximately 196 years to replace England's housing stock if development continues at 2013 levels. Although it now seems likely that this rate will continue to rise (Allen, 2014), if the UK is to rely upon new build housing in order to meet its optimistic carbon reduction targets by 2050 (36 years time), then new build house construction output will have to increase considerably, compared with 2013 levels, if the benefit from improved thermally efficient new dwellings is to outweigh the less thermally efficient existing housing stock.

However, even based on the 2007 development rate for England (163,547) (NHBC, 2013), it would still take approximately 140 years to replace the existing housing stock. Indeed, to replace existing stock (everything before 1991) by 2050, England would need a development rate of approximately 560,000 dwellings per year. It is therefore imperative that the focus shifts from new build housing to improving our existing housing stock.

The Cornish Context

Within Cornwall there exists a significant stock of existing buildings that need to be thermally upgraded in order to increase energy efficiency, reduce carbon emissions, improve the quality of life of the occupants, and help with fuel poverty. In 2011 there were around 230,400 dwellings in Cornwall (Cornwall Council, 2011). Of these, 28% of dwellings were built prior to 1919 (Sleeman, 2010), which is much higher than the English average of 18% (DCLG, 2014a).

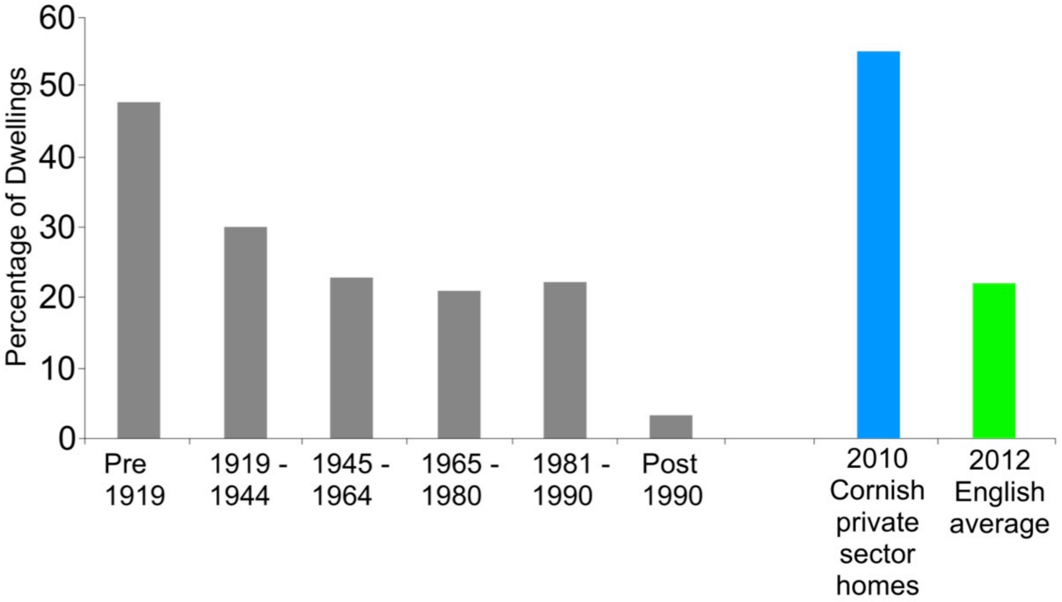


Figure 2. Percentage of dwellings in England failing the Decent Homes Standard by dwelling age. Including Cornish and English average for context (DCLG, 2012).

Sleeman (2010) also indicated that 55% of Cornish private sector homes are termed '*non decent*' with respect to the 'Decent Homes Standard' set out by the government. This compares poorly with the English average of 22% in 2012 (DCLG, 2014a). Figure 2 shows data from 2010, that a greater percentage of English dwellings failing the decent home standard' were built before 1919. This corresponds with the increased number of Cornish dwellings built prior to 1919 and percentage of those failing the decent home standard.

Updated in 2006, the 'Decent Home Standard' is used to define the quality of a dwelling. A decent home is one that meets the following criteria (DCLG, 2006):

a) It meets the current statutory minimum standard for housing
b) It is in a reasonable state of repair
c) It has reasonably modern facilities and services

d) It provides a reasonable degree of thermal comfort

With regards to the last point, Sleeman (2010) states that 31% of private sector Cornish dwellings lack decent levels of thermal comfort compared with the national figure of 18%. Furthermore, it is reported by the South West Housing Body (2005) that 11% of dwellings in the South West of England do not have central heating compared with 9% nationally. This is seen as compounding the issue of fuel poverty as households in this region find it more difficult to achieve a comfortable environment than others.

The *South West Regional Housing Strategy* (South west housing body, 2005) reports that overall fuel poverty percentages in the South West are impacted by the increased number of rural dwellings in this area. It is reported that these dwellings are more likely to:

- Lack access to a gas supply, resulting in high carbon intensive fuel use (Electricity, oil and gas) (Boardman, 2007);
- Lack decent levels of thermal insulation due to the common occurrence of solid wall constructions;
- Present heat losses due to a high proportion of detached dwellings in rural areas.

With reference to rural dwellings, Geddes *et al.* (2011) states that 21% of rural households experienced fuel poverty compared with 11% in suburban areas and 10% in urban areas. Also, rural dwellings have higher annual CO_2 emissions (8.1 tonnes per year) compared with those in suburban areas (5.3 tonnes per year) (DCLG, 2012).

Having reviewed the Cornish and South West of England context, it has become clear that, due to a combination of several local problems such as rural locations, weather and the ageing dwellings/materials (with materials likely to be past their life expectancy), there is a real need to improve the existing building in this region, which are currently failing the decent homes standard.

Causes of existing building failure

Before addressing building failure (of the decent homes standard), it is first important to understand some of the causes leading to failure.

A report by the *National Association of Home Builders / Bank of America Home Equity* (2007) studied the expected lifespan of certain dwelling components. The report found that whilst masonry construction had a life expectancy of over 100 years, aluminium and timber windows were only expected to last between 15–30 years. Although this report focused on North American dwellings, similar principles are found with UK homes according to a report defining a 'decent home' by the UK government Department for Communities and Local Government (DCLG, 2006). In this report, it is suggested that wall structures have an average life of about 80 years, roofs of between 30-50 years and windows/doors have between 30-40 years life expectancy. Therefore, with approximately 70% of English dwellings being over 30 years old (DCLG, 2014a), it should be expected that certain elements, such as windows, might not be performing as originally intended. Oliver (2012) referred to dwelling life-expectancies by pointing out the industry accepted figure of 60 years for a dwellings life-span. However, many dwellings in England are older than 60 years of age and still functioning well, making such a figure appear arbitrary, particularly as residents upgrade shorter lifespan items such as windows more frequently than other elements such as masonry walls.

Brand (1995) discusses the different layers of a building from ‘stuff’ to ‘skin’, suggesting that different layers have varying degrees of expected lifespan, which should be positioned in the layered structure according to their need to be repaired/replaced. For example, an internal wall finishes layer might have a shorter life span (5 to 20 years) compared with the services layer (5 to 30 years) and compared with the structure layer (60 to 80+ years). The layering of materials is important, because different layers/components will fail at different rates, and will become more or less simple to repair depending on their location in the construction.

The significance of material/construction life expectancies relates closely with component failure, since nearing or reaching the end of a component’s life expectancy period, failure might become more expected. Whilst building failures might be as a result of life expectancy age or ware and tear factors, they might also be as a result of poor construction workmanship or details. Houghton-Evans (2005) explained that the primary cause of building defects is poor design and workmanship, where a lack of understanding of materials and construction whilst the building is being designed and built have compromised the lifespan and potential durability of the building fabric. To address the issue of poor design and workmanship building regulations are often used to stipulate the minimum construction standards that new buildings and components should meet. In England and Wales, these regulations have improved since their 1667 introduction year (Lay, 2000) to the present day. The most significant regulation relating to the

Conservation of Fuel and Power is Part L. The most recent version of this regulation available at the time of this thesis, stipulates minimum U-values for walls in new dwellings of 0.18W/m^{2}K (DCLG, 2014b), which compared with those set in 1976 are significantly improved. However, with approximately 80% of English dwellings built prior to 1980, the likelihood is that pre 1990 U-values of 1.0W/m^{2}K (Lowe & Bell, 1998) or greater should be expected.

Helping to illustrate how building performance has improved in relatively recent years, Figure 3. shows correlations between age, improving SAP ratings and energy (DCLG, 2010a). As might be expected, older dwellings equate to increased energy use/CO_2 emissions.

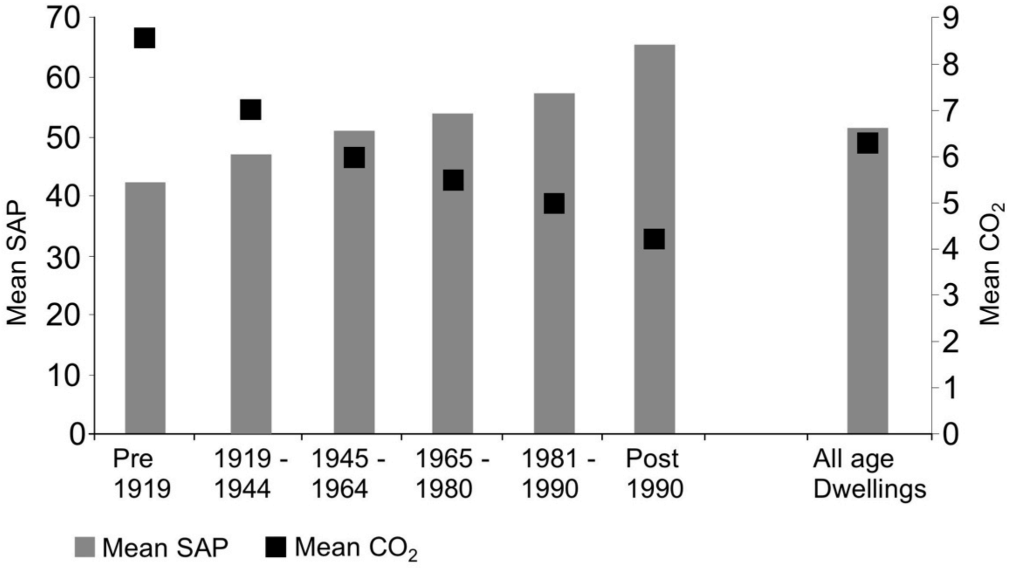


Figure 3. Mean SAP rating and annual CO_2 emissions (tonnes/yr) by dwelling age (DCLG, 2010a).

Combining the issue of failing building components with those buildings constructed to a lesser standard (compared with present day, 2015) underlines the need for continued improvements to existing buildings. Kelly (2008) supports this by suggesting that if existing buildings are to meet the UK's 2050 carbon reduction targets, there are four key areas of improvement:

1. *New measures to improve the thermal envelope of buildings – materials, installation processes, controls, etc.*
2. *Decarbonising the grid and other sources of energy*
3. *Improving the energy efficiency of appliances*
4. *Changes in personal attitudes and behaviour concerning profligate energy consumption*

Whilst occupant education is fundamental to the efficient use of energy systems, it can be argued that minimising the energy demand should be addressed before considering the energy supply (Liddell, 2008). For example, making use of more efficient/ lower energy electricity consuming appliances should be considered before deciding upon the most efficient way to power them. Likewise, building fabric and controls should be improved/optimised to minimise unwanted energy (heat) loss or gain before proposing systems and sources of energy supply. Since space heating accounts for the largest proportion of domestic energy use, it is improvements in building fabric thermal performance (heat loss/gain) that should be addressed in particular.

Beginning to address the building fabric in relation to thermal performance is Brand (1995), who explains that the weather-proof layer of a building is the most important layer in environmental control by minimising the gain or loss of heat (depending on the climate). Although heat gain can be a thermal comfort issue to some buildings during the summer months of the UK climate, it is often heat loss that poses the most significant challenges to the conservation of energy and thermal comfort.

1.3 Building Defects

When discussing the issue of buildings and constructions failing to meet expected standards of thermal comfort and energy efficiency, one key factor is that some buildings were fabricated to lesser standards of construction in the first place (dependant on the age of construction). Another key factor is the degradation or poor construction of building components, which is commonly referred to as a building defect.

Houghton-Evans (2005) defines a 'defect' as

> *"The absence of something essential to completeness, a lack or a deficiency arising from an incorrectly designed or built component of a building - a product of fault."*

This is supported by Mansor *et al.* (2012) who explain that defects are where components fail to 'conform' with the typical/standard state and can lead to damage, which can result in other issues, such as:

- Harm/injury to occupants
- Performance reduction (such as increased heat loss/gain)
- Expense (to repair)
- Reduction in component appearance/aesthetics
- Damage to interconnected/adjoining components. For example small failures in one component that may seem insignificant could lead to more serious problems in another component (Parfitt, 2012).

With regards to categories of building defects, Marshall *et al.* (2009) and Douglas & Noy (2011) have published details on the most commonly encountered defects within UK buildings, which include:

- Settlement, cracking and structural movement
- Delamination and frost damage
- Insect and fungal attack
- Damp penetration
- Condensation
- Cold bridging
- Water, drainage and electrical service failures
- Draughts from air-leaking around poorly sealed building components such as windows and doors

As the key theme of this thesis is on the thermal performance of existing buildings, only those defects that are thermally significant will be investigated through this thesis. Considering the type of thermally significant defects found in buildings, Walker (2004) listed three key overall areas of heat loss:

- Moisture ingress
- Ventilation loss
- Conduction loss

It is important to note that some building defects may be interrelated. For example, cracks might start through settlement/ground movement, though worsen due to moisture ingress and lead to unwanted ventilation heat losses (Bakri & Mydin, 2014). Also some defects might only become apparent over prolonged periods of time, for example moisture ingress can, over time, lead to a degradation in material components and mould growth, which in turn can have an impact on material lifespan overall thermal performance (Burkinshaw & Parrett, 2003).

It is also important to consider the physics behind thermally significant building defects. Referring back to Walker's list of key overall areas of heat loss, all three defect types will be subject to conduction, convection and radiation. Figure 4. illustrates the key heat transfer mechanisms subject to an unspecified target (with indicative internal and external air temperatures). Although this relates to a steady state/dry target, adding moisture or air movement to the construction will have the effect of altering the material properties of the structure by increasing conduction (evaporative cooling and forced convection for example). It is therefore important to not treat conduction heat losses in isolation from the other heat transfer mechanisms.

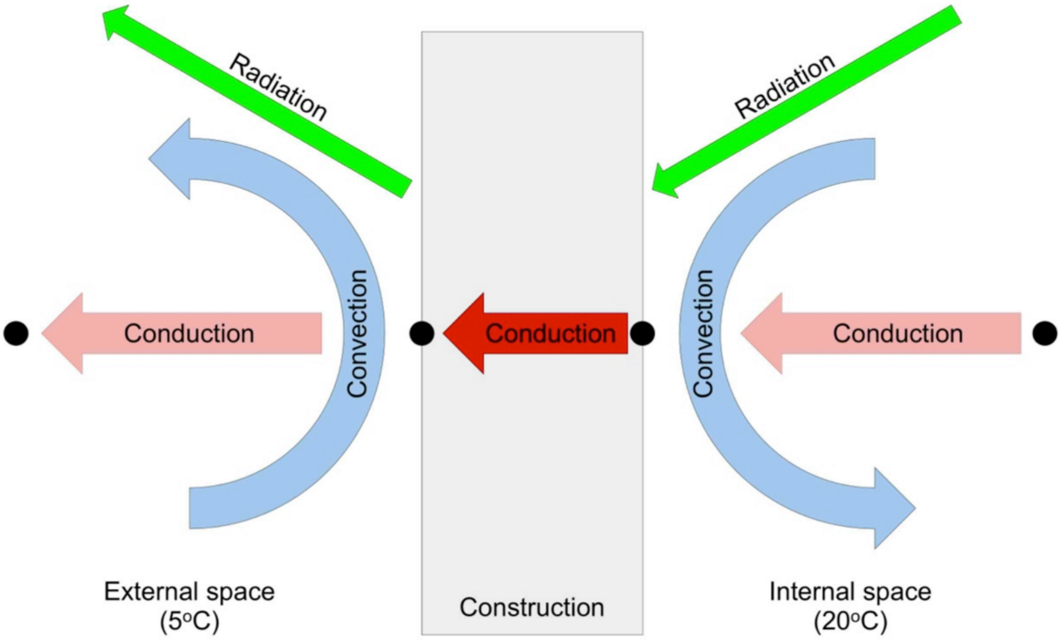


Figure 4. The three heat transfer mechanisms subject to an unspecified structure. Adapted from De Wilde (2009).

Prevalence of building defects

Pan & Thomas (2013) describe how the number of defects found in each dwelling is a 'key indicator of quality'. Where the fewer defects found, the better the overall quality. Whilst aligning more with new-build dwellings, in existing dwellings, the same adage applies, since fewer building defects present equal a lower risk from harm and performance reduction etc.

Houghton-Evans (2005) presents a diagram which illustrates the distribution of building defects by building type (Figure 5).

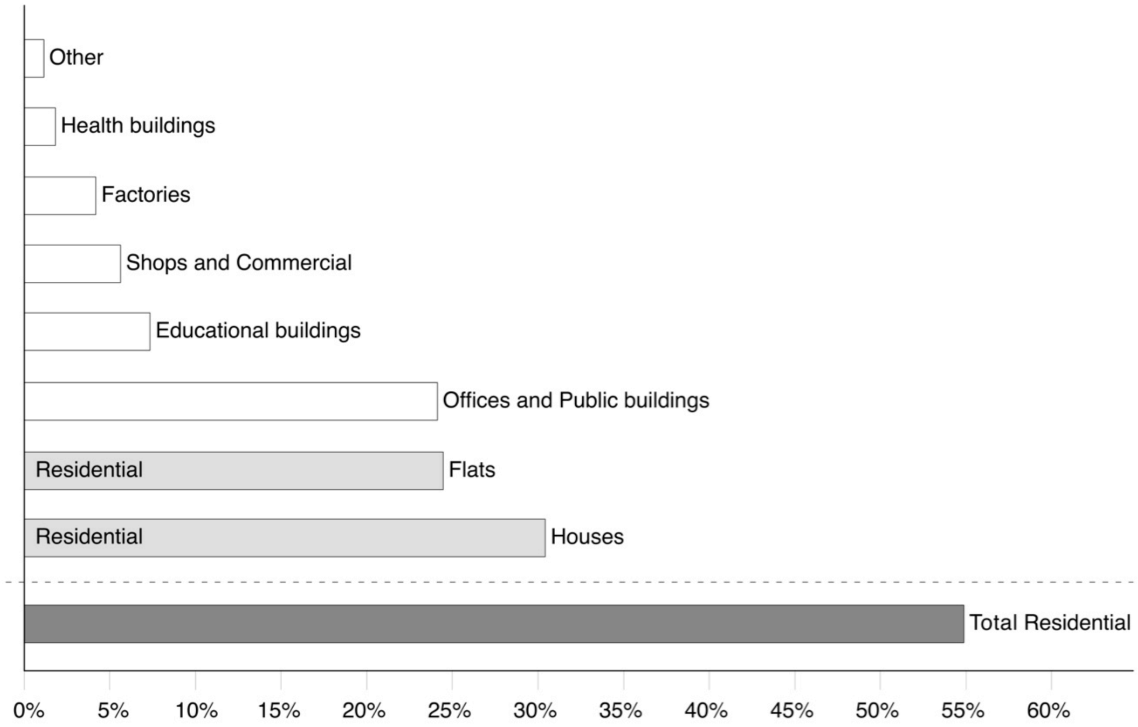


Figure 5. Distribution of defects by building type. Adapted from Houghton-Evans (2005).

Studying the percentage of defects found by building type, it is clear that some building types, such as offices and residential buildings are more susceptible to defects than others such as health buildings. Whilst building defects are present in non-domestic buildings, results from figure 5 found that after combining both residential groupings (Flats and Houses), total residential buildings were 31% more likely to experience defects than the next nearest non-domestic group of Offices and Public buildings. Although it is not clear which defects have been included for this study (i.e. these might include non thermally significant defects such as subsidence), the results from this diagram clearly highlight the need to focus the investigation in this thesis on residential dwellings.

The need for defect detection

In light of the occurrence and nature of building defects in existing residential dwellings, there is a significant need to better understand thermally significant building defects, if the thermal performance of existing buildings is to be improved, thereby reducing fuel poverty and carbon emissions issues.

However, at present it is sometimes difficult to estimate the extent of reduced thermal performance that a particular defect might create. This is partially due to a lack of understanding of the detected defect. These difficulties result in mismatch between estimated heat loss/gain/defect severity and actual heat loss/gain/defect severity. This aspect is clearly a performance gap (Menezes et al., 2012; Wilde, 2014), which needs to be addressed by better defect detection and understanding.

Methods of defect detection

The ability to successfully identify defects within buildings is fundamental to the subsequent success and suitability of any remedial action taken (Houghton-Evans, 2005). This ability relies upon two key aspects: the knowledge and experience of the assessor and the suitability of the analysis methodology or tool.

Currently, there are many different methods and tools available to building professionals investigating building defects (ATTMA, 2010; Douglas & Noy, 2011; Wingfield et al., 2010) Tools include:

- Moisture ingress
    - Surface moisture meters - Protimeter
    - Calcium Carbide measurements
- Structural defects and thermal bridging
    - Borescope
    - Ultrasound / Impulse radar
- Ventilation heat loss
    - Airtightness testing
- Conduction heat loss
    - Heat flux meters
    - Thermal probes
    - Data loggers
- Whole house heat loss
    - Data loggers
    - Coheating testing

Building surveyors also frequently rely on their practical knowledge and experience (Douglas & Noy, 2011). Visual analysis in particular is a common method of detecting defects (Vatan, 2011), for example, recognising mould spores on the surface of a wall. However, Feilden (2003) stated that there is often less than 10% of the building fabric available for visual inspection, with the remainder being hidden from view (beneath the ground / structure). Once discovered, building professionals then broadly have two forms of testing available (Doran, Douglas & Pratley, 2009): Destructive and non-destructive testing. While destructive testing offers a more comprehensive understanding of the defect symptoms, it takes a long time to undertake, is invasive and might only assess a defect in one small area. Non-destructive testing however makes use of potential defect 'clues' that can be seen on the surface or without opening up a structure. This is much less invasive, quicker and more cost effective (Feilden, 2003).

Although non-destructive testing is the most common method for building surveys due the increased *speed* and *non-invasive* nature of this approach, Houghton-Evans (2005) states that the ability to successfully repair building defects based on non-destructive analysis is largely constrained by the failure to successfully characterise defect '*symptoms and causes'.* This is supported by Matheson (2005) and Cowdy (2012) who both report how pre-purchase building surveys often fail to identify some significant building defects. One reason for this is that some defects (such as damp/moisture) are hidden and not always easy to identify using traditional non-destructive surveying techniques. Typical non-destructive testing techniques include: impulse radar, ultrasound, coheating and air-tightness testing for example.

1.4 Thermography

Another non-destructive tool for detecting potential building defects is infrared thermography. Thermography is an emerging technology used by construction professionals as a tool focused upon the thermal performance and condition of existing buildings (UKTA, 2007). A thermal camera is used to detect infrared radiation, which is emitted from the surface of an object and is converted into a thermal image (Hart, 1990). Because a thermal camera can quickly detect thermally significant defects and heat loss from the built fabric, thermography is uniquely placed to help tackle increased energy use, fuel poverty and thermal comfort issues.

Whilst most non-destructive testing methods have been designed to address one specific defect or issue in great detail (e.g. air tightness testing for ventilation heat loss), infrared thermography is the only tool that can be used to observe multiple defect types. Thermography is therefore the best placed non-destructive testing tool for detecting thermally significant building defects, and could significantly help to minimise energy inefficiency in existing buildings due to unexpected heat loss.

Given the difficulties experienced in detecting and understanding building defects within existing buildings, it is possible that thermography can help professionals to reduce the performance gap between the estimated effect (thermal performance/efficiency) a defect has and its actual effect. For example, thermography enables the 'visualisiation' of energy performance gaps, which can be compared with estimates/predictions. One example of this was presented by Fox *et al.* (2012), who compared thermography with computer simulation for the measurement of heat flow through sample materials. Another method of reducing the performance gap being explored by others (Madding, 2008) is the use of quantitative analysis to measure real building thermal performance.

1.5 Knowledge Gaps and Key Issues

Aside from the better understanding and visulalisation of key performance gaps found in building defects and thermal conductivity from using thermography, it is known that there is a key performance gap within the field of thermography itself. This performance gap is the disparity found between capturing thermal images and being able to accurately interpret the heat loss patterns presented in these images. For instance, it is relatively easy to point a thermal camera at a building a capture an image, yet there are numerous limitations (from thermal camera specification/technical ability and external influences) that will constrain the accuracy of this thermal image. These might lead to missinterpretations that ultimately question the value of this non-destructive approach for investigating thermal performance.

Camera specification (thermal resolution) and operator skill (at using the camera and dealing with known limitations) are seen as two of the main barriers to thermal image interpretation (Mauriello, Norooz & Froehlich, 2015). Indeed, it is imortant that thermographers are adequately trained (to PCN qualifications) to make the best use of the camera equipment and to identify sources of error in captured images. Although addressing these two issues will help thermographers to minimise or at least recognise the thermography performance gap, training will not eliminate the gap. Another way of looking at the thermography performance gap is to consider it from the perspective of building defects. Currently well trained thermographers with high specification thermal cameras often detect potential building defects (unexpected hot or cold spots within a thermal image). However *detection* is not the key to understanding a defect. To do this the defect needs to be *characterised*.

Another key barrier to thermal image interpretation and defect characterisation is thermography methodology. At present traditional thermographic surveys comprise of single point in time image capturing methods. Yet this type of image recording poses the potential for misinterpretation because it does not fully account for certain critical limitations such as the effects from transient conditions (thermal mass and dampening effects for example), which are not always visible in instantaneous single point in time thermal images (Pearson, 2011), making defect characterisation very difficult.

There is therefore a real need to make use of alternative methodologies, which address some of the known limitations, so that the thermography performance gap can be further reduced. By using alternative methodologies to overcome key limitations when inspecting existing buildings, trained thermographers will be better placed to understand and factor in limitations such as transient climatic changes. This will make defect characterisation much more accurate, thus enabling key decision makers (clients/building managers etc.) to make better choices on defect remediation measures.

Despite the emergence of new passive building thermography methodologies, such methodologies are not well known or applied in practice. Furthermore, some methodologies appear to be used inappropriately, leading to image data misinterpretations, which seem to be limiting the ability to accurately identify building defects and fabric thermal performance. Consequently, there is a great need to compare new methodologies with traditional methods, understand key benefits and limitations, and to understand how each different methodology can be most appropriately utilised. Once aware of these factors, it is important to consider how each thermography methodology can be coordinated with each other and or alternative methods of non-destructive testing so that more considered programs of inspection methods can be used to minimise the thermography performance gap.

1.6 Research Aim and Objectives

This research project will investigate the practical application of three different passive building thermography methodologies, focusing on how successful they are at detecting and characterising thermally significant building defects within existing dwellings.

Based on the knowledge gaps and key issues, the research aim for this thesis is described below:

> *The aim of the research is to advance academic and industry understanding of three very different passive building thermography methodologies. In particular this study explores the practical benefits and limitations of each methodology to determine how successful they are at defect detection and characterisation. Equipped with this knowledge, other thermographers and building managers can use this work to make improved decisions for the selection of the most appropriate passive building thermography methodology for specific defects or scenarios.*

In order to achieve the research aim, a series of research objectives have been identified as key areas for investigation throughout this thesis. These objectives will:

Objective 1. Review the current application of existing and emerging thermography methodologies for building inspection.

Objective 2. Critically evaluate the perceived strengths and limitations associated with existing and emerging thermography methodologies.

Objective 3. Explore the traditional walk-through thermography methodology.

Objective 4. Explore time-lapse thermography methodology.

Objective 5. Explore walk-past thermography methodology.

Objective 6. Develop a rationale for selecting passive thermography methodologies.

In summary, objectives 1 and 2 establish the current context to building thermography, by exploring the current application of different methodologies and evaluating the core benefits and limitations to defect detection using this technology. The findings from objectives 1 and 2 will form a foundation to the research, from which objectives 3, 4 and 5 will advance through explorations of three different thermography methodologies. Finally, objective 6 seeks to draw together the research obtain from objectives 1 to 5 by establishing a methodology selection rational for other thermographers and building managers.

1.7 Thesis structure

Because this thesis specifically investigates different methods of using thermography, it is necessary to differentiate between the *thesis methodology* (how the thesis has been structured), *research methodology* (how the research was undertaken) and the *thermography methods* (forms of thermography survey. E.g. time-lapse, walk-through etc.).

Within this section, the *thesis methodology* shall be presented. This specifically focuses on how the thesis has been arranged from chapter to chapter. Dealing with the research content, chapter 4 begins to address this by describing the *research methodology*. This establishes the overarching methodology used for conducting the research activities. Also dealing with the content of the thesis, specific details relating to each individual *thermography method* shall be presented at the start of each case study/experiment section (primary research chapter). This will cover survey specific details such as time-scales/survey durations, particular equipment and methods of using the equipment for example.

This thesis has been structured around 10 chapters, which work towards addressing the aim and objectives set out in this chapter. Figure 6 illustrates the overall thesis structure and how each chapter informs/flows from one to the next.

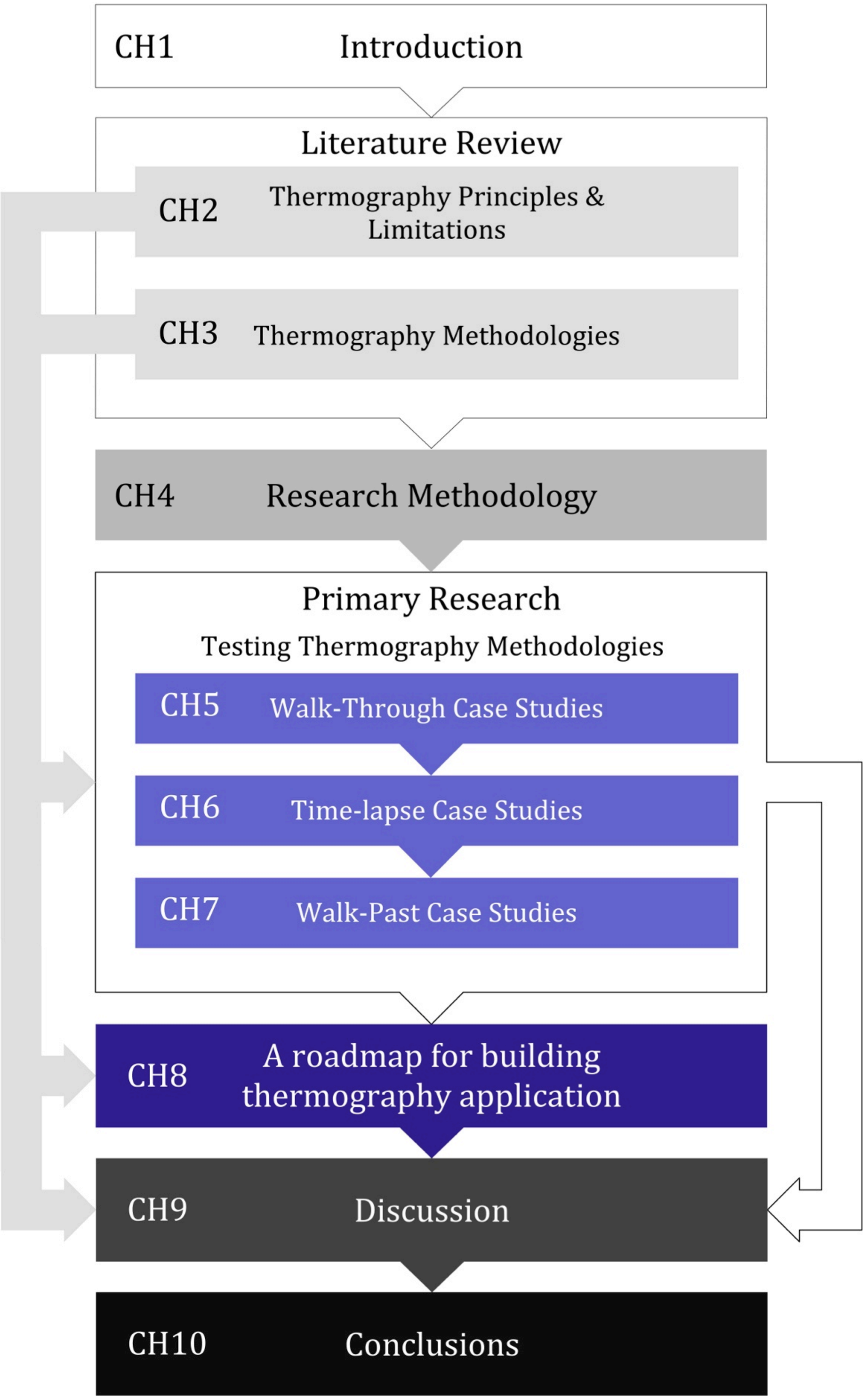


Figure 6. Thesis structure diagram

Beginning the thesis, this chapter (chapter 1) has introduced an overview of the project, and has positioned the work in a broader context through a discussion of the issues that are driving the need to investigate existing dwellings in the South West of England. Chapter 1 also presents the research aim and objectives, which have been developed based on identified problems and gaps in existing knowledge.

A detailed literature review has been covered in chapters 2 and 3. Chapter 2 starts by explaining the key principles of building thermography, known limitations to this technology, difficulties encountered with image interpretation and common thermally significant building defects that are commonly detected using thermography. Chapter 3 focuses specifically on the different building thermography methodologies currently used in science and practice. This section explores how thermography methodologies are currently chosen and how commonly applied each methodology is.

Since each primary research chapter contains a detailed methodology at the start, chapter 4 presents an overarching methodology, which explains how the secondary research has collected and the content narrowed, describes the overall research approach (including constraints and control issues) and explains the ethical issues present in this work.

Chapters 5, 6 and 7 present findings from the primary research elements of this project. Chapter 5 starts with an investigation of *Walk-through thermography*, which is the traditional method of thermographic inspection. By involvement in a large-scale thermographic survey in Cornwall, this chapter describes a more detailed practical methodology than has been published before and critically explores the limitations and challenges to image interpretation from single moment in time analysis. For details of the large-scale project, see Goodhew *et al.* (2013). In direct response to the limitations and challenges to traditional thermography, chapter 6 explore the use of *time-lapse thermography* as a methodology for addressing these issues. Chapter 6 comprises of three sections that include controlled laboratory research and real building case studies. Both qualitative and quantitative (in-situ U-value measurement) analysis is conducted through chapter 6. Since a number of thermographers report using pass-by thermography for quantitative building analysis, chapter 7 explores a form of this methodology. *Walk-past thermography*. The work in this chapter highlights the limitations of this and presents a previously unexplored potential useful application.

Following on from the primary research chapters, chapter 8 presents a strategy for combining several thermography methodologies. Additionally, this chapter proposes a method for deciding upon the most appropriate thermography methodology for a particular task or defect.

While chapters 5. 6 and 7 culminate with a discussion that focuses specifically on the research undertaken during each chapter, chapter 9 presents a thesis wide discussion, where all of the issues encountered during the secondary and primary research phases are considered as a whole.

Chapter 10 concludes the thesis, drawing particular attention to how the research has addressed the research objectives and aim. The contribution to knowledge that this research brings is examined and the opportunity for future work, which might follow is discussed/proposed.

2.0 Principles and limitations of thermography

Thermography is a technique that can be used to record temperature variations through the display of thermal patterns. Whilst Maldague (2001b) explains that a thermograph relates to a contact method of temperature recording using liquid crystal paints, the work in this thesis specifically relates to the non-contact method of infrared thermography, which is performed using infrared imaging devices (thermal cameras).

Thermal cameras detect infrared radiation, which is emitted from the surface of an object and converts this measured signal into a readable thermal image (Hart, 1990). Providing there is a sufficient difference in heat and or mass transfer across a material or building fabric, thermography can be used as a tool to quickly identify hot or cold areas of interest. Other key benefits to modern day thermal cameras include offering real time analysis of digital thermal imagery, which allows for quick viewing and panning around buildings to identify potential areas of concern. Also, the addition of in-camera evaluation permits multi-point detection (ITC, 2006; Walker, 2004), which can be utilised for quantitative or qualitative analysis (Bursell, 2007; Mobley, 2002).

Yet there exist a large number of limitations to this technology, which can significantly impact on the ability to interpret accurate surface temperatures from measured infrared radiation. To begin with, thermal cameras are constrained by the technical performance of their components (sensor, lens, etc.), which can limit creation of useful/meaningful thermal images. Secondly, there are limitations from the surrounding external environment (not camera specific). Such limitations include climatic conditions, emissivity variation and human image interpretation skills for example. These limitations are seen as very significant to thermography, and are discussed by Brady (2008) and Hart (1991), who express caution over the reliance on thermal images due to the impact that external controls such as changing climatic conditions and operator error can have on results. Therefore, before reviewing the methods of utilising thermography, it is first important to understand the principles and limitations that dictate the context for performing thermographic surveys. This is the focus of this literature review chapter, which will also set the wider scene of history, underlying physics and defect detection using this technology.

2.1 Historical Background

The science of thermography began in 1800 with the discovery of infrared radiation by astronomer Sir William Herschel (Vollmer & Möllmann, 2010). Herschel became interested in the temperature differences between the different colours of the visible spectrum when measuring these from light shone through a prism (Maldague, 2001b). As Herschel measured beyond the visible red part of the spectrum with a blackened thermometer, he discovered that the temperature rose further, and therefore became the first to detect the infrared portion of the electromagnetic spectrum. It was not until 1840, however, that the first image of heat was produced. This was created by Herschel's son, Sir John Herschel, who utilized carbon and alcohol to record an image called a 'thermograph' (Ring, 2012).

Following John Herschel's work, many patents were filed for uses of this emerging technology, in particular for military purposes, such as the detection of ships, personnel and aircraft (FLIR, 2011a).

Further developments were made between the two world war periods, with the introduction of the ‘photon detector’ and the ‘image converter’. Initially, the military pursued the use of image converter technology, since it allowed personnel to see in the dark (FLIR, 2011a). However, this technology had a drawback; an infrared search beam shone at the enemy had the counter effect of giving away the location of the operator.

Shortly after World War II, development in thermographic technology shifted from the image converter to the photon detector, which did not require a search beam, and in 1946 a new technology called the ‘infrared line scanner’ was produced, which enabled the creation of 2D thermal images (Holst, 2000).

However, it wasn’t until 1966 that the first commercial real-time thermal cameras became available, which took up to 20 images per second. These early commercial cameras were very large, heavy and consumed lots of energy, some of which required bulky equipment to support the camera. Furthermore, they required cooling with materials such as liquid nitrogen and compressed gas (Lyon & Orlove, 2003).

Considering the history of thermography for building inspections, a key driver was the 1973 energy crisis (Maldague, 2001a), when thermography for use in buildings began to grow rapidly through the 70s and 80s. However during this time it was not easy to record and print single images, and thermal camera equipment was very cumbersome, and commercial application was low. With a reduction in unit size, the emergence of the digital movement increased portability, lowering costs, and with the introduction of uncooled microbolometers in the 1990s (Vollmer &

Möllmann, 2010), thermal cameras have become more commercially focused in recent years, designed less with scientific applications in mind (Lyon & Orlove, 2003), particularly within the construction industry (Snell, 2008).

Figure 7 illustrates the historical timeline of key events in the development of thermography.

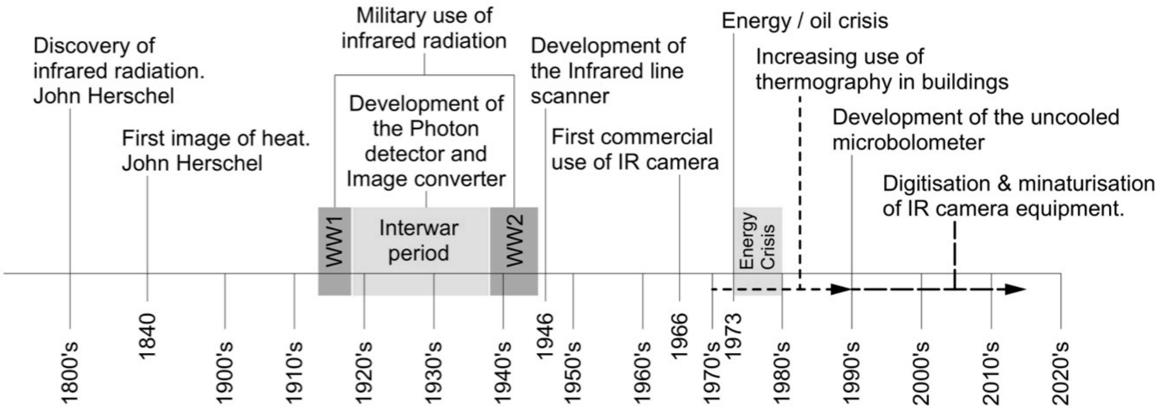


Figure 7. Historical timeline.

2.2 Underlying Physics

Because temperature readings provided by a thermal camera are processed from an infrared radiation measurement the temperature viewed by the thermal camera is known as the apparent temperature (Avdelidis & Moropoulou, 2004; Lucier, 2002). This is the temperature that is 'apparent' to the camera under the conditions and based on the camera settings and subject to environmental controls at the time of capture. Furthermore, the apparent temperature is only that of the target's surface (Maldague, 2000).

The first law of thermodynamics states that heat cannot be created or destroyed, though it can be transferred (via conduction, convection or radiation) (Szokolay, 2008). The second law states that heat will always travel from or through materials of high temperature to materials of a lower temperature until they reach thermal equilibrium. When an object reaches thermal equilibrium it becomes difficult to observe through a thermal camera, since at this point there is little heat transfer occurring and the temperature difference will be too insignificant to provide thermal contrast. Further thermodynamic laws, which have aided the development of infrared technology over time include:

- *Kirchhoff's law of thermal radiation* states that a blackbody will emit (at any wavelength) all of its absorbed radiation until thermal equilibrium is achieved (Maldague, 2001a; Minkina & Dudzik, 2009).
- *Planck's law* describes how emitted infrared radiation from a blackbody directly relates to the wavelength for different temperatures (Hart, 1991; Maldague, 2001a; Walker, 2004).
- *Wien's displacement law* determined the wavelength at which the greatest radiation spectral emittance is produced for a known temperature (Hart, 1991; Holst, 2000; Maldague, 2001a). This law helps to indicate at which wavelength emissions from a surface would be most discernable for a set temperature.
- *Stefan-Boltzmann's law* integrates Planck's law and considers the maximum level of radiation that can be emitted from an objects surface for different surface temperatures as if it was a blackbody (Holst, 2000; Jensen, 2000; Minkina & Dudzik, 2009). Additionally, Stefan-Boltzmann's law specifies that a blackbody's radiant power is proportional with the fourth power of its absolute temperature (FLIR, 2011a; Pleşu, Teodoriu & Ţăranu, 2012).

All are well documented and for a deeper review of these, see Howell, *et al.* (2010), Atkins (2010), Minkina and Dudzik (2009).

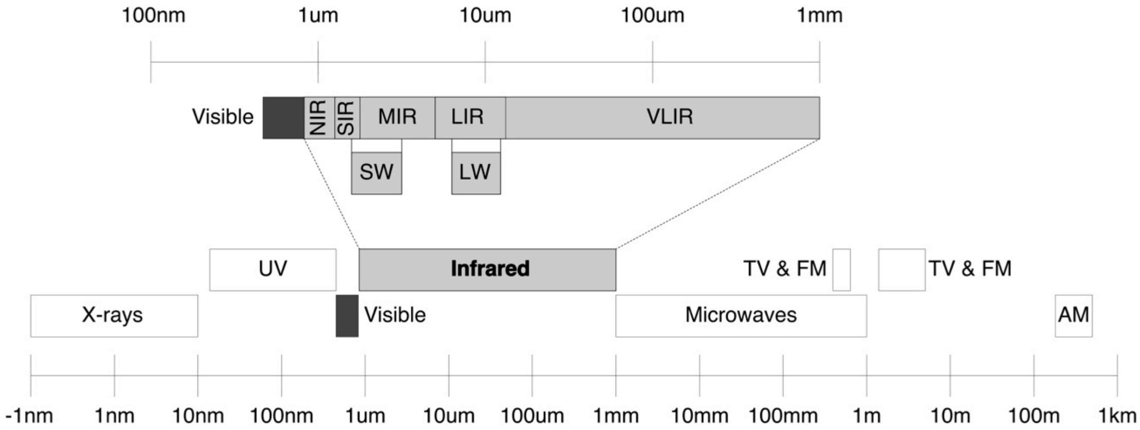


Figure 8. The electromagnetic spectrum. Adapted from ITC (2006).

Infrared radiation falls between 0.74μm and 1000μm (Hart, 1991) on the spectrum (Figure 8) and this large region is then sub-divided into smaller regions (Holst, 2000) from near infrared to very long wavelength infrared. In practice though, there are only two useable regions, which are termed (Minkina & Dudzik, 2009):

- Short wavelength (SWL): 2μm - 5μm
- Long wavelength (LWL): 8μm - 14μm

Thermal cameras are equipped to observe only one of these two regions. SWL cameras are more sensitive to high energy levels of radiation emissions (Nowicki, 2004), and are therefore particularly suited to observing particularly hot processes (Walker, 2004). SWL cameras are however more subject to atmospheric attenuation, which can cause problems with image results at large distances or if there are high levels of airborne particles such as moisture from high humidity conditions. LWL cameras are less prone to atmospheric attenuation, and are not normally required to observe high-energy objects. This makes LWL cameras the most common form of thermal camera for building inspections (Walker, 2004).

2.3 Limitations of thermal camera technology

When selecting a thermal camera for a survey, in addition to choosing whether to use a LWL or SWL thermal camera, it is important to understand the equipment technical specifications. As might be expected, thermal camera specifications vary with the cost of each unit. However the ability to discern unexpected hot or cold spots is greatly dependant on camera specification.

Whilst certain aspects of a camera's specification might be chosen for user features, such as whether the camera can record photographs at the same time as a thermal image for example, there is one specification that is much more critical to image presentation. This is thermal resolution. Jensen (2000) discusses resolution in terms of data acquisition using remote sensing and explains that there are four key areas of thermal resolution:

- Spectral resolution
- Spatial resolution
- Radiometric resolution
- Temporal resolution

As already mentioned, the *spectral resolution* used for building thermography is the long wavelength infrared region (8-14μm) of the electromagnetic spectrum.

Spatial resolution refers to the smallest discernable target that the detector can measure (Jensen, 2000). If too small, the target may not be detected or the sensor might not be able to quantifiably measure it well enough (ITC, 2006). One factor that dictates spatial resolution, is the size of the detector array (Schwoegler, 2011a), where a greater number of pixels in the array equal an improved spatial resolution (Walker, 2004). Current thermal camera detector arrays range from between 60x60 and 640x480 pixels. RESNET (2012) recommend that detector arrays be no smaller than 120x120 pixels. Appendix A.1 illustrates the difference in spatial resolution between three different detector sizes. From this experiment, it can be observed how an increase in clarity/definition can be seen from larger sensors.

Detector field of view (FOV) is another dictating factor of spatial resolution. FOV refers to the total horizontal and vertical area detectable by the camera (Snell, 2002; Vollmer & Möllmann, 2010). RESNET (2012) recommend a FOV of about 20 degrees. Yet to determine the smallest discernable target a detector pixel can perceive (Schwoegler, 2011a), a measurement known as the instantaneous field of view (IFOV) is used. The IFOV is the angle of infrared radiation detection by one detector pixel (Holst, 2000). If an observed target is too small for a pixel with a high IFOV, it is unlikely to be detected (ITC, 2006; Walker, 2004). IFOV is measured in 'mrad' where the smaller the value, the greater the spatial resolution. Spatial resolution is largely influenced by distance from the target. As the thermal camera moves away from the target, the sensors pixels then encompass a much larger area. As this area per pixel increases, the radiation received by the thermal becomes more difficult to accurately process.

Radiometric resolution refers to the smallest temperature differential that can be perceived by the camera's pixels (Holst, 2000). Also referred to as 'thermal sensitivity', measurement is known as the Noise Equivalent Temperature Difference (NETD), which is the temperature sensitivity of the noise from either the detector or measurement system (Electrophysics, 2011; Minkina & Dudzik, 2009) measured in degrees millikelvin (mK). Schwoegler (2011a) suggested that an NETD of at least 100mK is required as a maximum, though a smaller NETD will equal greater detector sensitivity.

When considering the ability for radiation to trigger a signal within a thermal camera, it is also important to consider the effects of optical interference, which is the blurring of radiation from the target source into the camera (ITC, 2006). Seeking to deal with issue of optical interface, some thermography commentators (Holst, 2000; Testo, 2010) discuss using the measuring instantaneous field of view (MIFOV) as a method of determining the true spatial resolution of the camera. This is the smallest target that can 'accurately' be measured, and is a figure often two or three times that of the IFOV.

Temporal resolution relates to the image refreshing frequency of the camera (Jensen, 2000). Holst (2000) recommends a typical frame rate of about 25 – 30Hz, though at low frequencies it becomes harder to hold the camera still, risking camera shake, blurring and reduced image quality.

2.4 Limitations from external controls

As discussed earlier, in addition to the limitations from the thermal camera technology itself, there are numerous external controls that can limit the ability to detect potential anomalies from thermal images. These include:

- Climatic conditions
- Emissivity variations
- Operator skill
- Foreground obstructions

Climatic conditions.

Although some defects (roof moisture for example) require different conditions to others (UKTA, 2007), there are certain standard environmental conditions that thermographers should try to adhere to when conducting external thermographic investigations in particular. These are described in great detail by Lo & Choi (2004), Pearson (2011) Brady (2008) Denio (2007), Vollmer & Möllmann (2010), Holst (2000), Möllmann & Vollmer (2008) and British Standard BS 13187:1999 (1999). Drawing on the advice presented in these sources, a number of rules have been established that dictate the best weather conditions for a passive building thermography survey. The weather condition rules for thermography are:

- Undertaken on a cloud covered night;
- Wind speeds should be no greater than 10 m/s;
- External air temperature fluctuations should be less than 10 degrees over a 24 hour period;
- There should be at least a 10 degree temperature difference between inside and outside spaces during the survey;
- The temperature difference between the inside and outside spaces should not be less than 3/U within a 24 hour period leading up to the survey;

- Internal temperatures should not vary by more than 2 degrees during a survey;
- External temperatures should not vary by more than 5 degrees during a survey;
- There should be no precipitation during survey;

And (unless a moisture survey is to be conducted):

- The day preceding the survey should be cloud covered;
- There should be no precipitation leading up to survey; and
- All surfaces should be dry.

A more detailed explanation of the climatic criteria can be found in appendix D.

Meeting such criteria for thermographic surveys when thermographers need to coordinate dates with clients in advance could easily be argued as an (almost) impossible task (Nowicki, 2004). Especially since the climatic weather conditions are constantly changing *'due to both atmospheric circulation and diurnal cycle'* (Schatzmann & Leitl, 2011). Many commentators such as Asdrubali *et al*. (2011) discussed this in relation to thermal imaging, suggesting that it is very difficult to conduct accurate external thermography due to such difficulties in achieving a steady state external environment.

With reference to a particular thermographic case study, Vollmer & Möllmann (2010) concluded that, due to such uncontrollable variables and fluctuations, accurate quantitative external thermography is too difficult to achieve outside the lab, a view shared by others (Hart, 1991; Hopper et al., 2012; Pearson, 2002). BS

EN 13187:1999 (1999) advise that when a survey is not conducted under a desirable conditions, any variables should be recorded and given consideration during the survey and any subsequent evaluation. This advice seems particularly pertinent as environmental conditions such as cloud cover, which might start out suitable, may change during the survey.

Despite consensus about these limitations, there seems to be some contradiction in the advice documented on the best conditions, such as when an overcast sky is desirable and what maximum wind speeds should be adhered to. These examples underline a common problem encountered when reviewing advice for conducting a thermographic building survey, which is a lack of consistency. Because of these contradictions, and the uncontrollable variations in environmental conditions, it could be argued that external thermography should be limited to qualitative analysis (Hopper *et al.*, 2012) only. This would appear reasonable given the observation of apparent rather than actual surface temperatures (Lucier, 2002). Adding to this, Pearson (2011) advises performing internal surveys in preference over external surveys, since the internal environment will be much more quasistationary and controllable than the external environment.

Emissivity variations.

Emissivity is a property of all materials, which represents the ability of an object to emit infrared radiation in comparison to that of a blackbody. This is measured on a scale of between 0 to 1 (Maldague, 2001b). A material's emissivity value is dictated by a number of issues:

- Surface finish. Specular or diffuse

- Geometry. The shape of an object
- Angle of measurement. Where the thermographer is in relation to the object
- Temperature and wavelength. Both of which can vary emissivity.

For more information on emissivity, refer to Balaras and Argiriou (2002), Walker (2004), Holst (2000), Hart (1991) and Vollmer & Möllmann (2010).

Variations in emissivity due to any of the known issues or due to the inability to obtain a measurement (such as from a low emissivity material for example) can result in missed detail or harmful misinterpretations. Hart (1991) discusses this limitation by stating that *'there is a high risk, during the analysis of a thermographic survey, that all irregularities in surface temperature will be mistakenly identified as structural defects.'* One example of misinterpretations due to emissivity might be the reflected radiation from a person (possibly the camera operator) from a low emissivity surface, which might be incorrectly interpreted as a building defect.

Figure 9 illustrates the problem of emissivity variations. On the left is a low emissivity metal cladding surface (emissivity of about 0.20). Initial observations might misinterpret the lower portion of the cladding as having greater heat loss than that above. Yet on closer inspection, this warmer patch is the result of reflected radiation from a passing cloud (and seagull). Because of the dominance from reflected radiation, it is much harder to understand how this element of construction is performing. In stark comparison, on the right of the image is a higher emissivity, rendered construction (emissivity of about 0.95). This surface presents a much more accurate representation of the heat flow through the construction than the cladding.

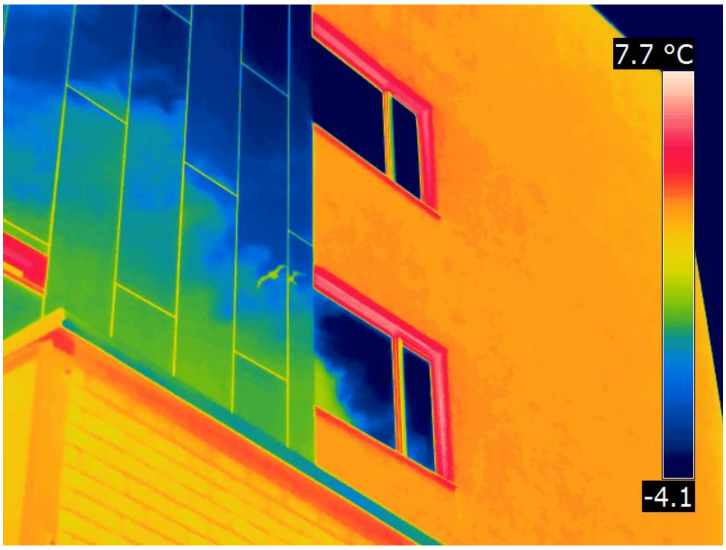


Figure 9. Illustration of high and low emissivity materials.

When undertaking quantitative analysis, it is important to measure in-situ surface emissivity values, which should be inputted to the thermal camera (Avdelidis & Moropoulou, 2003). This will enable the thermal camera to make an allowance for surface emissivity when measuring apparent surface temperature. Although this camera input will not effect the appearance of the thermal image (Barreira & de Freitas, 2007), Moropoulou and Avdelidis (2001) argue that an understanding of surface emissivity is important for qualitative analysis, since the effects of reflections from high emissivity materials can have an impact on image analysis. Discussing this issue further, Marshall (1982) recommends obtaining accurate emissivity values for materials being observed qualitatively, because it is sometimes difficult to determine whether the observed radiative source is a physical or emissivity anomaly.

An appreciation of surface emissivity becomes even more important when performing external thermography; this is due to the increased likelihood of greater radiative sources such as the sun and sky reflecting off of a surface (Marinetti & Cesaratto, 2012). When performing internal surveys, the reflective radiative sources can to some extent be controlled and are not as significant. Nevertheless, it is still important to minimise the radiative sources reflecting off a surface. Recommendations include avoiding operator and camera reflections FLIR (2011a) and moving around a target. If the anomalous heat source moves with the operator, then it is likely to be reflected radiation from a surrounding object (Testo, 2010). Sadineni *et al.* (2011) advocate shielding high emissivity sources and applying materials of known high emissivity over lower emissivity surfaces.

Operator skill.

The ability to successfully record and interpret a thermal image is also largely dependant on the camera operator and analyst. It is easy to suggest that anyone can pick up a thermal camera and obtain meaningful results from it. Using unskilled personnel for thermographic building surveys therefore has huge potential for failure, where reflections from low emissivity surfaces might be misinterpreted as defects and other defects might be missed completely (Snell & Schwoegler, 2012). It is important that the operator understands how to thermally tune an image by adjusting the level and span settings (similar to speed and aperture settings in a photographic camera) so that the range of displayed temperatures accurately correlates with the highest and lowest temperature signals present in the FOV. Other critical operator controllable camera settings include camera focus and composition. It is not just the quality of the image that is affected by an out of focus thermal image. This will also affect the temperature reading (Fluke, 2010; Nowicki, 2004) due to increased optical scatter, which could lead to an incorrectly observed or missed thermal anomaly. The effects of this are illustrated in appendix A.2, which shows the difference between a focused and non-focused thermal image. Analysing the focused and un-focused thermal images in this experiment show how a focused thermal image is much more defined and presents a more accurate temperature measurement than the un-focused image, which has less defined edges and a lower maximum temperature reading.

It could also be argued that those displaying these images have a professional and moral obligation to ensure that the images read by others are portraying a picture as accurately as possible. Therefore it is important that thermographers are suitably qualified (Snell & Spring, 2008). Training such as the PCN Certification scheme, consisting of three levels (BINDT, 2009), should enable better camera control.

Foreground obstructions.

These can be found during both internal and external inspections. Internally, Colantonio & McIntosh (2007) explained that furniture, suspended ceilings and pictures can mask certain parts of a structure, therefore concealing potential anomalies. If during an inspection any of these items are removed, FLIR (2011a) warns that misinterpretations could be made. This is because furniture such as picture frames or sofas that are close to a surface will contribute to the fabric's insulation. When removed, the newly revealed surface is likely to appear cooler than adjacent surfaces and could suggest a defect such as missing insulation. Figure 10 shows an example of this effect where it is very difficult to discern whether a defect is present in this location or not. Whilst FLIR (2011a) makes recommendations for any internal obstructions to be removed at least 6 hours before a survey, RESNET (2012) advocates that obstructions should be removed at least 12 hours before the survey. Although these suggestions are ideal, they are not practical for all situations. Requesting that homeowners re-position furniture and pictures before a thermographic survey might be particularly challenging.

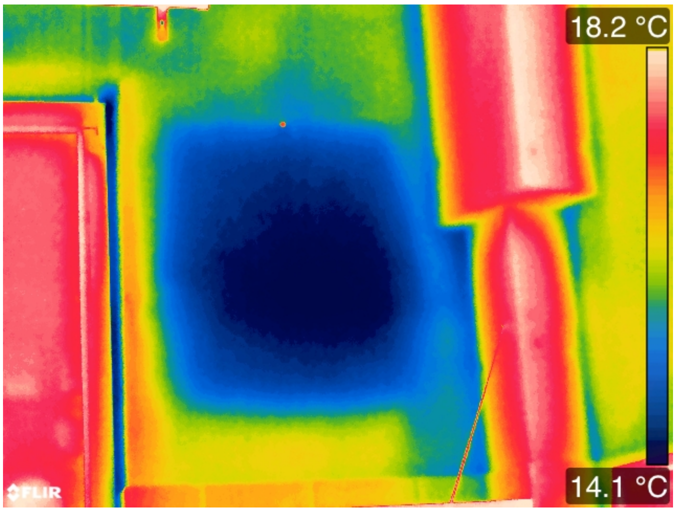


Figure 10. Illustration of a recently removed picture from an external wall.

Externally, Clark *et al.* (2003) cite a number of potential obstructing foreground objects, which include other structures and trees. In addition, Phan (2012) included vehicles as obstructions to parts of the building, which if not controlled by the occupants of the building being surveyed might be impossible to move. Indeed, trees, bushes, buildings etc. are immovable objects, which need to be dealt with by moving around until a clearer view of the target object can be observed. Like internal obstructions, external features such as trees, bushes, cars and neighbouring buildings can further impact the thermal imaging. Firstly, such objects need to be considered as potential sources of reflected radiation (particularly from low emissivity surfaces) (Möllmann, Pinno & Vollmer, 2008). Secondly, objects such as trees might shade parts of the structure unevenly from the sun (Hart, 1991). The effects of irregular solar shading during the day might present themselves in the evening due to disparities in thermal mass over a surface, which might not be instantly considered during a survey. Finally, those items that are close to the target building (such as foliage) might restrict the movement of air across a surface and act as an insulator to a part of the structure. It is possible that the effects of this could also manifest on internal surfaces during internal thermography.

2.5 Image Interpretation

In recognition of the complexities generated by both camera specific and external limitations, it is not difficult to comprehend the challenges involved with thermal image interpretation.

At a very simplistic level (and depending on the colour palette), bright colours usually indicate hot areas, while darker colours are cooler surfaces (Balaras & Argiriou, 2002; Goodhew et al., 2009), and due to the visual nature of thermography, thermal images are frequently used graphically to raise issues.

However, one of the most fundamental, yet difficult, skills for a thermographer to learn is how to read, identify and interpret defects based on their pattern characteristic. Work by Mauriello *et al.* (2015) interviewed a number of building thermographers and identified that along with camera sensitivity, image interpretation was seen as the greatest challenge to thermography.

Image interpretation is particularly important for inspections, which seek to observe defects using a qualitative methodology. Supporting this assertion, Gonçalves *et al.* (2007) suggested that thermography cannot definitively distinguish defects unaided by other equipment or investigation, and that thermographers need to be very careful when making assumptions about defects, which may well be incorrect. To help overcome this, Stockton (2007) highlights the need for building thermographers to have an understanding of building physics (such as thermal mass), which should be supported by knowledge of building materials and types of construction build-up (Eads, Epperly & Snell, 2000). It is also not unreasonable to expect that thermographers should hold a certain degree of knowledge on different defect types (Snell & Spring, 2008). Therefore, it is important that each of the aspects highlighted in figure 11 are understood before assessments can be made on how a building is performing using building thermography.

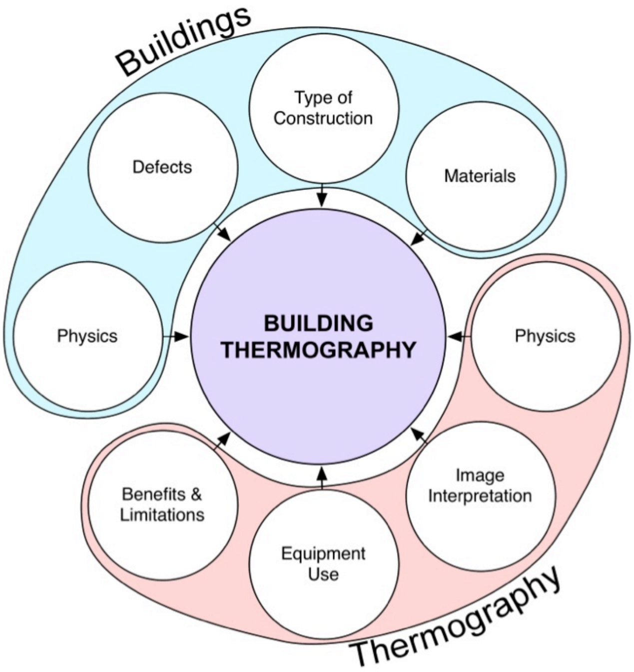


Figure 11. The various disciplines, which support building thermography. Adapted from ITC (2006).

Whilst it is important to ensure that each of these disciplines are considered during the performance of a thermographic survey for optimal image interpretation, it is also good practice to include information on parameters and conditions, so that others reading the patterns can best understand the problems.

One example of where thermal imagery may have been misleading can be observed in Figure 12. These thermal images were part of an advert by Anglian Windows in the Guardian Newspaper (2009) and were used to emphasise the improvements that could be made by fitting their double glazed windows. Despite the likely improvements that double-glazing might have over single glazing, the images are very misleading. Because neither image includes a scale bar, it is unclear what the temperature level is, making it hard to assess whether the new windows have made much of an impact or not. Furthermore, it is difficult to know what the conditions were and whether there are differences in occupancy between the two images.

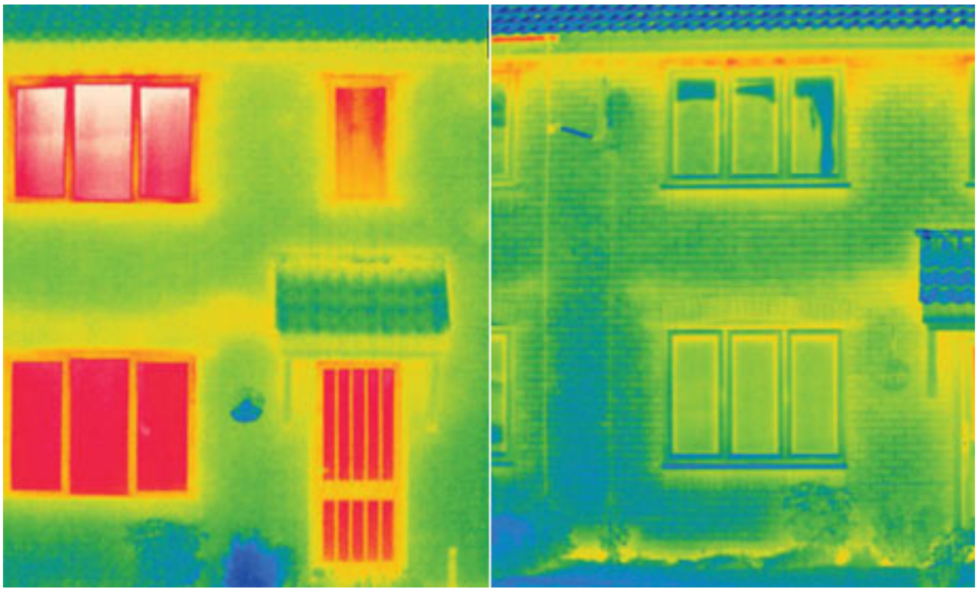


Figure 12. Before (left) and after (right) double-glazing. Anglian Windows (2009).

However, accuracy aside, this advert is a good example of how people can and are using the graphic power of thermography to convey information about heat loss, which may or may not be correct. It is relatively easy to tune a thermal image to look good or bad, and it is possible to deliberately or unknowingly use misleading images which are open to misinterpretation (Vollmer & Möllmann, 2010). Colour palette selection can also affect the interpretation of a thermal image, particularly as people often associate red with danger. Vollmer & Möllmann (2010), discussed the importance of colour, especially when there is the absence of a scale bar, or when an image has been inverted so as to try and mask data or mislead the viewer into thinking that a building is performing better or worse than it is in reality.

2.6 Summary of chapter 2

It has been suggested that thermographers do not need to be experts to capture thermal images (PCE, 2014). While it is relatively easy to capture a thermal image, the findings from chapter 2 have shown that in order to capture meaningful thermal images, an awareness of the topics discussed throughout this chapter is essential. Furthermore, while capturing a thermal image is one part of the process, literature has shown that image interpretation is of greater importance and difficulty. Particularly when set in the context of external climatic conditions and how these can impact on the ability to detect thermal patterns.

Following this detailed literature review into the science underpinning thermography, the effects of thermal resolution, and the key limitations constraining that constrain image interpretation, it can now be concluded that thermographers do need to be experts in a range of different fields in order to capture meaningful infrared images and begin to interpret the thermal patterns.

3.0 Methodologies for passive building thermography

Until quite recently, most of the research and practical use of building thermography had centred on employing a walk-around / through methodology to detect sources of unacceptable energy use. However, in light of the known limitations set out in chapter 2 (such as weather conditions, emissivity and camera parameters) some thermographers are now creating new, building thermography methodologies, which address some of these. This chapter details each of the passive building thermography methodologies that have been reported as being currently used in practice and academic research.

To begin with, this chapter breaks down each element of the decision-making process that is currently used to establish a basic principle thermography methodology. This paves the way for a deeper analysis of the specific methodologies that can be selected for analysing a building using passive thermography.

3.1 Principle methods for thermographic analysis

Before a building thermography inspection can be planned, a thermographer first needs to question which principle methods they will use for analysis. This decision will be informed by the questions posed in Figure 13, which has been based upon the author’s training and experience of surveying buildings in the UK.

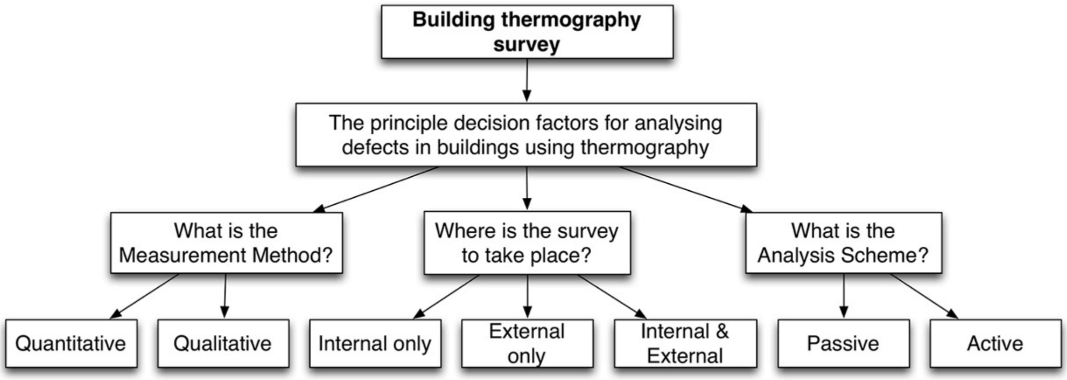


Figure 13. Key decision-making process for the determination of a building thermography methodology.

Analysis Schemes

Two commonly used analysis schemes exist for building thermography: *passive* and *active*. Active thermography is where an external stimulus, such as a burst or gradual rise in heat, is exerted on the object observed (Grys, 2012; Spring, Huff & Schwoegler, 2011). This induces an effect within the material that allows better visualisation of a hidden defect (Asdrubali, Baldinelli & Bianchi, 2011; Sharlon, 2007). Conversely, passive thermography is where the target being observed is at its normal temperature state (Kominsky, Luckino & Martin, 2007).

Although active thermography offers a useful insight into sub-surface defects (Aggelis et al., 2010), a drawback to this methodology is that prior knowledge of the defect's existence is usually required before analysis. Also active thermography tends to focus on detailed areas of a building's fabric, where specific defects are closely examined. Work by Maierhofer *et al.* (2010) offers one example where active thermography was used to focus on specific subsurface defect locations within historic buildings. However, because most building thermography surveys observe the entire building fabric, looking for unknown defects without the aid of artificial stimulus (aside from internal climatic control typical of the occupant's normal behaviour), (Avdelidis & Moropoulou, 2004; Maldague, 2002) typical building thermography surveys are considered to be conducted under passive schemes.

Measurement Methods

There are two methods of measuring thermal images: *qualitative* and *quantitative* analysis. Qualitative analysis in thermography is the visual evaluation of colour patterns within a thermal image, which represent differences in measured radiation (ITC, 2006). Thermographers need to be able to read thermal patterns in images in order to decide whether these patterns show potential problems.

Walker (2004) described three key techniques that can be used for qualitative analysis:

1. **Signature thermal patterns –** these are what you might expect to see due to past thermographic or technical experience (Brady, 2008). As more experience in defect pattern recognition is gained, thermographers become better at visually diagnosing problems and finding potential solutions (Hart, 1991);
2. **Symmetrical thermal patterns –** this is where two or more parts of one target are compared for anomalies. One example of this technique can be seen through medical assessment of the human body. Differences between symmetrical parts/sides of the body may indicate an illness/injury. In construction, this technique might be used for observing an external wall for signs of moisture ingress or insulation deficiencies;

3. **Comparison** – this is similar to symmetrical observation, where comparisons can be made with other similar targets (Beard, 2007). If one object appears different to an identical object, a defect could be present. BS EN 13187:1999 (1999) makes recommendations for comparison with reference thermal images, either obtained from other field surveys or from laboratory experiments.

Hart (1991), however, urges caution when relying upon comparison techniques for external thermography. This is due to environmental conditions, which might affect different parts of a building more than other parts even though the construction is the same. Brady (2008) further cautions by explaining that different building orientations will present different patterns at different times of the day, particularly if there has been extensive solar gain during the day.

Quantitative analysis adds to this by seeking to quantify thermal gradients for numerical analysis (Walker, 2004). This is possible due to the ability for each pixel (microbolometer) in a thermal camera to give a calculable apparent radiation value. To help quantify certain aspects viewed within a thermal camera's FOV, there are often measurement tools, such as:

- Spot temperature;
- Box or circle areas;
- Isotherm levels; and
- Temperature differential

Although many thermographers use a quantitative measurement method for building analysis, such as the determination of thermal transmittance (Fokaides & Kalogirou, 2011; Madding, 2008), there are others, who caution against the use of thermography as a quantitative tool (Pearson, 2002), stressing the challenges in achieving meaningful, accurate results within environments that are often anything but steady-state. Kylili *et al.* (2014) explain that passive thermography, which this thesis is solely concerned with, is typically qualitative in nature.

Location

Building thermography can be undertaken both externally and internally. External thermography is more susceptible to transient environmental conditions than internal thermography, which provides a much more controlled environment that has slower and less significant climatic fluctuations (Balaras & Argiriou, 2002). When viewing defects, Pearson (2011) suggests that any areas of heat loss observed in external thermography will almost always present themselves more clearly on internal thermography at the same time. This is illustrated in figure 14, which shows external wall with slumped cellulose insulation. The location of this (appearing cool) defect internally corresponds to a hot region found on the same wall when viewed externally. As reported by Williamson (2014), it is not uncommon to find defects internally, though not externally.

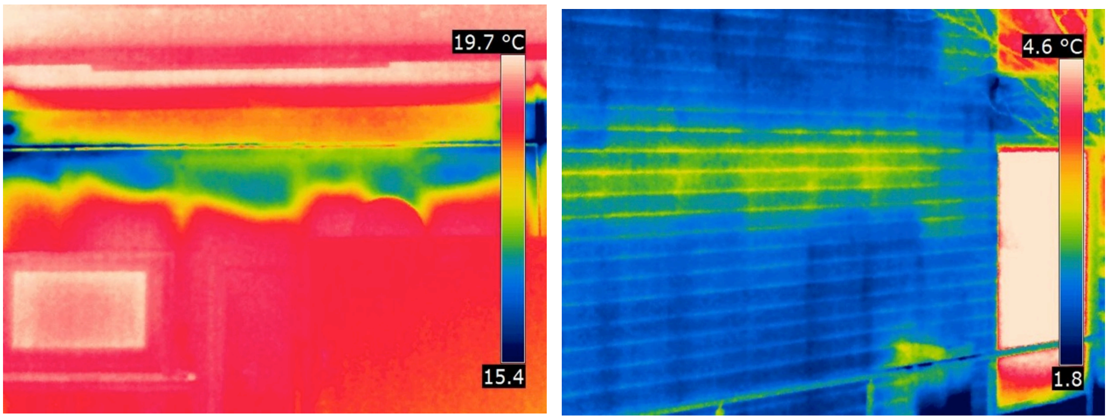


Figure 14. Two thermal images of the same wall area viewed from either side.

Despite commentators such as Vollmer & Möllmann (2010) arguing in favour of indoor over outdoor surveys, internal thermography relies upon the occupants permitting access to certain parts of a building.

3.2 Specific Applications

With an understanding of principle methods for thermographic survey detection, it is next important to consider the specific applications for thermographic inspection on existing buildings. There are typically two applications for building thermography. *Defect detection* and *energy performance measurement*. While the former tends to utilise qualitative analysis, the latter makes use of quantitative analysis.

3.2.1 Defect detection

There are a number of energy specific building defects that thermography can be been used for. The following section lists details of each commonly detectable defect and their specific pattern characteristics. With regards to pattern characteristics in general however, cold spots/areas when viewed from the inside will indicate areas of potential defect/poor performance, though when seen from the outside might indicate non-defective/properly performing areas of construction (RESNET, 2012). The same adage is reversed for warm spots/areas.

Conduction heat loss and thermal bridging.

All building components will incur a degree of conduction heat loss, as heat flows from one side of the construction to the other. The amount of heat loss through construction depends on how conductive the materials are and the temperature difference between internal and external environments. Thermography can be used to check for insulation continuity in walls and roofs for example (Figure 15) (Hart, 1991; Titman, 2001), which will identify areas of increased heat loss over a building's surface. Identifying areas of missing or damaged insulation could help to minimise condensation and mould growth (Snell & Spring, 2008), which unless controlled, might lead to potentially unhealthy environments. Thermography can also be used to detect thermal bridges, which usually occur at junctions and corners (Figure 16) (Jeong et al., 2007) where details are hard to complete and remediate.

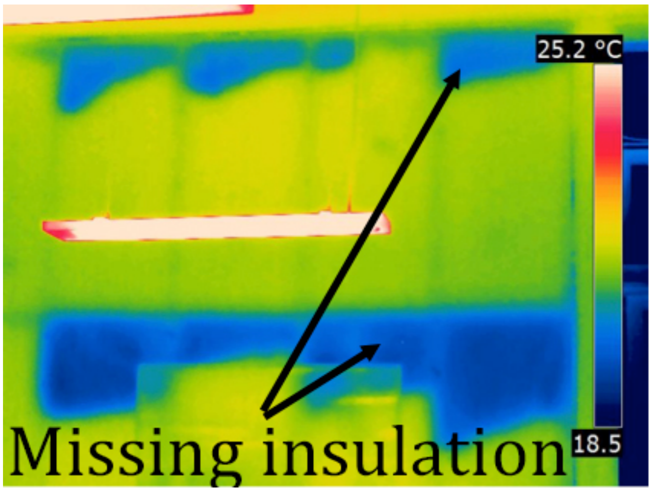


Figure 15. Missing cellulose insulation building defect.

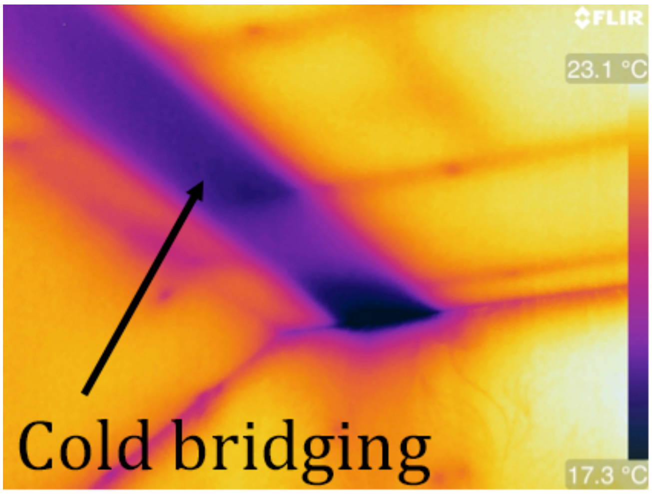


Figure 16. Cold bridging observed in a steel lintel.

Conduction heat loss and thermal bridging defects tend to produce a clearly defined and even temperature difference between better and poorer areas of construction (BSi, 1999). Defect patterns will also often resemble elements of construction (RESNET, 2012).

Ventilation heat loss.

Thermography can also detect the effects from convective ventilation heat loss (Hart, 1990; Pettersson & Axen, 1980). Common areas of air leakage tend to occur around openings (doors and windows) and at the junction between components where gaps might be present (Figure 17) (Nowicki, 2004). While it has been suggested (Armstrong, 2008) that ventilation heat loss can account for over half the total energy use in a building, Brooks (2007) also stated that unwelcome ventilation sources can present a more substantial problem for occupant thermal comfort and will be more likely to result in complaints of draughts.

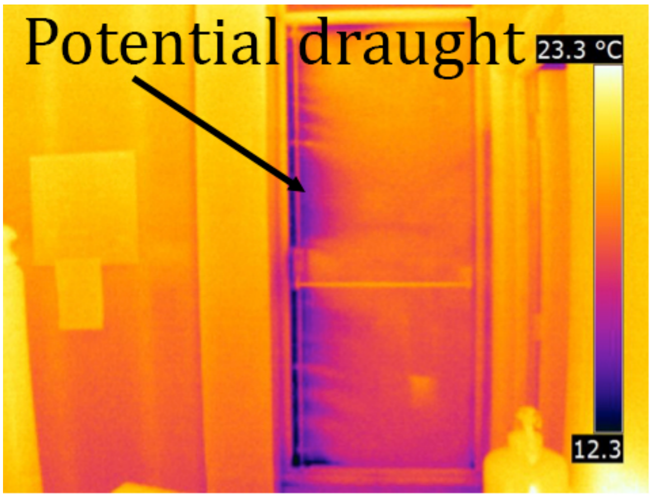


Figure 17. Unwanted air movement around an external door.

Unwanted ventilation patterns will produce uneven shapes over a surface often with a 'fanning' shape gradating away from the source (Chown & Burn, 1983; FLIR, 2011a). It might also be possible to observe ventilation patterns beneath a construction layer, such as within cavities (Colantonio, 1999).

Moisture condensation.

Checking a building's air-tightness is also critical to controlling the accumulation of moisture within a building. This is discussed by Kalamees (2007) who suggested that unwanted air leakage through a construction could lead to condensation and mould growth, which in turn could degrade a material's performance lifespan. Furthermore, areas of poorer thermal performance, such as cold bridging, are also likely to experience condensation accumulation and subsequent mould growth on cooler surfaces (Burkinshaw & Parrett, 2003), which may result in a diminished internal air quality, possibly causing respiratory related health problems (Dobbs & Stockton, 2005).

Moisture ingress.

Penetrative and rising damp, are often associated with moisture from outside a building entering parts of the building fabric or the living space, usually via capillary action or sorption and their detection is another application for thermographic inspection (BRE, 1997). As moisture passes through materials, penetrative damp is likely to degrade materials (Avdelidis, Moropoulou & Theoulakis, 2003) and have an impact upon the building's thermal performance through an increase in conductivity and evaporative cooling (Chown & Burn, 1983; Vollmer & Möllmann, 2010), which will become more significant with increased air movements.

Observing moisture from inside a building is thought to be more problematic, particularly with regards to determining whether the moisture is penetrative, rising or condensation related (Snell, 2008). Figure 18 illustrates the difficulties with interpreting moisture defects in buildings, as this could be either moisture ingress or condensation. To help overcome problems in differentiating moisture defects and to validate thermographic results, some (Brady, 2008; Kominsky, Luckino & Martin, 2007; Stirling, 2002) advocate the use of additional tools, such as moisture meters, calcium carbide sampling and, in certain situations, destructive investigation. However, thermography can be useful in directing the use of these other tools and inspection work.

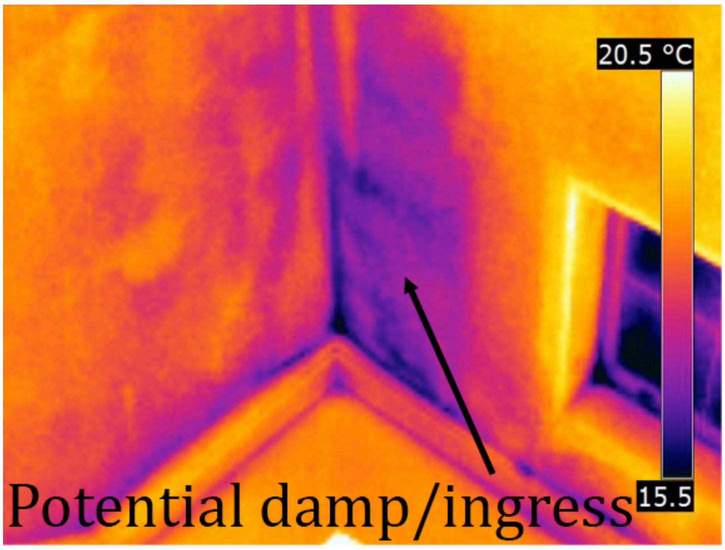


Figure 18. Potential moisture related building defect.

Moisture defects will present a mottled, patchy appearance with low temperature variations over the defect area (Balaras & Argiriou, 2002).

Defective services.

Titman (2001) discussed this application, describing the usefulness of building thermography for detecting buried/hidden and or defective services within old buildings, particularly where little or no record is kept. One such example is the identification of under-floor heating installations (Nowicki, 2004), where thermography could help to determine the quality of workmanship or whether there were any leaks in the service piping (Figure 19) (Snell & Spring, 2008).

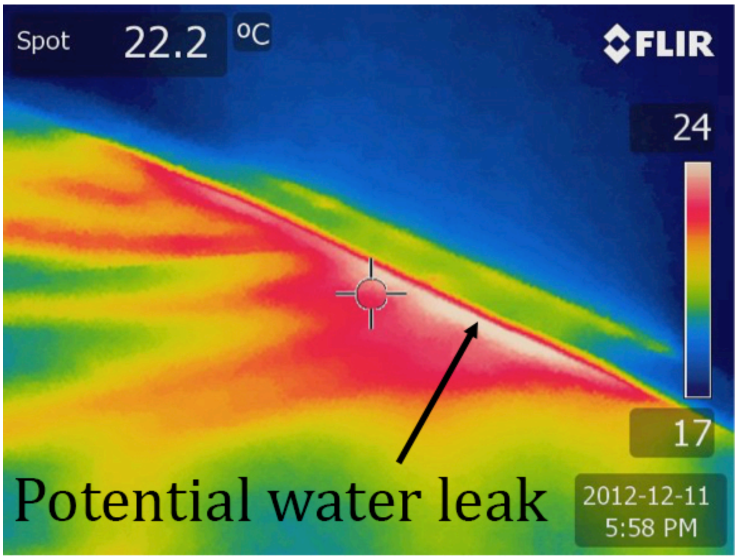


Figure 19. Potential defect with under floor heating system.

Structural defects.

Detecting structural defects in buildings is another use of thermography. As well as identifying structural failures (Walker, 2004), locating thermal expansion defects can help to minimise other subsequent defects that might lead to increased energy loss issues.

Detecting material delaminations is another use of thermography, and is an important field, since failures can result in serious injury should a component fall (Snell & Spring, 2008). Work by Clark, *et al* (2003) studied the successful use of thermography in detecting delaminations within concrete and masonry bridges. They determined that although defect detection might be impeded, delaminations could be identified even in imperfect conditions. Nevertheless, it is important to utilise other forms of analysis in combination with thermography, such as hammer tapping over the suspected area of delamination for validation (Lo & Choi, 2004).

3.2.2 Energy performance measurement

While locating thermally significant building defects is one aspect of assessing building thermal performance, another is through estimating the level of the heat loss/gain experienced from a building. This quantification of heat is another application area for building thermography.

Work by Madding (2008) and Fokaides & Kalogirou (2011) offers one example of performance-based research, where a quantitative measurement method has been used to determine fabric U-Values through the application of thermography. Another example has seen thermographers estimating CO2 emissions (IRT surveys, 2012a).

As an alternative to the measurement of heat loss with thermography, some thermographers use a quantitative methodology for the determination of the critical temperature risk factor. A feature of some thermal cameras, this calculation is known as the Thermal Index (TI), Insulation Level or Temperature Factor. A dimensionless value, it is used as an indicator of thermal performance, likelihood of condensation, thermal bridging and continuity of insulation (FLIR, 2007; MCRMA, 2006; Pearson, 2011; Ward, 2006).

Another form of quantitative passive thermography has been the measurement of CO_2 emissions by a team of commercial thermographers (IRT surveys, 2012b), who have been utilising quantitative thermography to measuring approximately 30,000 housing association properties in Scotland (Kennedy, 2012a; Kennedy, 2012b).

Yet the accurate application of U-value, TI and CO_2 analysis seem problematic since accurate heat loss measurements (with thermography) require 'steady state' conditions. Because steady state conditions are almost impossible to achieve on a continuous basis (Pearson, 2011), it seems appropriate to recommend the use of the energy performance measurement as an estimation tool at best, helping to 'approximately' quantify the thermal performance of a construction build-up. This argument is supported by Schwoegler (2011a), who claimed that unless careful consideration is given to environmental variables, entering environmental data into the camera by the user could be "*potentially misleading and dangerous*".

3.3 Specific Application Methodologies

Having determined the initial methodology criteria for a thermographic building survey and gaining a deeper understanding of the types of defect/application that building thermography can be used for, further decision-making is required for the specific application methodology to be used. Currently, six application methodologies are being utilised. These include (organised from fastest to slowest):

- Aerial surveys
- UAV fly-past surveys
- Street pass-by surveys
- Traditional thermography: perimeter walk around surveys (external only) and walk through surveys (internal and external)
- Repeat surveys
- Time-lapse surveys

Aerial Surveys

Aerial thermography has been used to assess buildings for a number of years, with considerable work being undertaken in the early 1980's (Artis & Carnahan, 1982; Brown, Cihlar & Teillet, 1981; Chang & Galowin, 1985; Schott, Biegel & Wilkinson, 1983; Treado & Burch, 1982). To perform an aerial survey, a thermal camera is fixed to an aeroplane or helicopter (Stockton, 2001), which flies over the target area several times recording thermal images, often of large or multiple buildings rather than single buildings. The results present a picture of heat loss from the buildings' roofs or district heating services (Berg & Ahlberg, 2014; Friman et al., 2014).

Aircraft usually need to fly at altitudes of 1200 – 1500 feet (366 - 457m). Because cameras typically used in building surveys do not have an adequate spatial resolution (Stockton, 2001),, much higher specification cameras or line-scanners are used (Colantonio & Theauvette, 2007), to help better discern key areas of heat loss at high altitudes. This however comes at a greater cost to the user, which was estimated by Allinson (2007) to be in the region of £50,000 for a large urban scale survey. Allinson also indicates how each camera pixel can only detect areas of approximately 1 square meter (at 760m altitude), which would mean that only very large defects could be detected using this methodology currently. Coupled with the high costs, this factor therefore questions the practical application of aerial thermography for successful residential surveys in particular as dwellings are on average 80 square meters in size (Roys, 2008), making it very difficult to discern finite detail.

Benefits of aerial thermography include identifying problems without needing to gain access to buildings and being able to observe problems on large buildings more efficiently (Stockton, 2002). However, speed is the significant benefit to this methodology, where many roofs can be observed in a night, enabling quick comparisons between roofs for identification of thermal bridges etc. (Bitelli et al., 2015). Because of these benefits, a number of qualitative uses for aerial thermography have been explored, including flat roof moisture surveys (2013). Yet most UK dwelling roofs are pitched, which make thermographic observation particularly difficult (due to angle related emissivity problems). Other limitations include image blurring, unknown internal temperatures, climate and emissivity variations, and tree obstructions, which can impact on image analysis (Allinson, 2007; Phan, 2012). Also it is not possible to observe wall or fenestration defects using this methodology.

UAV Fly-Past Surveys

A recent advancement to aerial passive building thermography has been the use of unmanned aerial vehicles (UAV) also termed as ‘drones’. Combining thermal cameras with emergent UAV technology (EASA, 2015) has permitted remote and sometimes automated fly-past opportunities that enable access to areas inaccessible by other means or potentially dangerous areas (Micro-Epsilon, 2013).

Work by Martínez-de Dios & Ollero (2006) looked at using UAV passive building thermography for detecting heat loss from windows. However, despite seeking to address recognised image stabilisation issues, vibrations from the UAV propellers threatened spatial resolution and effects from wind can lead to blurred images. It seems that the stability of UAVs continues to be one of the most significant technical issues with this methodology (Eschmann et al., 2012). Other factors limiting the widespread use of a UAV passive building thermography include licensing restrictions and equipment costs, with basic UAVs currently starting at around £1,500 (Mikrocopter, 2013). This unit cost is however much lower than mid-high specification thermal camera unit cost (approximately £20,000) and the estimated cost of a single aerial thermography survey (£50,000), making UAV thermography an attractive alternative for roof surveys.

In the UK, the Civil Aviation Authority (CAA) sets out regulations which carefully control the use of unmanned surveillance aircraft and under section 166 & 167 of the CAP 393 Air Navigation: The Order and the Regulations (CAA, 2012) for aerial work, permission is required from the CAA for a person to fly a small unmanned aircraft (UAV) (less than 20kg). Regulations include maximum altitudes (<400m high), restrictions on flying over people, buildings (not under control of the pilot) and maintaining a clear line of sight to the UAV at all times. Other agencies such as the European Aviation Safety Agency (EASA) and American Federal Aviation Administration (FAA) also place restrictions on the use of UAVs. Additional regulations include airworthiness certificates for equipment (FAA, 2015) and restrictions on flying over airports, or near manned aircraft (EASA, 2015).

Despite governmental restrictions, there appears to be great potential for the application of a fly-by passive building thermography methodology whereby UAV mounted thermal cameras could obtain better viewing angles of tall buildings and roofs (González-Aguilera et al., 2013; Tommasi et al., 2014) compared with existing street level surveys. This point is particularly significant, since a UAV could be manoeuvred to help minimise the negative effects to surface emissivity changes from acute viewing angles. Furthermore, UAVs can get closer to high-level targets than other aircraft or personnel, which can help to increase defect spatial resolution. Work by Eschmann, *et al.* (2012) explained how UAVs can be set on automated flight paths. The recorded images can later be pieced together into a much larger thermal image where the spatial resolution is multiplied over the number of images used. Work by Mauriello & Froehlich (2014) found that UAV thermography is very quick, particularly when extracting image data from live video streaming.

Street Pass-by Surveys

Following the relatively recent introduction of Google 'Streetview' in 2007 (Olanoff, 2013), passive building thermography researchers and practitioners have been considering ways of utilising a similar 'pass-by' methodology for building thermography (Heaton, 2011).

Work by the Massachusetts Institute of Technology (MIT) explored a drive-by methodology where several thermal cameras mounted on the roof of a car imaged properties (Phan, 2012). MIT's research involved driving through predominantly residential streets with thermal cameras (Shao, 2011) recording images of different sections of a property. The images from each camera were combined into a larger image, giving a greater spatial resolution (Dusto, 2011; Nusca, 2011; Phan, 2012). During the study, approximately 25,000 properties in Cambridge, Massachusetts, were analysed and using software developed by MIT (Phan, 2012). MIT claim to identify specific features or defects using quantitative analysis to determine the severity of defects and estimate the cost and financial returns of rectifying these (Chandler, 2011; Lebwohl, 2011). The work at MIT is now applied in practice through a Boston based business called Essess (BBC, 2015; Essess, 2015).

It is clear that driving past buildings with a thermal camera will permit a larger number of properties to be surveyed in one night compared with thermography collected by foot. However, the temporal resolution and speed at which many modern day thermal cameras are able to record images is not currently sufficient without costly improvement or utilising a set-up comprising of multiple cameras as proposed by Phan (2012).

IRT Surveys are another team of thermographers (IRT surveys, 2012b; IRT surveys, 2012a; Red Current, 2012b) who also appear to be collecting single images of single external front elevations of multiple dwellings in one survey period using a walk-past methodology. The specific details of this methodology have not been made clear by IRT Surveys, so only implied assumptions can be made from published literature by Clyde Valley Housing Association (Currie, 2012), for whom the studies were undertaken (approximately 30,000 buildings in Scotland). Without robust validation of IRT's methodology, questions over the ability/success of this methodology will remain.

Utilising a walk-past methodology limits the number of properties that can be surveyed in one night when compared to a drive-by thermography. However, walk-past has the advantage of enabling more careful image capture using typical building related thermal cameras as this methodology does not require the high temporal resolutions needed by drive-by thermography.

Prior to the drive-by investigations conducted at MIT, Phan (2012) undertook preliminary walk-past studies of dwellings located in Lexington, Somerville, Belmont and Cambridge, Massachusetts during January 2010. For this, they rented a FLIR P-660 thermal camera and conducted walk-past surveys over 7 nights from 6pm to 2am. Phan used the following methodology to collect thermal images of dwellings from a street perspective (Phan, 2012):

- Find desired home to image
- Find reasonable distance to stand from the home
- Align camera to take an image
- Focus and lock the thermal setting onto the scene
- Capture the image in the selected area

This often involved recording multiple images of one elevation, which were then pieced together into one large mosaic image. Key observations from this work by Phan include:

- One dwelling survey takes approximately 10-15 minutes to complete.
- Approximately 20-30 homes could be surveyed per night.
- At this rate, it would be difficult to scale this methodology up to look at entire towns/cities.
- Working in cold weather conditions is physically demanding.
- Heat loss from draughts, poor insulation, windows, doors and roofs were discovered.
- Inconsistencies were found in collected data from one dwelling to the next.

- Weather (such as rain and snow) affected the quality of the thermal images.

While the objective of the research was to implement a drive-past methodology, Phan played down the benefits found from walk-past thermography (such as increased speed compared with traditional thermography). Furthermore despite reports of working in '*extreme weather'* Phan did not adequately consider how weather affected the thermal images, a common factor that limits thermography.

Despite being very fast, and capable of collecting many dwelling surveys during one survey session (Lebwohl, 2011), Schwoegler (2011b) cautions against using a drive-by methodology to *"quantify energy leaks".* He cites emissivity variances, changing view angles, thermal mass variations and unknown occupancy habits (providing different internal temperatures) as key limitations. A further limitation to a pass-by methodology is that it only captures one external elevation of a building. While one elevation might indicate how the remaining elevations are performing (presence of defect), un-inspected elevations might harbour different defects (or have a very different construction) to the one imaged, and would subsequently be missed. The potential consequences of which could be compounded if the elevations missed have increased exposure to prevailing weather conditions such as driving rain or wind.

Despite these issues, using a drive-by methodology under a qualitative basis could be useful for quickly identifying specific defects such as ventilation and insulation losses that might be present in a building and worthy of further investigation (Shao, 2011).

Traditional Passive Building Thermography

There are two similar forms of passive building thermography commonly used by practicing building thermographers. Walk-around and walk-through thermography. Because of their ubiquitous use, they are referred to throughout this thesis as 'traditional' passive building thermography methodologies. Both forms of traditional passive building thermography methodology involve the acquisition of multiple images from around the building, recording specific areas of interest in reports (UKTA, 2007).

- *Perimeter Walk-around thermography (external only)*

  Whereas pass-by thermography captures only one external elevation, walk-around thermography observes every external elevation. Speed seems to be the primary driver for this type of survey.

  Red Current (2012a) is one professional thermography company offering walk-around thermography. The cost of this is £250, which is almost half that of a walk-through survey (£400). This cost issue becomes more significant when multiplied over many properties and may explain how cost could influence decisions on thermography application. Aside from cost, Holst (2000) further identified that external thermography avoids access issues, particularly with larger buildings, and proposed that internal inspections should only be used to clarify external observations (Colantonio, 1999). This advice seems contrary to Vollmer & Möllmann (2010), who state that external thermography at best should be used as a tool for gaining an overview of a building, suggesting areas for further inspection with an internal survey.

Yet external thermography can be considered more susceptible to environmental conditions compared with internal thermography (Vollmer & Möllmann, 2010). Correspondingly, Hart (1991) pointed out that different façade orientations will deliver different readings depending on solar, wind or moisture exposure.

Although walk-around thermography minimises the time spent surveying and eliminates issues with access, because it only observes the external façade, there are some defects that cannot be detected using this methodology alone. Loft insulation inspections are one example, where insulation defects are not always detectable because of the viewing angle from street level to pitched roof (Westerhold, 2013).

- *Walk-through thermography (Internal and External)*

  Walk-through thermography is an enhancement on walk-around thermography as the thermographer performs internal as well as external imaging. This presents a clearer picture of building defects compared with external surveying alone (Pearson, 2011). The procedure for conducting walk-through thermography involves the thermographer inspecting every surface inside and outside of the building, recording potential defects from several different angles and making field notes on the likely observed issues (ASTM, 1997). This increased rigour comes at a cost in both money, as noted by Red Current's (2012a) service charges, and time. Westerhold

(2013) noted the time-consuming nature of performing a walk-through methodology due to the multiple rooms, walls and floors that could require imaging, which contrasts unfavourably with the time taken for external-only image collection from walk-around surveys.

Repeat Surveys

As reported in chapter 1, all building materials will degrade over time. Yet material degradation will likely occur differentially from one material to the next and is subject to factors such as material specification, location, weathering, pollution, construction detail and maintenance (Halliday, 2008; Harris, 1981). Seeking to address building degradation, some clients and building professionals are now starting to consider the use of repeat thermography as a means of monitoring the continued performance of buildings, and as an early warning tool for detecting developing defects before they present themselves as more serious problems (Lucier & Phillips, 2003).

Although not a specific methodology in its own right (compared with the other methods), repeat thermography offers an alternative method of using any passive building thermography methodology over staged periods. For example, traditional walk-past thermography might be undertaken on an annual basis to detect material degradation/changes.

Roof moisture surveys often utilise repeat thermography (Brost, 2010; Tibbs, 2004), where annual inspections are conducted to verify construction condition with particular regard to penetrative moisture. Work by Edis, Flores-Colen & Brito

(2014) made use of repeat thermography to assess the effects of moisture ingress within cement adhered cladding on facades. This included thermography surveys during both dry and wet periods and an assessment of the effect that solar gain has on wet constructions viewed by thermography. Another use has been for detecting structural failures in buildings. Work by Paoletti *et al*. (2013) and Bisegna *et al.* (2014) utilised before and after thermography on a historic building to assess the ability for thermography to detect location/sources of pre-earthquake damage in buildings.

Before and after (construction) surveys offer another application for repeat thermography and are typically performed to identify problem areas and check the success of remedial action and workmanship following repairs (Hopper *et al.*, 2012; Walker, 2004; Williamson, 2014). Rarely used, this application of thermography can be of specific benefit to both new build and refurbishment through post occupancy evaluation, where the success of recently completed works can be assessed (Halliday, 2008). This could provide a tool for helping occupants to understand when and where defects are occurring (Goodhew *et al.*, 2009), and to offer a visual feedback/education tool for design and construction teams, indicating areas of success or failure (Snell & Schwoegler, 2012).

Time-Lapse Surveys

Most passive building thermography methodologies capture images at a single point in time. This aligns with a stationary perception of building heat loss where steady state temperature differences can be used to assess heat flow through building fabric. Yet, this has the potential for misinterpretation because indoor and outdoor conditions are rarely in a steady state.

Changing conditions, such as moisture in walls or heat stored within thermally massive building components (Hart, 1990), can cause material properties to fluctuate which, in the case of moisture in walls, could damage and reduce the overall performance of the construction (Mumovic et al., 2006). Using single point in time thermography, such transient conditions are not visible in instantaneous thermal images (Pearson, 2011) due to the long time-scales involved with the occurrence of some environmental changes.

Some thermal cameras now have the ability to record movie sequences and time-lapse images, enabling thermographers to observe changes in material surface conditions over seconds, minutes or hours (Drollette, 2001; FLIR, 2014b; Lucier, 2002). Despite this, the snapshot approach to passive building thermography remains routine. Furthermore, transient climatic changes appear to be ignored, be it purposefully or not. This is despite extensive literature documenting such environmental limitations (BSi, 1999; Lo & Choi, 2004; UKTA, 2007). An apparent lack of understanding could be detrimental to defect detection particularly in certain structures, such as heavy weight buildings, which require approximately 24 hours of no solar gain on a wall for an accurate thermographic inspection, as reported by Chown and Burn (1983).

One area of work utilising a passive time-lapse methodology has been moisture analysis, such as in work by Grinzato *et al.* (2010) who used it to explore the evaporation process and drying periods of different plaster build-ups. Their work resulted in the creation of temperature decay curves (over time), which presented differences in moisture patterns amongst a collection of material samples. Another application of a time-lapse methodology has been to determine the thermal performance of construction build-ups (Fokaides & Kalogirou, 2011; Madding, 2008). Work by Larbi Youcef *et al*. (2012) used passive building thermography over a number of days to help measure the performance of insulated building walls. Conclusions from this work suggested that additional parameters were necessary for such a study, which relates back to Hart's (1991) recommendation for the additional use of heat flux meters for thermal performance measurements.

Whilst most of the research using a time-lapse passive building thermography appears to quantify performance, only one literature source makes any attempt at utilising time-lapse thermography for qualitative analysis. This work by Freitas, Freitas & Barreira (2014) explored the use of time-lapse thermography to better understand plaster detachments on walls. Although some qualitative analysis was undertaken to observe thermal pattern changes over time, the focus was on quantitative analysis of surface temperature changes. There is no literature specifically investigating the benefits that time-lapse thermography can have to qualitative analysis, yet this work by Freitas, Freitas & Barreira (2014) suggests how such an investigation could prove useful at visualising defect patterns evolving over time to better understand the nature of defects.

3.4 The Approach for Analysing the Application Methodologies

To assess how frequently reported each passive building thermography methodology was amongst the literature for energy related building defects, a key-word (Jesson, Matheson & Lacey, 2011) search was conducted over a wide range of literature sources. Such sources included academic journals, governmental guidance notes and commercial web pages. From these, documented bibliographies and references were explored for deeper investigation (Reed, 1998). A total of 226 published literature sources were referenced, which spanned between the periods of 1980 to (the beginning of) 2015.

Collected literature sources were recorded in a methodology matrix, which focused each source into specific categories that could be counted for occurrence analysis. Each source of literature was read and assigned to a specific category based on which methodology was being used or reported on.

All collected literature on building thermography was systematically reviewed and categorised based on a series of defined filters (see Figure 20), which formed the basis of the key-word search and helped to classify ideas for analysis and further investigation (Ridley, 2008). Some of these filters were based on the key decision-making process diagram (Figure 13); whilst others determined the defect type, document type and application methodology. The methods used to generate the narrowed filter categories for the methodology matrix were derived from existing literature on passive building thermography, which had been formulated from reading past journal papers and other sources of key literature.

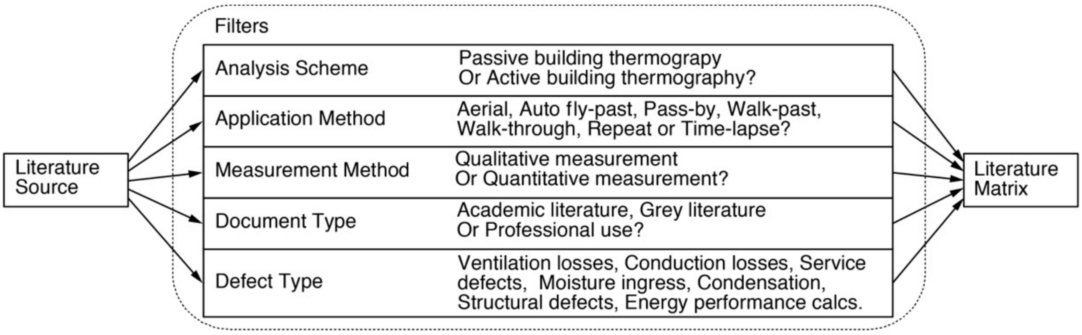


Figure 20. Literature filter diagram.

Analysis Scheme Filter

This filter sought to identify whether the literature reported a passive or active thermography analysis scheme. As a result of documented opinions, which stated that building thermography typically employs a passive analysis scheme (Avdelidis & Moropoulou, 2004; Maldague, 2002), this review specifically sought information on building defects using passive building thermography methodologies. Therefore, sources reporting on active building thermography were not included within the literature review matrix.

Application Method Filter

This filter sought to identify which application methodology the literature was referring to or using.

Measurement Method Filter

An examination of the measurement method looked for indicators as to whether the literature referred to a quantitative or qualitative measurement approach.

Document Type Filter

This filter determined the background to the literature source. Documents were defined as being either from:

- Academic literature. Including published books and peer reviewed documentation such as journal and conference papers. These sources suggested scientific interest, development and investigation.
- Grey literature. This category dealt with informally published literature. Documents such as government or professional guides, legislation or

technical reports fell under this category. Grey literature is important because significant developments to passive building thermography have been made under this type of document.

- Professional use. This category collected all the remaining literature sources and included web sites, which reported on the implementation of passive building thermography. Because many practitioners perform and help to develop new passive building thermography methodologies, it was important to gain an understanding of their work despite a lack of published material.

Defect Type Filter

Dealing with energy related building defects, described under chapter 2.2, the aim of this filter was to indicate which defects were being detected by passive building thermography methodologies.

Following the focusing process of literature filters, a strategic method of presenting patterns was deemed necessary: a literature synthesis matrix was chosen (Ingram et al., 2006). This review methodology tool was chosen due to a lack of cross-comparison between much of the passive building thermography literature. Additionally, to date there has been no investigation into the effectiveness of detecting defects and how this compares with other passive building thermography methodologies. Using a matrix allowed for a more analytical comparison of each methodology, how they were being used, what limitations exist and how comparative links can be made. With reference to work by Klopper *et al.* (2007), who reported on the use of a matrix for literature reviews, a specially designed literature matrix (see Table 1) was devised that catalogued and counted the occurrences of texts following the filtering process.

Having collected the matrix results, the findings were critically analysed to help explore the benefits, limitations and key drivers that have shaped the development of the different passive building thermography methodologies.

3.5 Results from the Literature Review MatrixTable 1 shows the completed literature review matrix, which includes a categorised numerical record of all the literature sources that were passed through the literature filtration process. For each application methodology, a total number of literature sources were collected irrespective of literature source (type) and measurement method. This provided a quick summary of the most commonly reported defects and methodologies, which proved to be traditional thermography, used for conductivity losses (74 sources), ventilation losses (56 sources) and moisture ingress defects (51 sources). From this matrix, specific patterns could be observed from the data. These included:

- The distribution of literature sources on particular defects by their source (Academic, grey or professional source),
- Comparing the distribution of literature amongst different building defect types and based on being either a qualitative or quantitative measurement method.
- Focusing on qualitative thermography in particular, how different thermography methodologies are being currently used to inspect particular defects.

Application method		Aerial thermography							Automated fly-by thermography							Pass-by thermography						
Literature Source		Academic document		Grey document		Prof. document		Total use	Academic document		Grey document		Prof. document		Total use	Academic document		Grey document		Prof. document		Total use
Measurement method	Q1 = Qualitative, Q2 = Quantitative	Q1	Q2	Q1	Q2	Q1	Q2		Q1	Q2	Q1	Q2	Q1	Q2		Q1	Q2	Q1	Q2	Q1	Q2	
Defect type	Ventilation losses	1	0	0	0	0	0	1	0	0	0	0	3	0	3	1	0	2	1	1	1	6
	Conductivity losses	8	5	0	0	3	2	18	3	0	0	0	8	0	11	2	0	2	1	1	1	7
	Defective services	3	0	0	0	0	0	3	2	0	0	0	5	0	7	0	0	0	0	0	0	0
	Moisture ingress	15	0	5	0	2	0	22	1	0	0	0	4	0	5	0	0	0	0	0	0	0
	Moisture condensation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Structural defects	0	0	0	0	0	0	0	1	0	0	0	1	0	2	0	0	0	0	0	0	0
Energy performance estimation		0	4	0	0	0	2	6	0	1	0	0	0	1	2	0	2	0	2	0	5	9

Application method		Traditional thermography - walk around & walk through							Repeat thermography							Time-lapse thermography						
Literature Source		Academic document		Grey document		Prof. document		Total use	Academic document		Grey document		Prof. document		Total use	Academic document		Grey document		Prof. document		Total use
Measurement method	Q1 = Qualitative, Q2 = Quantitative	Q1	Q2	Q1	Q2	Q1	Q2		Q1	Q2	Q1	Q2	Q1	Q2		Q1	Q2	Q1	Q2	Q1	Q2	
Defect type	Ventilation losses	19	0	20	0	17	0	56	3	0	1	0	2	0	6	0	0	0	0	0	0	0
	Conductivity losses	29	1	20	5	19	0	74	5	0	1	0	2	1	9	1	3	0	0	0	0	4
	Defective services	4	0	3	0	7	0	14	1	0	0	0	0	0	1	0	0	0	0	0	0	0
	Moisture ingress	25	1	13	0	12	0	51	1	1	1	0	5	0	8	1	2	0	0	0	0	3
	Moisture condensation	11	0	7	4	10	0	32	0	0	0	0	1	0	1	0	0	0	0	0	0	0
	Structural defects	10	1	4	0	3	0	18	3	1	0	0	0	0	4	1	1	0	0	0	0	2
Energy performance estimation		0	8	0	5	0	1	14	0	2	0	1	0	1	4	0	9	0	0	0	0	9

Table 1. Completed literature review matrix.

Documentation of Methodologies

Figure 21 suggests that while academic work can be observed within all passive building thermography methodologies, a professional application is present in all but the time-lapse methodology. One theory for this may be a limited understanding of this methodology, while another could be because it is more disruptive (to occupants), costly, time-consuming and more complex to set-up compared with the other passive building thermography methodologies.

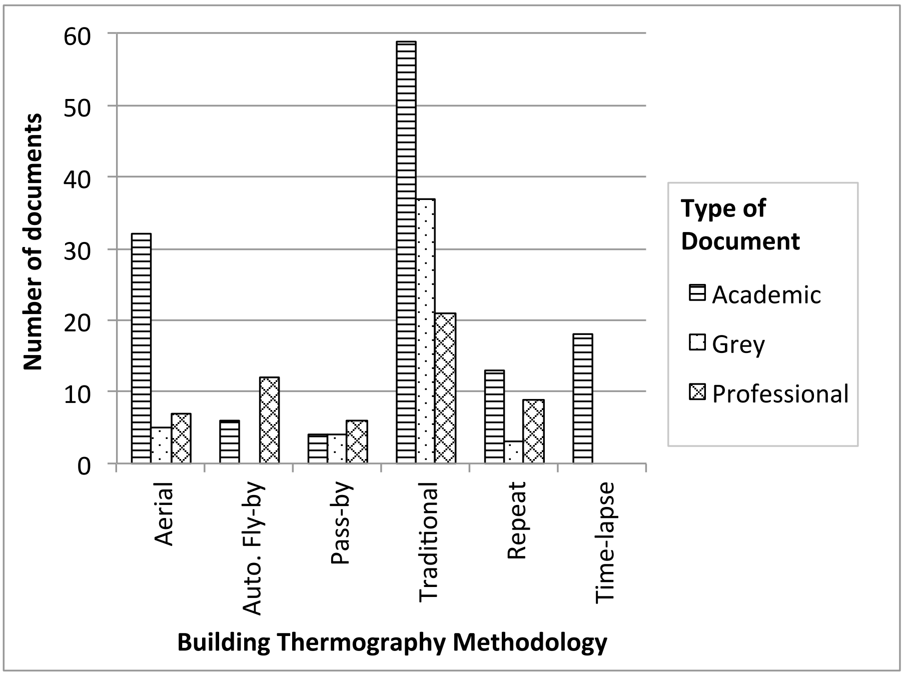


Figure 21. Literature by source and building thermography methodology.

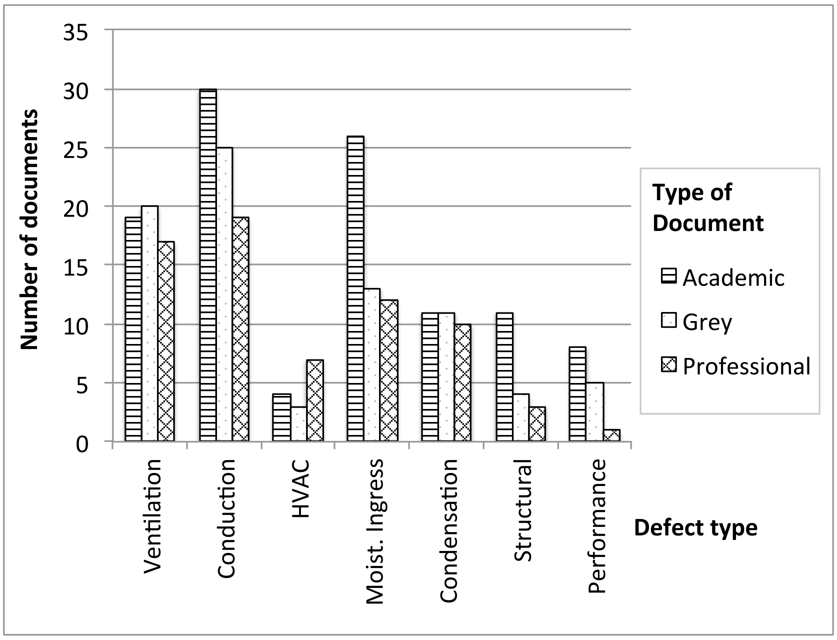


Figure 22. Literature by source and defect type for traditional passive building thermography methodology.

Figure 21 also reinforces the hypothesis that much of the available literature centres on more traditional methodologies. The automated fly-by and pass-by methodologies have seen more professional application than academic research. With regards to the limited academic and grey literature on fly-by and bass-by thermography, this reinforced findings that these are relatively new methodologies.

Focusing on traditional passive building thermography, figure 22 shows that much of the documentation discussing ventilation losses, conduction losses and condensation defects comes from grey literature sources, while moisture ingress and structural related issues appear to be much more academic led.

Qualitative and Quantitative Use of Methodologies

Comparing the data, with regards to the measurement method applied for each of the application methodologies, figure 23 provides evidence that supports statements from Kee (1997) and Kominsky *et al*. (2007), that passive building thermography is primarily performed on a qualitative basis. However, this does not appear to be the case for pass-by and time-lapse thermography, which were primarily reported as being used for quantitative applications.

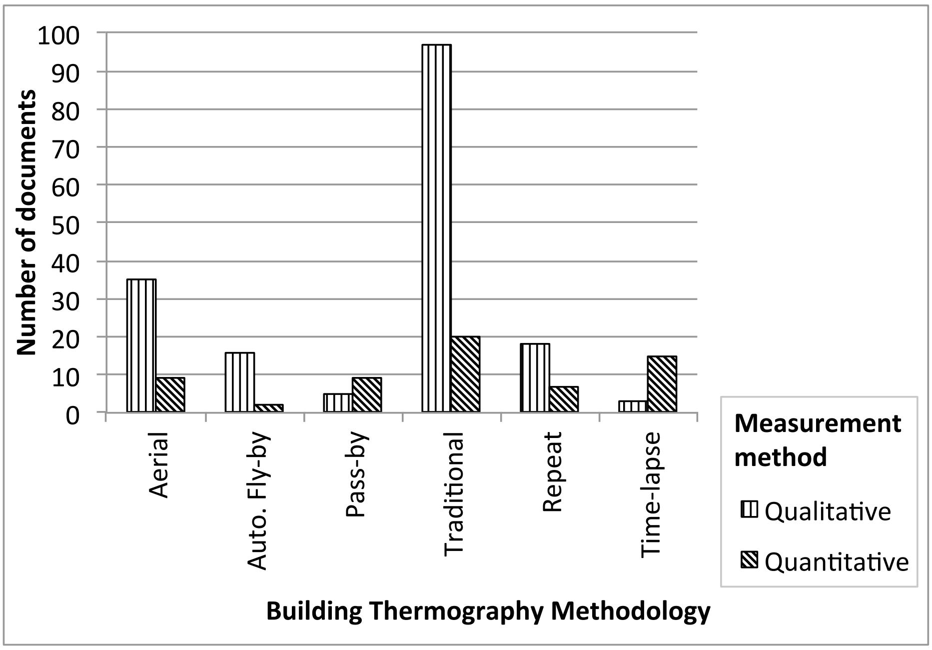


Figure 23. Literature by building thermography methodology.

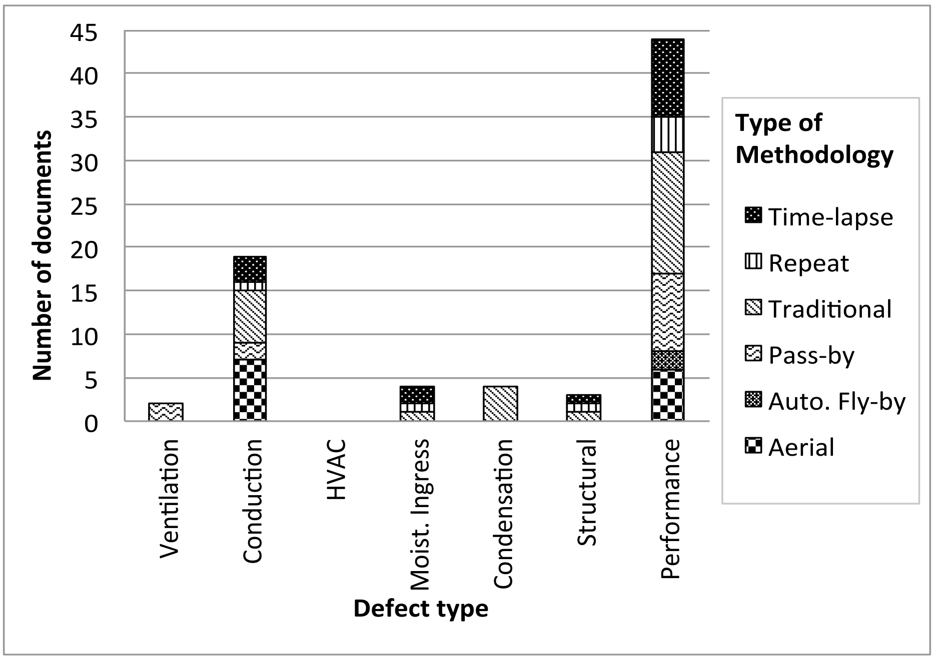


Figure 24. Quantitative literature only by building thermography methodology and by building defect type.

However, examining quantitative applications within passive building thermography methodologies (Figure 24), shows that most of the research in this area targets energy performance estimation, such as U-value measurement, which although not specifically classed as a building defect will largely be effected by other energy related defects such as ventilation and conduction losses.

Qualitative Application of Passive Building Thermography Methodologies

Figure 25 indicates how each of the passive building thermography methodologies are currently being utilised for qualitative defect detection. Confirming their significance in construction, the three defects: ventilation losses, conductivity deficiencies and moisture ingress, can be seen to have had considerable mention within academic and professional literature. Focusing on only the documented professional use, figure 26 shows that conductivity and moisture ingress again seem to be the defects with most focus.

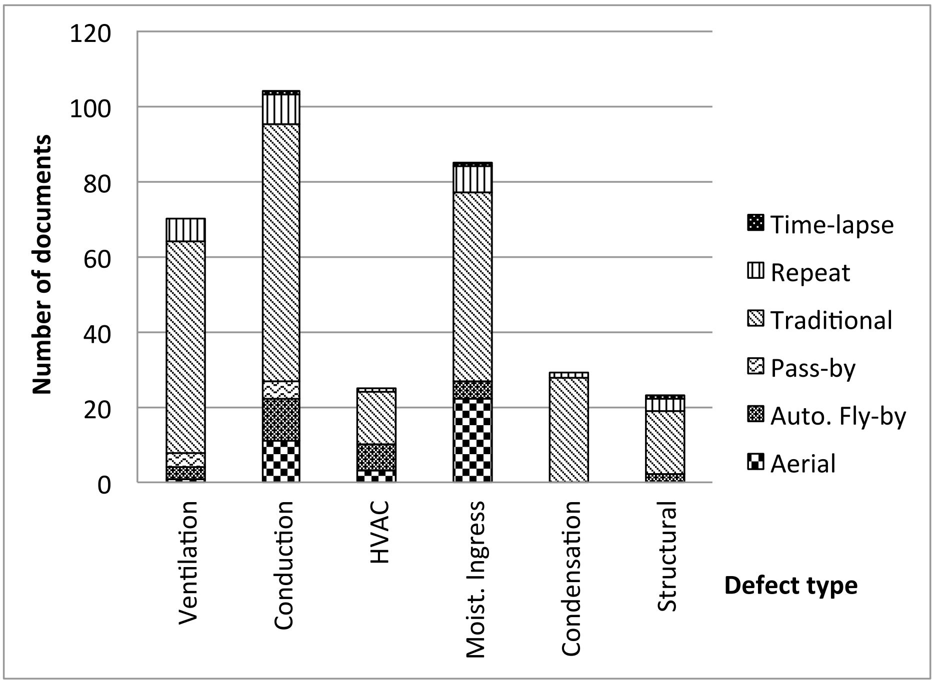


Figure 25. Qualitative literature analysis by passive building thermography methodology and by defect type for all literature sources.

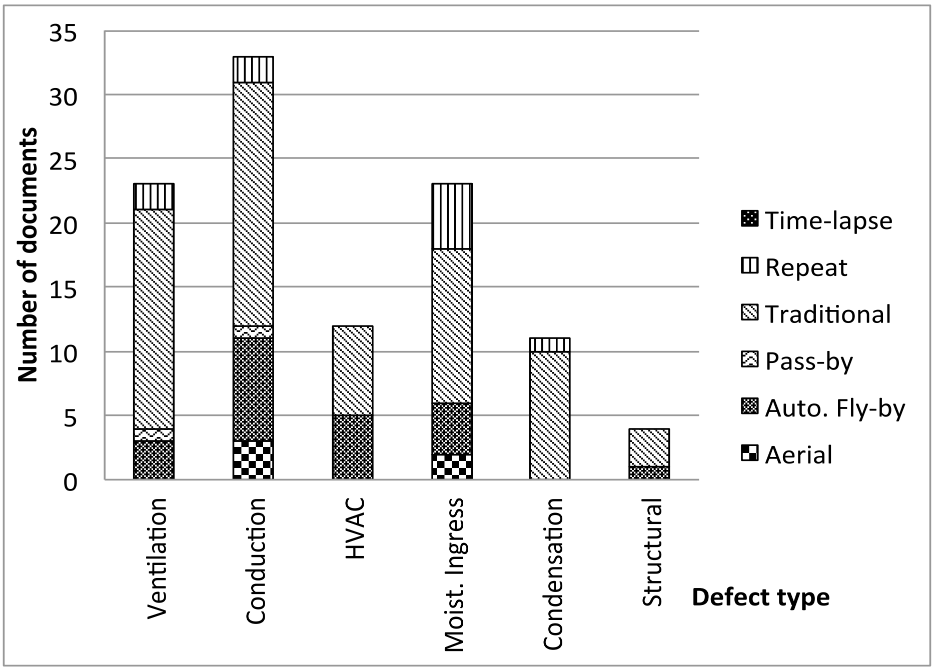


Figure 26. Qualitative literature by passive building thermography methodology and by building defect type for professional literature source only.

Figure 25 and 26 also show that traditional methodologies are the most commonly applied thermography method for defect detection and that all thermally significant defects have been detected using traditional thermography. This is possibly due to the frequent use of this methodology; however, it could also suggest limitations within the other passive building thermography methodologies. For example, repeat thermography is the only other methodology that has also been recorded as observing condensation defects, which could suggest a difficulty in obtaining a qualitative result using methodologies that are externally focused.

3.6 Application Methodology Drivers and Limitations

This section discusses some of the key drivers that are shaping existing and emerging building thermography methodologies. Considering these drivers alongside potential limitations of the methodologies can help thermographers to understand how new methodologies are being developed, where particular methodologies might be best applied and how they could be combined as part of multiple survey tools.

Perceived Defect Detection Ability vs. Time

Two of the key drivers shaping passive building thermography methodologies are time and detection ability. Maldague (1994) stated that internal thermography is more time-consuming compared with external thermography. When related to costs (Red Current, 2012a), it is easy to see how lengthier methodologies equate to an increased cost to thermographer and client. Referring back to Table 1, it can be observed that none of the reviewed professional literature makes reference to use of a time-lapse passive building thermography methodology. As well as being a new methodology and holding the potential for further research/use in the future, this pattern could suggest that these slower methodologies are currently prohibitively time-consuming and costly for practical use. Arguably, methodologies that are faster than the traditional methodologies have been developed out of an aspiration to speed up and lower the cost of performing building thermography for defect detection and thermal performance determination. This correlates with the recent professional uptake in UAV fly-by and pass-by thermography.

Although speed and cost is important when considering the commercial implementation of thermography for building assessment, with greater speed comes a reduction in defect detection ability, which provides a less clear picture of the overall energy performance of the building. Considering pass-by thermography, as only observing external elevations, a reduction in spatial resolution will be magnified given the likely large distance from camera to target. These limitations could therefore lead to a misinterpretation of images or to missing certain defects.

Figure 27 supports this position, showing that aside from total energy performance estimations, only ventilation and conduction loss defects have been identified to date using a pass-by methodology, therefore missing one of the main thermally significant defect groups: moisture.

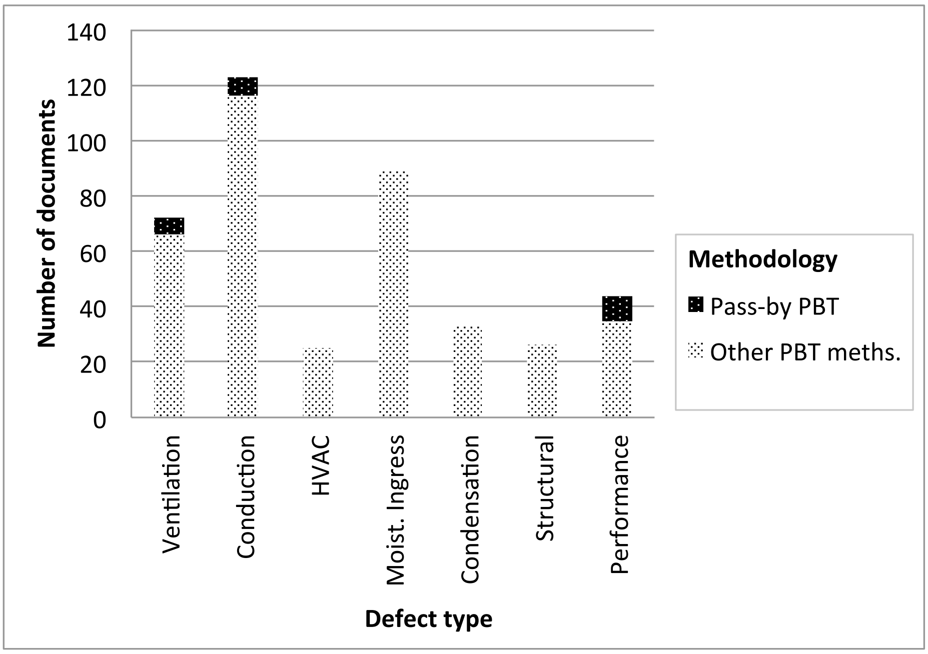


Figure 27. Literature by defect type with a focus on pass-by passive building thermography.

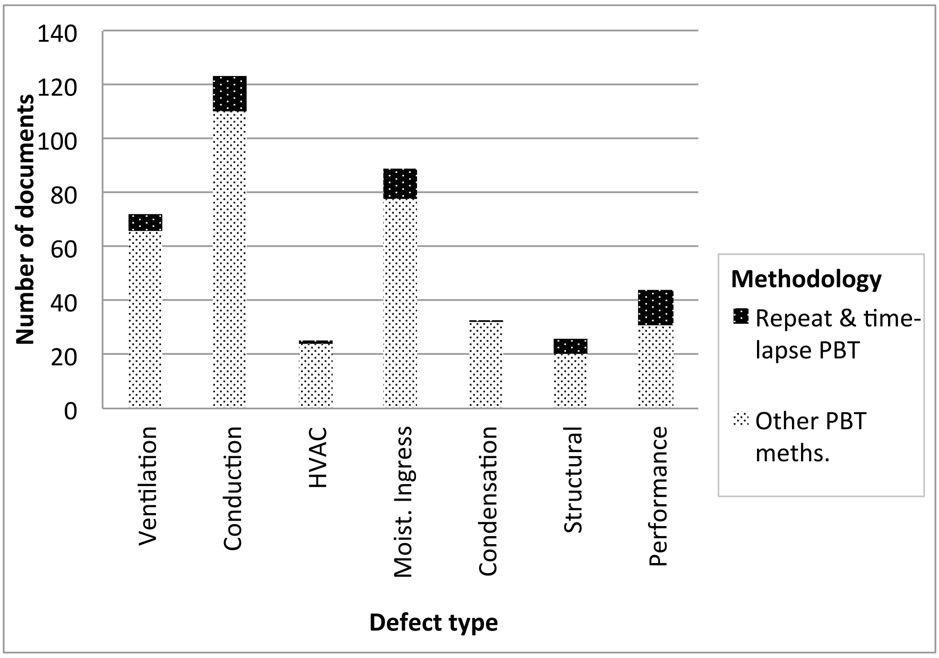


Figure 28. Literature by defect type with a focus on repeat and time-lapse passive building thermography.

One clear limitation to defect detection using aerial, automated fly-by, pass-by and traditional walk-around methodologies is the absence of internal investigations, meaning that any internal defects are likely to be ignored. This limitation becomes amplified due to construction features such as low emissivity claddings and air gaps between external wall layers, both of which can mask internal defects (Stockton, 2011). Another limitation rests with the camera specification, where even relatively high resolutions of 640x480 pixels appear insufficient for capturing defect detail, within singular image assessments of whole façades, that might involve the thermographer recording images at distances greater than 10m from the target surface.

Add to these limitations differences in emissivity, steep view angles, thermal mass and façade orientation differences, and concerns start to be raised (Schwoegler, 2011b) over claims (IRT surveys, 2012a; Phan, 2012) that methodologies such as pass-by passive building thermography can be used for quantitative total heat loss and CO_2 estimation. Doubts centre on whether it is possible to determine a building's total heat loss, or energy use based on only partial external information gathered over one single image.

Energy performance determination is the most common application of pass-by thermography. Because each of the many pixels in a thermal camera records an apparent temperature reading, comparing a pass-by methodology with collecting surface temperature data from several thermocouples or infrared thermometer readings, pass-by thermography might indeed prove a useful exercise in obtaining fast whole elevation data, which could then be interpreted for energy performance. The concerns and limitations, however, caution against too much reliance on the accuracy of the results, which will offer estimates at best.

However, some of the slower methodologies address defect detection in an alternative, more rigorous, manner. Figure 28 shows that all of the defect groups are detected using the slower methodologies of repeat and time-lapse thermography, with moisture ingress being one of the key defects, that appear more detectable using lengthier analysis. This is significant since the slower passive building thermography methodologies take better account of the transient environmental conditions acting on a building, and the dynamic changes within building materials than the faster methodologies.

While much of the passive building thermography research has focused on individual methodologies in isolation, a single paper reports on how different passive building thermography methodologies might work to complement each other. This is work on large building investigations by Brady (2010), who made use of aerial thermography as an initial methodology that reviewed the overall condition of a flat roof. Within these whole roof thermal images, areas of interest (potential defects) were pinpointed. After this, a walk-on roof 'traditional' thermography methodology was used to investigate these areas of interest in greater detail by getting closer up. Brady used a similar approach to external wall surveys. Starting with a multi-image panoramic thermal image to identify potential areas of interest from afar, before moving in closer with the thermal camera.

Results from Brady's (2010) work showed that having a larger aerial picture of the roof helped to pinpoint potential problem areas, which allowed for faster and improved staff efficiency when conducting more detailed close up thermography. Brady's work offers an example for future coordination where different scales of thermography could be combined as part of a phased surveying approach. This topic is considered in more detail during chapter 8.

Technological Development

Recent advances in thermal camera technology, such as the digitisation of image collection (Holst, 2000), have likely helped to shape the way in which passive building thermography methodologies are performed. This is supported by Figure 29, which shows the documented patterns of passive building thermography methodology occurrence by documentation publication date. This is for the period of between 1980 (date of first reference) and 2014 (last full year of literature collection). It is observed how early reported methodologies consisted of either aerial or traditional methods for passive building thermography, while newer methodologies were introduced within the past 10 years. Another observation can be made from the more recent accumulation of literature on passive building thermography, which underlines the growing application of thermography for building assessment.

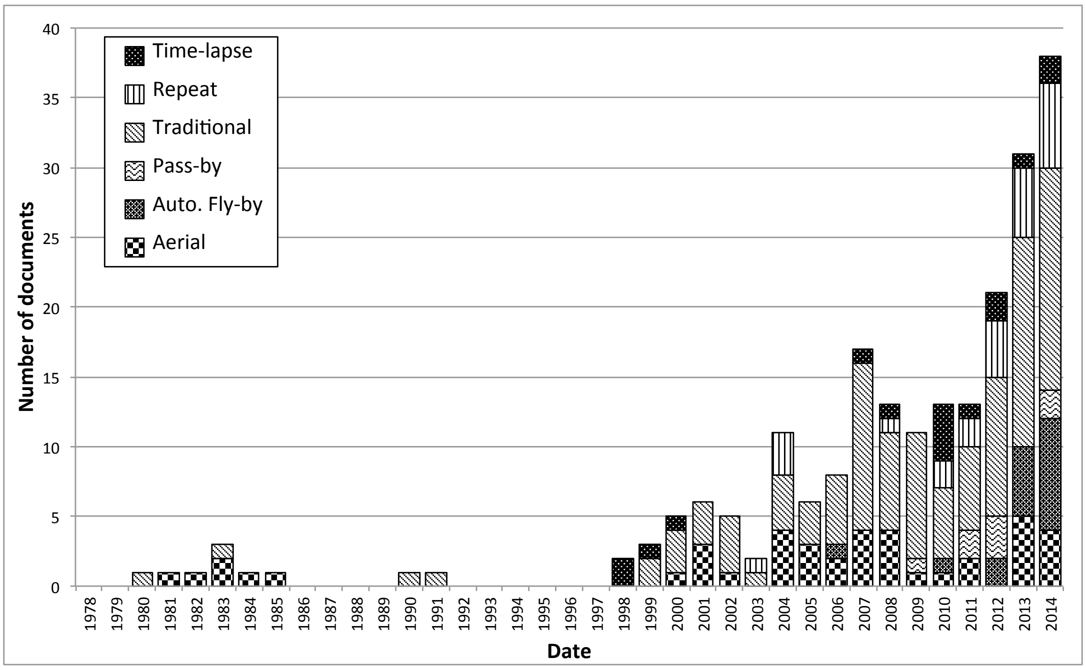


Figure 29. Occurrence of literature referencing passive building thermography methodology and by date (1980 – 2014).

Whilst advances in thermal camera technology have enabled more efficient passive building thermography methods, it is also important to note that thermographers have been considering ways of utilising other more recent technological developments. Two examples of these have been through automated fly-by (attaching cameras to small unmanned aircraft (Martinez-de Dios & Ollero, 2006)) and pass-by (attaching cameras to cars (Phan, 2012)) passive building thermography.

This combination of technology is opening up novel opportunities for passive building thermography that need further investigation in order to fully assess the potential benefits and limitations.

Estimation of Energy use and Thermal Performance

Another driver for passive building thermography methodology development has been the estimation of total façade energy use using quantitative measurement methods. U-Value estimation (Fokaides & Kalogirou, 2011; Madding, 2008) and CO_2 quantification (IRT surveys, 2012a), are two examples, which represent evidence of a growing appeal amongst thermographers (and possibly clients) to quantify how a building is performing in terms of energy use.

The literature (IRT surveys, 2012a; SFHA, 2011) suggests that some thermographers are utilising a quantitative measurement approach whilst performing traditional and pass-by thermography methodologies, measuring the data obtained from single images to estimate heat loss and energy use. Yet, adding to the concern that buildings are subject to transient changes, Hookins (2009) urges caution over this methodology, arguing that there would be too many variables for accurate quantitative analysis to be conducted on a snapshot basis. Stockton (2011) related this to cost, arguing that obtaining accurate quantitative assumptions on heat loss performance incurs greater costs compared with qualitative image interpretation. This could present a barrier to quantitative commercial application.

Furthermore, when estimating energy use or thermal performance, it is essential to determine the presence of defects, especially since defects that permit heat to escape from the building will lead directly to a reduction in energy performance. This factor might not be fully considered, nor practical to include when undertaking simplistic whole-house estimations, though could cause inaccuracies (compared with actual performance) to resultant calculations.

Seeking to better understand changes in U-values for a construction over time, Albatici, Tonelli and Chiogna (2015) carried out an experiment, where repeat thermographic measurements were taken of a real building. From these measurements, U-values were equated. Results showed that the most accurate thermographic measurements were taken in the early morning (between 4 and 6am), and that 'heavy' wall constructions (Brick) offered more easily repeatable measurements compared with 'lighter' wall constructions (timber frame/insulated). They also found that the best results came from walls that were north or east facing. Comprising of three years research, this work makes a good advancement to the field of transient U-value analysis, however it focuses more on long-term transients rather than diurnal transient changes.

The consideration of much shorter transients in the field of thermography U-value measurement has been taken by researchers such as Madding (2008) and Kato, Kuroki & Hagihara (2007). These appear to be applying quantitative analysis to time-lapse thermography. Although their work primarily uses steady state lab conditions, some investigations by Madding used a quantitative time-lapse methodology in a real building situation with internal thermography. Set within changing real world conditions, it could be argued that the methodology merely presents approximations of building performance; however, depending on the discrepancy factors encountered, such approximations might be worthwhile exercises in 'suggesting' the performance. Discussing discrepancy factors, Pearson (2011) stated that the accuracy of calculated U-values from thermography are at best ±25%, though values could be less accurate for well insulated walls, and that measurements do not seem to take into consideration stored heat, since they are based on a snap-shot of a wall at one particular time, and might not be observing the flow of stored heat. Madding's methodology utilised a periodic image collection format from the inside only and would have been subject to far fewer climatic variations had it been conducted externally. Therefore, it could be argued that the discrepancy factor may be less than Pearson's ±25%. Also, by conducting a time-lapse survey a more accurate approximation could be determined by averaging the data from all images as opposed to a single snapshot image under a faster passive building thermography methodology.

3.7 Summary of chapter 3

This chapter has reviewed the trends in existing thermography literature, and has highlighted the different passive building thermography methodologies, which are currently being researched and applied to existing buildings. This includes Traditional perimeter walk around surveys, Traditional walk through surveys, Aerial surveys, Repeat surveys, Time-lapse surveys, Street pass-by surveys and Automated fly-past surveys.

These have been influenced by recent key drivers, such as increased speed and efficiency, reduction in surveying cost, determination of building performance, improvements in technology and deeper understanding of building defects.

The increased use of passive building thermography for defect detection suggests that building thermography is becoming progressively requested and utilised within building refurbishment work, something that is likely to increase in combination with advancements in technology and cost reductions.

A further observation is that some methodologies are increasingly being used to estimate building energy performance. Yet in doing so some of the past lessons and limitations to thermography discussed in chapter 2, such as environmental conditions, emissivity and spatial resolution, appear to be forgotten or ignored. This work has also shown that some of the passive building thermography methodologies might be suitable for detecting some defects, but not others. Also, in some situations defects such as moisture ingress, condensation losses or ventilation losses might be completely overlooked, especially when only viewing a building from the outside, which might mean that internal defects such as condensation defects may be missed. Furthermore, there might be circumstances in which internal defects show on the external elevation during an external only thermographic survey, though these could be misinterpreted due to a lack of understanding of the construction or internal conditions.

Yet failure to recognise the direction that passive building thermography is heading in would be remiss, particularly as thermal camera and surveying costs appear to be driving faster surveys. At present, increased speed seems to go hand-in-hand with reduced defect detectability, largely due to a diminished spatial resolution.

This work has shown that there is the potential for using several passive building thermography methodologies together in a phased approach. For example, a less costly and faster survey could be conducted to identify certain defects quickly before enabling more time consuming and expensive surveys to hone in on these with greater detail and spatial resolution if deemed necessary.

To further investigate the findings and assertions from current literature sources, and to better understand how different thermography methodologies could be used for improved image interpretation and subsequent defect characterisation it is clear that practical experimentation is needed. To do this, each thermography methodology needs to be examined on real buildings/materials. This shall form the basis for the primary research presented in chapters 5 to 7, where three of the six methodologies have been investigated. However before commencing work on the specific primary research projects, it is first important to consider the overarching research methodology strategy. This is the focus of the next chapter.

4.0 Research Methodology

In chapter 1, the thesis methodology was presented, which outlined the structure of the thesis as a separate entity to the research projects undertaken within the thesis. In this chapter, the overarching research methodology will be outlined. Whilst specific information relating to the design, equipment and application of each thermography method is presented at the start of each primary research chapter, this chapter focuses on the key research methodological aspects, which relate to all of the thermography methods used.

This chapter also outlines how the 'content' was narrowed from the literature review into the primary research focus.

4.1 Methodology for narrowing the content.

4.1.1 Development of aim and objectives

Before setting out to investigate a research problem it was important to select a topic that has recognised issues. The overarching topic for this thesis sought to explore '*Thermography for thermal building assessment and improvement'.* This overarching topic gave an outline to the project, which was then explored through targeted research that helped to refine some key issues (Boudah, 2011; Ferfolja & Burnett, 2002) and led to the formulation of an overarching research aim, as set out in chapter 1.

4.1.2 Use of secondary research

Secondary research was used to gain a deeper understanding of the benefits, limitations and uses for thermography in buildings and is presented in chapters 2 & 3. The purpose of secondary research is to gain an appreciation of the current knowledge within the topic field. This knowledge then serves as the benchmark with which primary research is compared (Gray, 2004).

Several strategies were used to collect secondary research on passive building thermography. The first of these was a literature review, presented in chapters 2 & 3. Another strategy for secondary research consisted of thermography training. There are currently three levels of thermography training available (BINDT, 2009; Infrared Consulting Services, 2014; ITC, 2014):

- **Level 1.** An introduction to thermography, which provides a basic overview of the physics and operation of the thermal camera.
- **Level 2.** Providing the necessary skills to analyse and interpret thermographic data using either qualitative or quantitative methods.
- **Level 3.** Equipped to develop thermographic methodologies, make recommendations for corrective action and provide training to other thermographers.

The author of this thesis undertook thermography training levels 1 and 2, which comprised of two separate week long courses conducted with iRed (2014) in 2012 and 2014 respectively. These are in accordance with BINDT (British Institute of Non-Destructive Testing) (BINDT, 2009), who administered the PCN certification.

Whilst secondary research in the form of literature sources offer one-way dialogue, training courses present the opportunity for a two way dialogue, where the student can ask questions and start discussions. From attending these two thermography courses, the author gained added knowledge on thermography through enquiry, experimentation and experiential case studies.

4.1.3 Use of primary research

Hox and Boeije (2005) explain that primary data is collected using research methods that are tailored to best address the aim and objectives posed by the body of work they serve.

Although secondary research can open up a window onto any past and current thinking on a particular subject, it must be remembered that the specific content of each secondary source holds its own agenda, which is likely to be different to that of the thesis aim and objectives. This is especially true for this thesis, since the main objective is to constitute new knowledge.

Two methods of primary research were chosen to investigate the aim and objectives for this thesis: experimentation and case studies. Johnson and Christensen (2004) describe experimentation as the observation of "*cause-and-effect relationships*" which, when conducted under controlled conditions as found within a laboratory, enables the manipulation of certain criteria (such as heat) to enact an effect, which will help to address a specific research issue. The case study is an observation of example cases, such as a particular building (Bryman, 2012). Thomas (2011) described the case study as being a methodology which enables observation of the subject from many angles before deducing analytical insights from the results. Each case study is comprised of field experimentation (Christensen, 2006), which seeks to control as many external variables as possible.

Having completed the literature review, a deeper understanding of the six different passive building thermography methodologies could be made. This clearly indicated how the different methodologies ranged from being either very fast/low resolution to very slow/high resolution. Given the time-scales involved with conducting thermography on real building case studies ‘only’ during the winter months of a three-year project, a decision was taken to select three out of the six methodologies to investigate. As the most common survey applied in practice, the walk-through methodology was chosen as the mid-point between fast and slow alternative methodologies. The next decision was to choose the other two methodologies from either extreme of the scale. At the very slow/high resolution scale, time-lapse thermography was chosen. Repeat thermography was declined due to the need for a before and after (remediation works) case study. At the very fast/low resolution scale, street walk-past thermography was chosen. Aerial, UAV and drive-by thermography was declined for this thesis due to the need for equipment (air craft, specialist vehicle equipment etc.) that was not available during this project.

Whilst acknowledging the fact that data from three survey methodologies had not been investigated first hand through primary research, this ensured adequate time could be invested in the chosen methodologies. Below is a summary of each primary research chapter:

Chapter 5. **Walk-through thermography.** Having identified through the secondary research chapter that a walk-through methodology is the most commonly used thermography methodology, this initial primary research chapter demonstrates that a better understanding of the benefits and limitations could be gained through practice, rather than solely from literature. This is referred to as a typical case (Gerring, 2007), which typifies the standard procedure. This chapter also enabled a specific focus on the methodology procedure used.

Chapter 6. **Time-lapse thermography.** Following the initial walk-through case study chapter and the literature review, the use of a time-lapse thermography methodology, is explored in this chapter. Both laboratory experiments and real building case studies are investigated with the aim to establish how successful a time-lapse methodology could be in qualitative defect detection and quantitative situ U-value measurement.

Chapter 7. **Walk-past thermography.** At the opposite end of the scale to time-lapse thermography, this case study examined dwelling elevations from a street. The aim of this research was to examine claims from others (Currie, 2012; IRT surveys, 2012a; Phan, 2012) that such a methodology could be used for quantitative analysis and how such a methodology could be useful in practice.

Each primary research chapter follows a similar structure:

1. Introduction
2. Detailed methodology
3. Experiment Results
4. Results discussion/analysis
5. Concluding summary

4.2 Overall research approach and design

Reviewing the use of primary research for this thesis has helped to consider the overarching strategy that can be used to undertake the experiment and case studies. The design of an overarching research approach is illustrated in figure 30. This diagram shows how for each case study and experiment (research methodology), there are a number of key influences/drivers that need consideration before an output/finding is generated.

The first driver to the research methodology is the 'input'. These comprises of case study dwellings and material samples for experimental inspection, though careful consideration is required over the rational behind their selection for investigation.

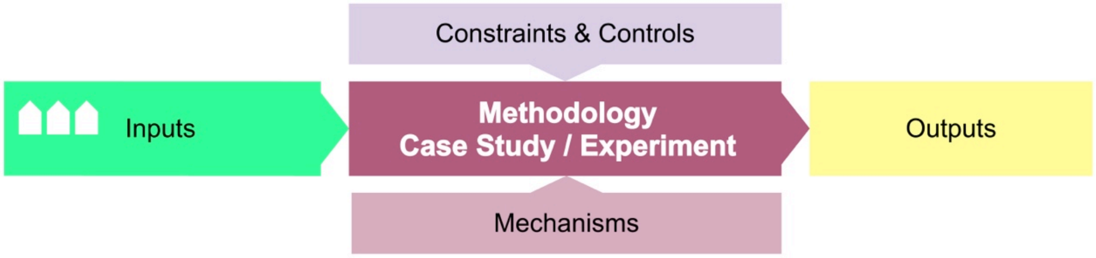


Figure 30. Overarching research approach.

To help facilitate the inspection of the inputs, it was also important to consider the key mechanisms that were used (for example, the camera, operator, software etc.) during each experiment/case study. The aim of this aspect was to utilise the most appropriate mechanisms for the research that worked within the confines of any known constraints. This last issue was the third key driver, which needed careful consideration. As identified through past literature, numerous limitations to thermography call for heightened awareness of constraints and controls to the research project (for example, weather and participants etc.)

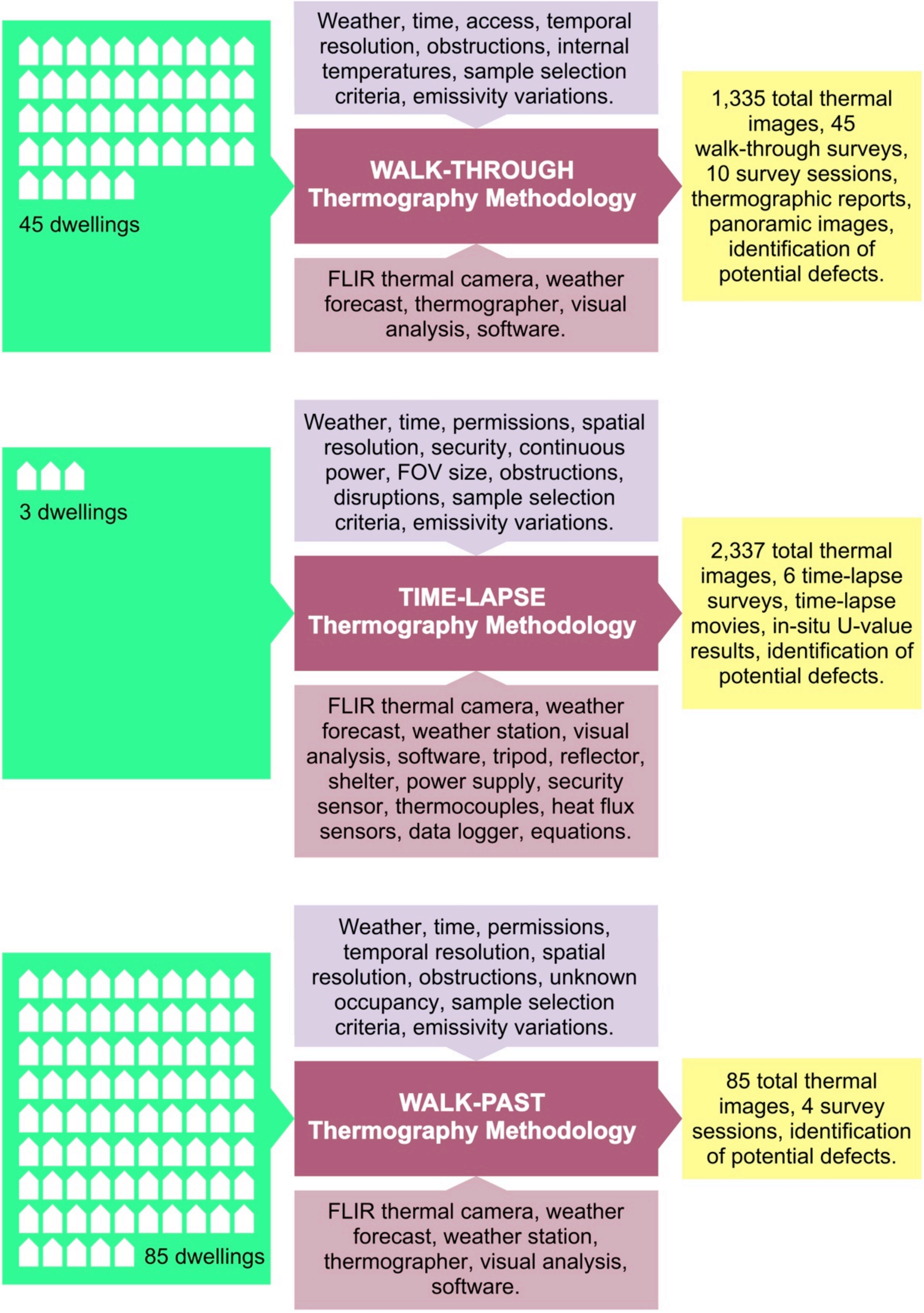


Figure 31. Overarching research methodology diagram.

Applying the overarching research approach (Figure 30) to the three different thermography methodologies chosen for inspection throughout this thesis, figure

31 highlights the key inputs, constraints & controls, mechanisms and outputs encountered from the thermography methodology specific experiments and case study investigations. This figure reflects the main aspects of the specific research activities/methodologies used during the investigation of each thermography method. A summary of the specific research used for each thermography method is presented below:

- Walk-through thermography (Chapter 5)
    - Qualitative analysis:
        - Walking through and around residential dwellings, scanning all of the building's surfaces for unexpected hot or cold spots. Any anomalies were recorded as single image thermograms.
- Time-lapse thermography (Chapter 6)
    - Qualitative analysis:
        - Positioning the thermal camera in a static position and setting a program to record thermal images of one particular viewpoint at pre-determined intervals. The images were then analysed as part of image sequences/time-lapse movies for potential anomalies.
    - Quantitative analysis:
        - Using a similar methodology to qualitative time-lapse thermography, spot and box area average temperatures were obtained from each thermal image in the sequence. Combining this temperature data with air and reflective temperature data, in-situ U-values were measured with the aid of mathematical equations.

        - Benchmarking the in-situ U-value measurements from thermography was the use of heat flux in-situ U-value measurement. These experiment were undertaken in parallel with the time-lapse thermography.
- Walk-past thermography (Chapter 7)
    - Qualitative analysis:
        - Walking along a street with the thermal camera, a single thermal image was recorded of each (participating) dwelling from the front elevation only. Images of similar dwellings were compared with each other using target comparison methods of analysis to determine whether potential anomalies were common/repeating on other dwellings.

For more detailed information on each thermography method and how these have been applied, please refer to the start of each primary research section.

By reviewing figure 31, it became clear that certain aspects were common throughout similar methodologies and should be considered at during this overarching methodology stage. Common aspects included weather; the selection of case study dwellings, the use of visual analysis and the use of typical thermography mechanisms (camera, thermographers, software etc.). These are discussed in the next sections of this chapter.

4.3 Common constraints and controls

Gray (2004) warns that limitations to research can lead to the generalisation of results. If ignored, limitations could compromise the design and execution of research methodologies; therefore, it is essential to identify likely sources of constraint and better understand how they might impact upon the ability to investigate the aim and objectives or how they might be controlled.

Whilst specific constraints and controls were encountered with each thermography method, and are presented in each primary research methodology sections, there were also a number of known constraints and controls, which were common throughout each of the case study inspections. These included:

- Variable weather conditions
- Internal heating variations
- Emissivity variations
- Foreground obstructions
- Sample selection challenges

Variable weather conditions

Christensen (2006) states that one of the most challenging aspects of performing experimental research is the inability to control non-manipulable variables. Weather was one such variable throughout this research project.

Based on the understanding that climatic conditions can have a significant impact upon a thermographic survey, the careful planning of survey dates were choreographed to meet the most ideal conditions, as described in chapter 2. This often meant confirming the survey date with householders only a day or two prior to the survey occurring. Forward planning a survey date with an external client, which met the optimal weather conditions recommended for external thermographic surveys (BSi, 1999; Lo & Choi, 2004; UKTA, 2007) proved particularly challenging, as would be expected from winter weather patterns in the UK.

For all real building case studies, local weather forecasts from the Met Office (2014) were observed for at least two days leading up to the start of the survey. Experimentation periods were chosen that minimised the likely presence of clear skies, precipitation and wind, and which had an external temperature that remained at least 10°K lower than internal air temperatures. If the conditions were forecast to not comply with recommendations set out by the UKTA (2007) and the British Standard for qualitative thermography (BSi, 1999) then the survey was postponed or cancelled. Householders were informed of the change in dates and again reminded of their right to withdraw should the new date no longer suit them. The purpose of this exercise was to ensure a period of relative uniformity in climatic conditions prior to the survey in order to have the least impact on materials and camera interference.

During all surveys, a weather decision methodology checklist was used, which enabled the thermographer to note important information such as weather conditions, air temperatures and thermal image cross-referencing with sketches/photos. An example of the methodology checklist can be viewed in appendix E. If upon starting the survey or during the survey, conditions did not comply with the weather forecast changed and did not comply with the weather decision methodology checklist, a note on the specific nature of the conditions would be made so that this could be factored into the analysis.

In addition to monitoring weather forecasts, atmospheric conditions were also monitored and recorded prior to and during each survey using a weather station. Conditions monitored using this equipment included air temperatures and wind speeds. Visual inspections and notes were made on the extent of cloud cover, which was the most challenging condition to monitor during all of the surveys.

Internal heating variations

While communicating (email & phone calls) with the householders to confirm survey details etc., a request was also made for them to turn their main heating supply on for at least two hours prior to, and left on during, the survey (Titman, 2001). This would ensure the presence of a suitable thermal gradient between inside and outside, and would make potential defects more apparent. Whilst many of the householders complied with this request, there were some who did not. This was particularly problematic to ascertain during the walk-past thermography surveys, since the internal air temperatures were unknown due to the lack of dwelling access.

Emissivity variations

For all experiment and case study investigations, emissivity values were measured in-situ using the emissivity measurement procedure set out by ITC (2006) and detailed in appendix C. Unless specific materials were being observed (such as during the quantitative time-lapse inspections), the emissivity value for the most predominant material in the FOV was obtained. Once the emissivity value had been measured, this was inputted in the camera settings so that the thermal camera could compensate for these apparent surface temperature variations.

Foreground obstructions

When conducting all thermographic surveys on the case study dwellings, it was common to find foreground objects obscuring parts of a construction. Objects such as trees, bushes and cars presented external problems, while internally, furniture (sofas and televisions, etc.), curtains and pictures frequently concealed parts of the building. It was rarely practical for case study residents to remove obstructive objects six hours prior to a survey as recommended by FLIR (2011a). During the walk-through inspections, obstructions could sometimes be dealt with by using different angles to view concealed elements, though during the walk-past and time-lapse surveys, where a more fixed view was used, it was not always possible to avoid the obstruction (particularly if the obstruction was fixed, such as a bush). This meant that foreground obstructions were recognised as an unavoidable limitation and consequently some defects present in the case study dwellings might have been missed.

Sample selection for case study dwellings

Case studies comprise of relatively small samples, which help provide insights into how the larger total of cases might perform. Difficulties however arise in the quantity and quality of the selected cases. Gerring (2007) discussed this problem highlighting the inevitable limitations that would be experienced from sampling five randomised cases from a total of 1000, which could lead to an unrepresentative view. Relating this to the total number of dwellings in England, which is 22.4 million. Even sampling a relatively small portion of these at 0.1% (22,400) would result in too great a number of dwellings to survey for the time scale of this project.

A rationale was developed to address this limitation. Because the focus area of this research project revolved around Cornwall, with the researchers residing in the South West of England, it was decided that the case study dwellings should be representative of a South West England vernacular. Furthermore, existing/non-new dwellings were targeted in anticipation that they would present a higher likelihood of defects compared with new dwellings. The specific criteria and methodologies used for selecting the case study dwellings is presented in greater detail within each case study research chapter.

The total number of dwellings that were surveyed for each building case study comprised of:

- Walk-past methodology – 77 dwellings
- Walk-through methodology – 45 dwellings
- Time-lapse methodology – 3 dwellings (4 different constructions)

The quantity of samples for each case study reflects the speed of survey, where the walk-past methodology was the fastest and time-lapse, the slowest. These quantities were also dependant on two factors. Firstly, they were dependant on the number of participants providing access to their dwellings. Secondly, the number of dwellings was dependant on the quantity of dwellings that could be practically surveyed during one evening. This last factor relied upon coordination with participants and weather constraints (in particular to the cold season), which again limited the sample size.

Creswell and Plano Clark (2011) discussed differences in sample size as a known limitation, particularly when conducting cross case study comparisons. They explained that whilst some case studies might focus on generalisation (such as walk-past and walk-through), others would hold a more in-depth focus (time-lapse).

Such differences in sample size between the case studies in this research project came about due to the time-scales involved with arranging / setting up and performing the thermography activity.

Due to the small time-lapse survey sample size, it was deemed unlikely that results would accurately represent the conditions in all dwellings. However, the aim of this research was not to pinpoint common defects in each building type, but to examine the validity of the thermography methodologies for improved defect detection. Therefore, a small sample size for time-lapse thermography was not judged as prohibitive, since the aim and objectives were adequately proved from this sample set (Yin, 2004).

For each methodology, convenience sampling was used for case study selection. Although this strategy of sampling is viewed by some as lacking purpose and leading to result bias (Lewis, 2003; Neergaard & Ulhøi, 2007), when sampling buildings, the challenge is gaining direct access. Therefore, dwellings were chosen that were in Devon or Cornwall, close to the author. Through convenience sampling, it may be easy to select the most convenient case study to inspect. However care was taken use theoretical sampling (Eisenhardt, 1989), where cases were chosen based on their theoretical interest. For example, buildings with known construction types or defects were preferred to modern constructions. Nevertheless, careful convenience sampling ensured that a cross section of different property constructions and periods were sampled.

Theoretical sampling was particularly important for the time-lapse case studies, since few cases could be investigated during this project. This called for extreme cases to be studied, thus presenting the greatest opportunity for valuable results (Eisenhardt, 1989; Flyvbjerg, 2006).

There were three key processes used for sourcing cases studies via convenience sampling.

- One process involved making contact with business partners and academic colleagues as a first step. These actors served as gatekeepers to a pool of potential case studies, and helped to provide access to these. In discussion with the gatekeepers, the most suitable potential case studies were selected based on the convenience sampling criteria described above. Once this process narrowed the possible case study dwellings, direct contact was made with the residents to seek their consent for the survey.

- The second process comprised of selecting suitable residential areas (based on the selection criteria) that were in close proximity to the author and consent from residents sought accordingly. Ease of access was deemed a key factor due to the need to inspect dwellings very late at night. This factor also made it easier to interact with consenting residents on very short notice periods (one day). This was particular useful when making quick decisions on surveying dates and times to fit with optimal weather forecasts.

- The third method of convenience sampling specifically related to time-lapse thermography. This involved making contact with close members of the project team to identify suitable dwellings (in accordance with the convenience selection criteria) that could be inspected for prolonged periods of time. Because of the intrusive nature of this methodology, where by extended access was required internally and externally, case study participants were selected based on their understanding of the restrictions imposed on their dwelling during the survey period.

4.4 Common methodology mechanisms

Common mechanisms used throughout the primary research thermography surveys included standard equipment (thermal cameras and weather station) and the use of visual analysis to assess the thermal images. Other mechanisms (such as heat flux sensor equipment and quantitative analysis methods etc.) were used in some of the specific experiments/case studies and further information these can be found under the methodology section at the start of each primary research chapter/part.

Visual Analysis

Photography and video are recognised methodological techniques that have been previously employed by researchers, often within the field of qualitative social science. Applications tend to include either gathering and analysing visual data or presenting visual data to others for responsive feedback (Schwartz, 1989).

Whilst there are other analysis tools which can gather and present heat flow data for a particular point on a building, such as heat flux sensors and thermal probes, what thermography offers is the ability to visualise this heat flow data over multiple points that form a discernable picture of a given view. This appears very similar to that of a photograph of the same scene. In a world where human interaction is often predominantly visual, this therefore opens up opportunities for whole-image analysis where data can be gathered, analysed and presented to others.

Thermograms were used as singular still images and as part of time-lapse video sequences. With reference to video in research, Haw and Hadfield (2011) explain the advantages as being able to:

- Capture a transient process, which can then be isolated from its context;
- Repeat, speed-up and slow-down footage for more detailed analysis;
- Magnify particular aspects of detail;
- Enlighten the researchers understanding of a particular issue.

Analysing the visual thermographic data is of paramount importance to this project, and is seen as one of the most challenging aspects as suggested by Heath *et al.* (2010). This supports literature in chapter 2, which suggests that image interpretation is regarded as one of the most difficult aspects of thermographic analysis.

Equipment

Common equipment used throughout all experiment and case study investigations included the thermal camera and a weather station.

Thermal cameras

Two thermal cameras were used for the experiment and case study inspections throughout the primary research chapters. These were a FLIR T620bx and a FLIR S65. Technical specifications for these cameras can be found in appendix B.

These cameras were selected as top-of-the-range models at the time of their purchase. The use of these cameras was based primarily upon their availability at the time of each research project, and the camera with the highest specification was always selected for use. For instance, during the hot-plate time-lapse experiment (Chapter 6 Part 1), only the FLIR S65 thermal camera was available. The higher specification FLIR T620bx thermal camera was purchased after this experiment and used on all subsequent projects.

The significance of the specification difference between the two cameras can be observed from their technical specifications listed in appendix B. The FLIR T620bx thermal camera had both improved/lower spatial resolution (IFOV) and thermal sensitivity (NETD) when compared with the FLIR S65 thermal camera. The T620bx also had a greater number of sensor pixels than the S65:

- T620bx. 640x480 pixels. IFOV = 0.69 mrad. & NETD = <40 mK at +30°C
- S65. 320x240 pixels. IFOV = 1.3 mrad. & NETD = 80 mK at 30° C

Therefore, it can be said that each individual pixel contained on the FLIR T620bx image sensor was able to detect lower temperatures and much smaller details than the S65, and the T620 had more of these pixels than the S65.

Both thermal cameras received an annual calibration check, to ensure that they were still accurately calibrated in accordance with the manufacturers limits.

Because all thermal camera sensors can take time to adjust to the atmospheric conditions of their surroundings, images taken before acclimatisation can be adversely affected (incorrect temperature measurements). To ensure that early images were not adversely effected by this event, the camera was switched on and left for 30 minutes to acclimatise to the atmospheric conditions before commencing the survey (Vollmer & Möllmann, 2010).

Another limitation inherent within the thermal camera technology is self-parasitic radiation. Bursell (2007) discusses the fact that radiated heat from the camera itself, and could have an impact on the ability of the camera to detect targets accurately.

Weather station

A WH1080 wireless weather station was used to assess internal and external climatic conditions prior to and during each of the case study investigations. This included measurement of internal & external air temperatures, wind speeds and presence of precipitation.

4.5 Research Ethics

Whenever conducting research involving human subjects, there is a requirement for ethical consideration and approval of the research methodology. Although the research in this thesis does not directly study the behaviour of human applicants, ethical consideration was required due to the investigation of property belonging to strangers.

An ethical plan was prepared in accordance with the guidelines set out by Plymouth University (Plymouth University). The accepted ethical plan can be reviewed in appendix H. Figure 32 presents an overview of the ethical principles used by this project.

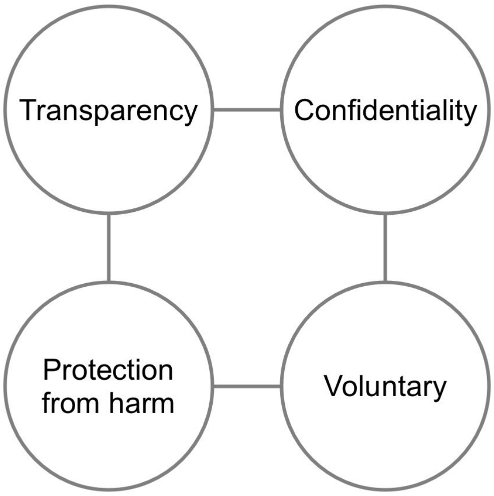


Figure 32. Key ethical principle diagram.

Transparency. It is essential that the purpose and methodology any research activity is made clear to potential participants. For each case study, all potential participants were contacted via letter, email or telephone to explain the research project before undertaking the activity. As part of this, the participant’s rights as part of the research process was explained (Creswell, 2003) include the right of the participant to withdraw at any point before or after the survey (within a cooling off period). All participation was *voluntary* and this was stressed/reaffirmed with participants at each stage of communication.

Confidentiality is the act of ensuring participant privacy, whereby any information held by the researcher on a particular dwelling is withheld from others. It was important to reassure potential participants of their confidentiality before they consent to the research (Gray, 2004). Due to the nature of this project, participant 'anonymity' (Bell, 2005) to the researcher was not possible given the need to physically visit each dwelling and in some cases meet with residents. All information referring to dwelling locations and names of owners/residents has been removed to anonymise the data should other researchers use this in the future.

Protection from harm. On the whole, this project was deemed to be a low risk to participant health (physical or psychological means (Drew, Hardman & Hosp, 2008; Plymouth University, 2013)), however certain aspects needed to be considered. With regards to physical harm, only the time-lapse thermography survey presented potential risks, such as loose power cables etc. All participants were made aware of such risks and avoided areas where the equipment was left.

Using a camera at night and within areas of the public realm presented a risk of psychological harm. This was to participants and the wider public, who might have unexpectedly encountered a thermographer with a camera at night. To mitigate this issue, participants were informed of the survey date and time. They were also told who would be visiting their house and that they would be carrying an ID card. In addition, high-visibility jackets were worn, so that members of the public might feel less anxious about their presence.

Conducting a thermographic survey of a stranger's property at night carries a potential risk of harm to the researcher (Lewis, 2003). Whilst this risk cannot be completely eliminated, it was minimised by:

- Ensuring that more than one person attended each survey.
- Informing someone else of the research time and location.
- Reviewing the survey area during daylight.

If at any point researchers felt at risk during a survey, the activity was ended instantly.

5.0 Walk-Through Thermography

Comprehensive secondary research described within chapter 3 found that the most commonly used building thermography methodologies practiced in commercial and academic fields were the walk-through and walk-around methodologies, collectively termed as traditional thermography methodologies.

It is important to gain direct experience of traditional thermography as a survey methodology before considering its limitations and ways in which new methodologies could improve upon the traditional approach. It would be remiss for a research project to rely solely upon documented commentary, reporting on research / examples that utilised traditional thermography.

Chapter 3 explained that a walk-around survey comprises of an external only survey (Red Current, 2012a), where the thermographer inspects all external surfaces of a building. A walk-through survey, however, includes the addition of an internal inspection (Pearson, 2011). Since the walk-through survey is a more comprehensive version of traditional thermography, this methodology has been selected as the focus for this chapter, as set out under **objective 3**.

5.1 Detailed Methodology

Despite the ubiquitous use of traditional thermography, very few literature sources specifically outline the methodological procedure for conducting a traditional walk-through thermographic survey. Consequently, this chapter seeks to establish a robust methodology, which draws upon past literature and first-hand experience.

As described in chapter 3, traditional thermography is often conducted using qualitative analysis methods. In line with this finding, the work in this chapter assesses the case study dwellings using qualitative thermography.

5.1.1 Structure of the case studies

All of the case study surveys in this chapter were undertaken by the author of this thesis as part of a separate large-scale thermographic survey in Cornwall. This project was called ‘Thermal Imaging Cornwall 2013’ (Cornwall Together, 2013; Goodhew *et al.*, 2013) and formed part of the broader “Cornwall Together Phase 2” project, which was funded jointly by the Eden Project and the DECC (Department of Energy & Climate Change). The objective of this separate project was to understand how thermal images can be best used to communicate energy issues to residents and how these might influence decisions on home improvements. This research used the thermal images in structured interviews (carried out by others) to gauge resident opinions. For further information on this separate project, please refer to Goodhew *et al.* (2013). For this separate research project, walk-through thermography surveys of 220 Cornish dwellings were carried out between February and March 2013.

As a qualified thermographer, the author of this thesis was invited to assist with training other members of the thermography team for this project and to undertake some of the surveys. In order to survey all 220 dwellings in a short space of time (two months) and under optimal weather conditions, a team approximately 8 thermographers were used to inspect the dwellings. As one of two members of the thermography team with formal thermography training (Level 2), the author of this thesis personally surveyed 45 of the 220 dwellings during this separate project.

Although being granted permission to include all of the 220 dwelling surveys in this thesis, only the 45 dwellings personally inspected by the author of this thesis have been included in this chapter. None of the images or data obtained by others has been included in this thesis. This is important because it was not always easy to determine whether a captured hot or cold spot (in an image) was portraying a potential building defect or something else, such as reflected radiation (emissivity issue). Also it is not easy to determine what influences are in effect on a building just from looking at one zoomed in thermal image of a portion of the construction. This acknowledged absence of quality control amongst other's images dictated the necessity to only include the 45 dwellings inspected by the author.

Each of the 45 dwelling surveys were collected during ten survey evening sessions that were conducted between February and March in 2013. Becoming involved with this separate project aided the research in this thesis by granting access to a large number of dwellings in a very short space of time.

Although the 45 dwelling surveys (undertaken by the author of this thesis) contributed to a separate project, it is important to stress that the results from this work was ultimately used for other completely different scientific purpose, and that none of the research contained in this chapter has been published elsewhere.

5.1.2 Case study selection

The selection process for the case study dwellings comprised of inviting members of the public to sign up for free thermal imaging of their homes. Within a couple of days 1001 householders had registered interest in this (Goodhew *et al.*, 2013). Each of the 1001 applicants were randomised and out of these 220 dwellings were selected for thermal imaging. These dwellings were then grouped together into regional areas so that multiple dwelling surveys could be conducted in a single evening. Areas included: Truro, Callington, St Austell, Camborne, Saltash, Looe, Launceston and Penzance. Figure 33 shows a map of the locations surveyed as part of this research. The author of this thesis undertook 45 randomised dwelling surveys (in each of the study areas shown on the map) from the overall collection of 220 dwelling surveys.

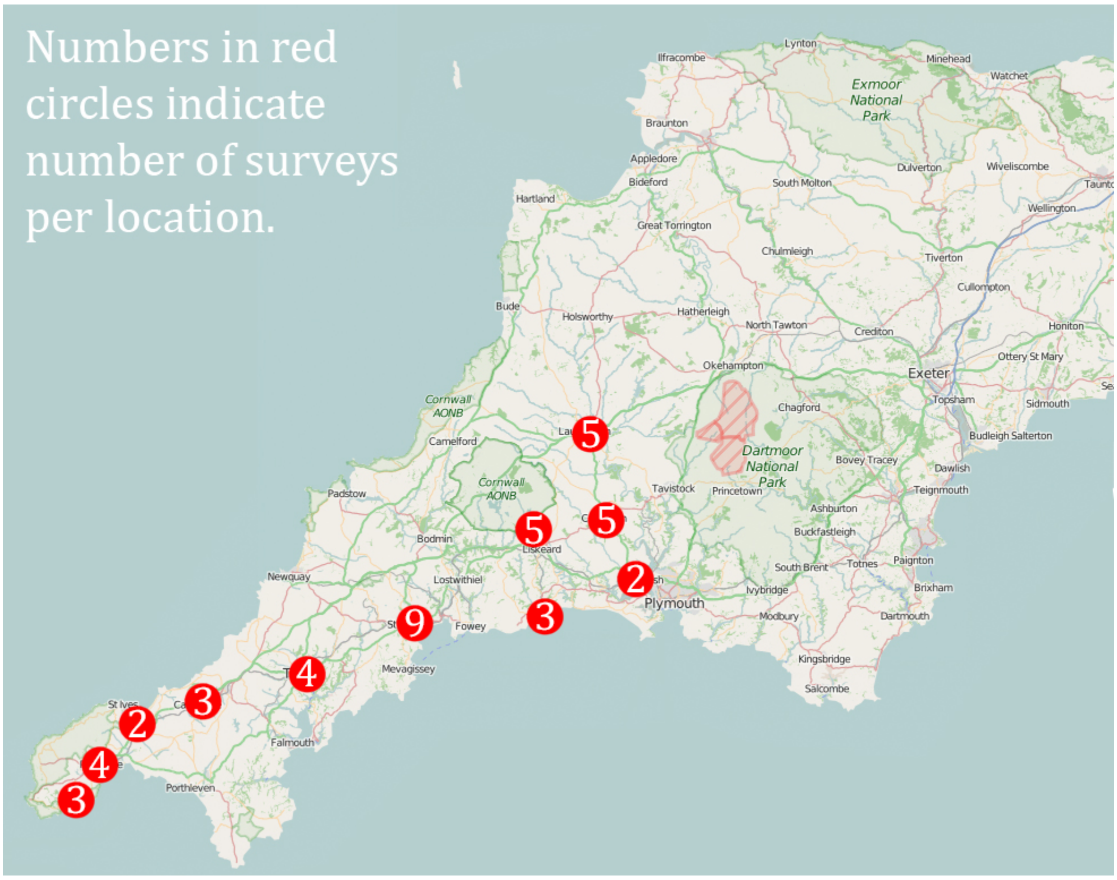


Figure 33. Walk-through methodology case study location map

Of the 45 dwellings surveyed, a cross-sectional selection of typical Cornish vernacular dwellings was included. Characteristics comprised of:

- Solid masonry, cavity wall, system built constructions;
- 75 % of the dwellings inspected were constructed within the past 100 years, with 25% constructed prior to 1919;
- Detached, semi-detached, terraced and bungalow dwellings;
- Owner occupied and tenanted dwellings;
- A mixture of single and double glazed dwellings;
- Some dwellings with cavity fill insulation;
- Between 1 and 3 storey height dwellings.

5.1.3 Data collection

Three key sources propose methodologies for traditional thermographic inspections. These are by the American Society for Testing and Materials (ASTM) (1997), the Residential Energy Services Network (RESNET) (2012) and British Standard BS EN 13187:1999 (1999). The procedures advocated in these three sources describe thermographic data collection, which includes scanning both internal and external building surfaces for potential defects and recording images of any perceived anomalies. The methodology used for the walk-through surveys in this research project followed the principles established by these three key sources and is described in appendix F.

On average, each survey took approximately 40 - 60 minutes to complete. Internal inspections took the most time to conduct, comprising on average of ¾ (75%) of the total survey time to complete compared with external inspections.

5.1.4 Methods of analysis and reporting

As mentioned earlier, the applicants for the original *Thermal Imaging Cornwall 2013* project were encouraged to participate by the offer of free thermal imaging. This meant that images needed to be analysed, and reports prepared, an important part of a traditional thermographic survey.

To begin with, the thermal images from each case study dwelling were reviewed. These were uploaded into the FLIR tools software (2013b), which enabled further image analysis through thermal tuning adjustments where necessary. This ensured that the temperature span was suitably spread over the entire range of temperatures that were being detected from the dwelling only (not including background items such as the sky or foliage) by the camera. Once the images had been prepared, these were inserted into a report. All thermal images contained a scale bar for temperature reference. To avoid liability issues due to potentially incorrect defect detection, no advice was given to participants on the thermal images shown in the report. To show the location of the thermal images, a photo or sketch was inserted adjacent to them.

Further image analysis was undertaken to address the objectives of this thesis. Each of the 45 case study dwellings had their basic information collated into a table. Table 2 shows the template for this. The data included: date of survey, air temperature, weather conditions recorded and property information.

Reference		Air temperatures			Conditions			Property information					
Date of survey	Case study ID	EXT (°C)	IN (°C)	ΔT (°C)	Rain	Cloud cover	Strong Wind	Age	Dwelling type	Tenure	Wall build-up	Cavity fill	Glazing type
28/03/13	A28	4.5	21.2	16.7	No	Yes	No	Post 1990	Detached	Owner	Cavity	Yes	Double
28/03/13	A29	4.9	20.1	15.2	No	Yes	No	Pre 1919	Detached	Owner	Solid	?	?
20/02/13	A30	6	22	16	No	Yes	Yes	1981 - 1990	Detached	Owner	Cavity	Yes	Double
19/03/13	A31	3.4	20	16.6	No	Yes	No	1981 - 1990	Detached	Owner	Cavity	Yes	Single
19/03/13	A32	4.1	21.1	17	No	Yes	No	1981 - 1990	Detached	Owner	Cavity	Yes	Single

Table 2. Case study dwelling basic information.

Next, each dwelling had its thermal images reviewed to determine what defects had been identified during the survey. As discussed in chapter 2, image interpretation is one of the most challenging aspects of thermal image analysis. To minimise the risk of misinterpreting defects, two level 2 qualified thermographers (BINDT, 2009) reviewed the case study thermal images and discussed the likely defect portrayed. Despite this rigour, image analysis remained a source for potential inaccuracies. The protocol adopted for categorising defect types, used the commonly accepted pattern characteristics set out in chapter 3, which lists descriptions of the pattern each defect most commonly displays:

- Ventilation losses – Fanning and uneven temperature gradients
- Conductivity losses – Defined patches of temperature variation
- Moisture related defects - mottled patchy temperature variations

Once the type of defects present in each case study had been determined, this data was inputted to a table, which charted defect occurrence per dwelling. Table 3 shows the template listing the defect types. When a defect type was detected at least once in a case study dwelling, this observation was marked in Table 3.

Defect type

Ventilation defect (door)		Ventilation defect (window)		Ventilation defect (structure)		Conductivity defect (door)		Conductivity defect (window)		Conductivity defect (roof)		Conductivity defect (wall)		Hidden services		Moisture Penetrative		Moisture Condensation / damp	
IN	EXT	IN	EXT	IN	EXT	IN	EXT	IN	EXT	IN	EXT	IN	EXT	IN	EXT	IN	EXT	IN	EXT
Yes		Yes					Yes			Yes		Yes	Yes	Yes					
Yes		Yes								Yes		Yes							
		Yes	Yes	Yes						Yes									
Yes	Yes					Yes	Yes	Yes	Yes	Yes		Yes	Yes						
Yes	Yes						Yes	Yes	Yes	Yes		Yes	Yes					Yes	

Table 3. Table template for counting the defect occurrence during each case study.

For each dwelling only one mark was given for each observed defect occurrence. This was irrespective of how many defects of this type were actually present in that dwelling since the objective of this research project was to determine the ability of this method to detect defects and identify their type.

5.1.5 Experimental conditions and mechanisms

A number of conditions and mechanisms were key to the walk-through case studies. These included:

- A FLIR T620bx thermal camera was used.
- Internal and external climatic conditions were monitored before and during the survey.
    - There was at least a 10-degree temperature difference between internal and external air temperatures in all dwellings.
- Material emissivities were measured and set in the thermal camera at the time of the survey
- Foreground obstructions were minimised where possible. Multiple viewing angles were used to look around obstructions, which also enabled a better understanding of potential defects to be made.

Further information on these conditions and mechanisms has been reported on in chapter 4.

5.1.6 Ethics

It was recognised that some of the randomly selected householder participants would be from vulnerable groups, defined as having specific learning difficulties or experiencing fuel poverty. Extra care was made to contact such vulnerable participants to explain the purpose of the research before visiting (Drew, Hardman & Hosp, 2008), their rights to consent and withdrawal, and to appreciate any sensitive issues that they might have. For example if visiting a dwelling occupied by a disabled person, the survey approach might need adjusting to accommodate their needs. Providing free thermal imaging to households experiencing fuel poverty provided an opportunity to potentially contribute towards bringing those participants out of fuel poverty (Drew, Hardman & Hosp, 2008; Orb, Eisenhauer & Wynaden, 2001) by discovering/showing areas of potential (unacceptable) heat loss, which could be further inspected using other more targeted inspection methods (such as destructive visual inspection) and then repaired, thereby reducing fuel needs.

To minimise any perceived threat to participant householders, contact was made prior to the survey, which along with an approximate time of survey, and a reminder of the householders right to withdraw, provided details on the thermographers who would be visiting them that evening. When contacting householders via email, photographs of the thermography team were included, so that participants knew who to expect that evening.

On the evening of the thermography surveys, a team of two visited each case study dwelling. They wore high visibility jackets, which displayed the name of the project

(Cornwall Together) and carried photo ID cards, which could be used to reassure participants of their legitimacy. As discussed earlier, prior to and immediately after each case study survey, the thermography team texted or phoned a contact based in Plymouth, so that someone was aware of team locations and could raise a safety alarm should a team not respond by a certain time.

After sending the householder thermography reports, all data relating to the householders' addresses, names and contact numbers were removed so that the case studies could be anonymised.

5.2 Results

5.2.1 Demographic results

Initial result analysis focused on the demographics of the 45 dwellings, which had been surveyed. This analysis proved particularly significant, since exactly one half (Figure 34) had been constructed after the introduction of the first national UK building regulations in 1966 (Killip, 2005), whilst approximately one third were constructed after the overhauled building regulations under the Building Act 1984 (Building Act, 1984). Although not entirely representative of the Cornish housing demographic, these results did compare with the English housing stock profile (DCLG, 2014a) illustrated in chapter 1, which suggested that 71% of English dwellings were constructed before 1980. Demographics for this research showed 66% of dwellings constructed prior to 1980. Lowe & Bell (1998) explain the historical development of the building regulations with regards to fabric U-values, indicating that wall U-values in 1976 started at 1.0W/m^{2}K and improved to 0.45W/m^{2}K by 1990. As of 2013, wall U-values for new dwellings are 0.18W/m^{2}K (DCLG, 2014b). This gradual lowering of target U-value illustrates how building standards have improved significantly over the years, as the UK seeks to minimise carbon emissions. Therefore older dwellings', in particular those built before the 1990's (12% of the dwellings inspected), U-value standards will likely show signs of increased heat loss due to lower standards in thermal insulation and could therefore compound fuel poverty issues.

Furthermore, this initial study closely matched data on the Cornish housing profile, which stated that 28% of dwellings were constructed prior to 1919 (Sleeman, 2010).

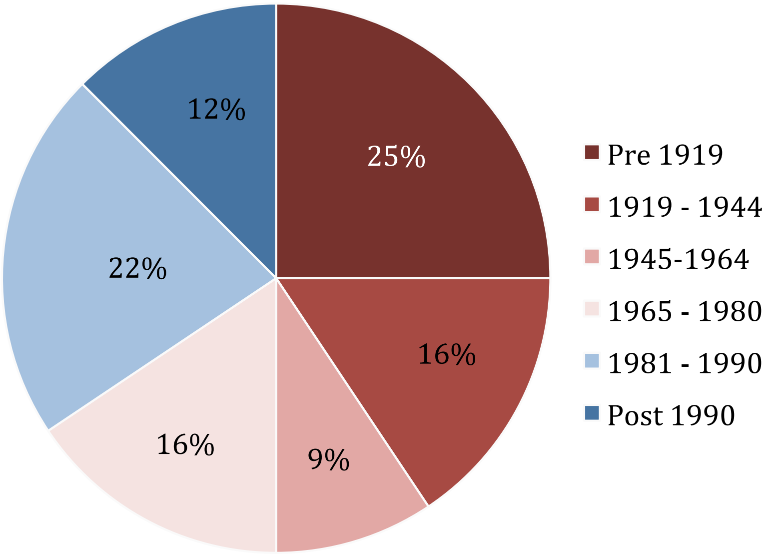


Figure 34. Demographic percentage of dwellings ages by period.

By mirroring national figures on dwelling periods, the results from Figure 34 suggested that a good cross section of dwellings had been inspected using this methodology.

Comparing methods of construction, 54% of all dwellings surveyed comprised of cavity wall construction, while 41% had a solid wall construction. All of the dwellings constructed pre 1919 had solid wall construction. Also, the occurrences of moisture defect were more prevalent in solid wall constructions (71%) compared with those with a cavity wall (40%).

Observing the thermal conductivity of dwellings by period found that 93% of dwellings constructed prior to the 1984 Building Act showed one or more thermal conductivity defects within an external wall, while this figure dropped to 75% for dwellings constructed between 1981 and 1990, and to 70% for those built after 1990, highlighting the impact that improved building regulations (in particular part L) have had on construction.

Further analysis was undertaken to compare glazing defects within dwellings. 48% of dwellings had double-glazing, with 37% only having single glazing, which would be a likely source of heat loss. On further investigation this assertion was supported; 88% of dwellings with single glazing showed signs of excessive heat loss from windows. These compared poorly with double glazed dwellings, of which only 46% of showed excessive window conductivity losses. This correlates with what would be expected between single and double-glazing.

All of the case study dwellings' potential building defects were counted to help identify the type of defects that a walk-through methodology could detect. The results of this exercise can be observed through table 4.

Reference		Air temperatures			Conditions			Property information						Defect type																			
Date of survey	Case study ID	EXT (°C)	IN (°C)	ΔT (°C)	Rain	Cloud cover	Strong Wind	Age	Dwelling type	Tenure	Wall build-up	Cavity fill	Glazing type	Ventilation defect (door)		Ventilation defect (window)		Ventilation defect (structure)		Conductivity defect (door)		Conductivity defect (window)		Conductivity defect (roof)		Conductivity defect (wall)		Hidden services		Moisture Penetrative		Moisture Condensation / damp	
														IN	EXT	IN	EXT	IN	EXT	IN	EXT	IN	EXT	IN	EXT	IN	EXT	IN	EXT	IN	EXT	IN	EXT
12/02/13	A1	3	15.3	12.3	Yes	Yes	No	Post 1990	Detached	Owner	Cavity	?	Double	Yes		Yes		Yes						Yes		Yes	Yes	Yes		Yes		Yes	
12/02/13	A2	3.5	22.3	18.8	No	Yes	No	Post 1990	Terraced	Owner	Cavity	?	Double	Yes		Yes								Yes		Yes	Yes						
12/02/13	A3	0.9	21.3	20.4	Yes	Yes	No	Post 1990	Terraced	Owner	Cavity	?	Double	Yes		Yes		Yes						Yes	Yes			Yes				Yes	
12/02/13	A4	2.8	17.7	14.9	No	Yes	No	1965 - 1980	Terraced	Owner	Cavity	Yes	Double	Yes			Yes							Yes		Yes	Yes	Yes				Yes	
27/03/13	A5	1.7	20.5	18.8	No	No	No	Pre 1919	Terraced	Owner	Solid	No	Single	Yes		Yes	Yes				Yes		Yes	Yes									
26/03/13	A6	0.7	22.6	21.9	No	Yes	No	1981 - 1990	Bungalow	Owner	Cavity	Yes	Double	Yes		Yes				Yes	Yes	Yes	Yes	Yes	Yes	Yes							
13/03/13	A7	2.7	22.1	19.4	No	No	No	1945-1964	Detached	Owner	Cavity	Yes	Double	Yes	Yes			Yes			Yes	Yes	Yes	Yes									
27/03/13	A8	2.8	17.1	14.3	No	Yes	No	Pre 1919	Semi detached	Owner	Solid	No	Single			Yes				Yes	Yes	Yes	Yes	Yes		Yes						Yes	
19/03/13	A9	2.8	20.9	18.1	No	Yes	No	Post 1990	Detached	Owner	Cavity	Yes	Single	Yes	Yes	Yes						Yes	Yes	Yes		Yes		Yes				Yes	
26/03/13	A10	-1.3	13.3	14.6	No	Yes	No	Post 1990	Detached	Owner	Cavity	Yes	Double	Yes		Yes				Yes	Yes		Yes	Yes		Yes		Yes					
20/02/13	A11	4.5	17.1	12.6	No	Yes	Yes	1965 - 1980	Bungalow	Owner	Cavity	No	Double							Yes	Yes		Yes	Yes	Yes	Yes	Yes					Yes	
20/03/13	A12	3.8	18.1	14.3	No	Yes	No	Post 1990	Detached	Owner	Cavity	?	Single	Yes	Yes	Yes					Yes			Yes									
25/02/13	A13	2.7	20	17.3	No	Yes	No	1945-1964	Semi detached	Owner	Cavity	Yes	Single	Yes				Yes		Yes			Yes	Yes	Yes							Yes	
25/02/13	A14	5.5	22.3	16.8	No	Yes	No	Pre 1919	Terraced	Owner	Solid	No	Single	Yes		Yes	Yes	Yes			Yes		Yes	Yes		Yes						Yes	
20/02/13	A15	4.3	17.6	13.3	No	Yes	Yes	Post 1990	Detached	Owner	Cavity	Yes	Double	Yes		Yes	Yes				Yes		Yes			Yes	Yes						
26/03/13	A16	-1.1	15.3	16.4	No	No	No	1965 - 1980	Unknown	Owner	Cavity	Yes	Double	Yes		Yes								Yes		Yes	Yes			Yes		Yes	
28/03/13	A17	2.1	20.9	18.8	No	Yes	No	1981 - 1990	Semi detached	Owner	Cavity	Yes	Double	Yes		Yes					Yes			Yes									
28/03/13	A18	2.5	19.8	17.3	No	Yes	No	1919 - 1944	Semi detached	Owner	Cavity	Yes	Single	Yes		Yes		Yes		Yes	Yes		Yes	Yes									
20/02/13	A19	6.1	18.8	12.7	No	Yes	Yes	1965 - 1980	Semi detached	Owner	Cavity	Yes	Double	Yes	Yes								Yes	Yes	Yes	Yes						Yes	
26/03/13	A20	1.1	17.4	16.3	No	Yes	No	1945-1964	Detached	Owner	Cavity	?	Double	Yes		Yes					Yes	Yes	Yes	Yes	Yes		Yes						
25/02/13	A21	4	20.8	16.8	No	Yes	No	Post 1990	Terraced	Owner	Cavity	Yes	Single	Yes		Yes	Yes				Yes		Yes	Yes					Yes				
28/03/13	A22	3.1	16.6	13.5	No	Yes	No	1945-1964	Semi detached	Local auth	Cavity	Yes	Double	Yes		Yes				Yes	Yes	Yes	Yes	Yes		Yes	Yes					Yes	
04/03/13	A23	2.7	17	14.3	No	No	No	Pre 1919	Detached	Owner	Solid	No	Double	Yes	Yes	Yes	Yes			Yes	Yes			Yes			Yes					Yes	
04/03/13	A24	3.7	18.5	14.8	No	No	No	1919 - 1944	Detached	Owner	Solid	No	Double	Yes		Yes				Yes				Yes									
27/03/13	A25	4.8	20.2	15.4	No	Yes	No	1981 - 1990	Detached	Owner	Cavity	Yes	Single	Yes		Yes		Yes		Yes	Yes	Yes	Yes	Yes	Yes		Yes						
20/02/13	A26	6.6	20.9	14.3	No	Yes	Yes	1981 - 1990	Detached	Owner	Cavity	Yes	Double				Yes				Yes		Yes				Yes						
27/03/13	A27	2.2	16.4	14.2	No	Yes	No	1919 - 1944	Semi detached	Owner	Solid	?	?	Yes		Yes				Yes	Yes	Yes	Yes	Yes		Yes	Yes			Yes		Yes	
28/03/13	A28	4.5	21.2	16.7	No	Yes	No	Post 1990	Detached	Owner	Cavity	Yes	Double	Yes		Yes					Yes			Yes		Yes	Yes	Yes					
28/03/13	A29	4.9	20.1	15.2	No	Yes	No	Pre 1919	Detached	Owner	Solid	?	?	Yes		Yes								Yes		Yes							
20/02/13	A30	6	22	16	No	Yes	Yes	1981 - 1990	Detached	Owner	Cavity	Yes	Double			Yes	Yes	Yes						Yes									
19/03/13	A31	3.4	20	16.6	No	Yes	No	1981 - 1990	Detached	Owner	Cavity	Yes	Single	Yes	Yes					Yes	Yes	Yes	Yes	Yes		Yes	Yes						
19/03/13	A32	4.1	21.1	17	No	Yes	No	1981 - 1990	Detached	Owner	Cavity	Yes	Single	Yes	Yes						Yes	Yes	Yes	Yes		Yes	Yes					Yes	
28/03/13	A33	4.8	22.5	17.7	No	No	No	1919 - 1944	Detached	Owner	Solid	?	?	Yes										Yes		Yes		Yes					
20/03/13	A34	0.8	19.1	18.3	No	Yes	No	1965 - 1980	Semi detached	Owner	Cavity	Yes	Single	Yes		Yes		Yes			Yes					Yes							
19/03/13	A35	1.2	16	14.8	No	Yes	No	Pre 1919	Detached	Owner	Solid	No	Single			Yes		Yes		Yes	Yes	Yes	Yes	Yes		Yes				Yes			
27/03/13	A36	2.6	20.3	17.7	No	Yes	No	Pre 1919	Terraced	Owner	Solid	Yes	Single	Yes						Yes	Yes	Yes	Yes	Yes		Yes	Yes					Yes	
28/03/13	A37	5.1	20.9	15.8	No	No	No	Post 1990	Detached	Owner	Cavity	?	?	Yes		Yes								Yes		Yes							
19/03/13	A38	0.4	17.8	17.4	No	Yes	No	Pre 1919	Detached	Owner	Solid	No	Single	Yes		Yes		Yes		Yes	Yes		Yes	Yes		Yes	Yes	Yes				Yes	
27/03/13	A39	1.9	18.7	16.8	No	No	No	1965 - 1980	Detached	Owner	Solid	No	Single	Yes		Yes						Yes	Yes	Yes		Yes	Yes					Yes	
13/03/13	A40	9	21.7	12.7	No	No	No	1945-1964	Detached	Owner	Cavity	Yes	Double	Yes		Yes		Yes						Yes		Yes	Yes					Yes	
13/03/13	A41	2.2	20	17.8	No	No	No	Pre 1919	Semi detached	Owner	Solid	No	Single	Yes		Yes	Yes	Yes		Yes	Yes	Yes	Yes	Yes		Yes						Yes	
20/03/13	A42	2.1	18.6	16.5	No	Yes	No	Pre 1919	Semi detached	Owner	Solid	No	Double	Yes	Yes	Yes					Yes	Yes	Yes	Yes		Yes	Yes					Yes	
13/03/13	A43	1.8	18	16.2	No	No	No	1919 - 1944	Semi detached	Owner	System	No	Double	Yes										Yes		Yes	Yes					Yes	
26/03/13	A44	-0.5	19.5	20	No	Yes	No	1965 - 1980	Detached	Owner	Cavity	?	Double	Yes		Yes	Yes				Yes			Yes	Yes		Yes						
28/03/13	A45	2.8	19.8	17	No	Yes	No	1981 - 1990	Detached	Owner	Cavity	Yes	Double	Yes		Yes		Yes		Yes	Yes	Yes	Yes	Yes		Yes						Yes	

Table 4. Complete results from all 45 case study dwellings

5.2.2 Results by defect type

Overall results from the defect counting exercise showed that 100% of the buildings inspected showed one or more thermally significant building defects. These defects can be separated into four overall groups:

- Ventilation defect
- Conductivity defect
- Moisture defect
- Service faults

Of these observed defects, the most commonly identified were ventilation and conductivity losses as illustrated in figure 35. These accounted for almost 90% of the total defects detected using a walk-through methodology.

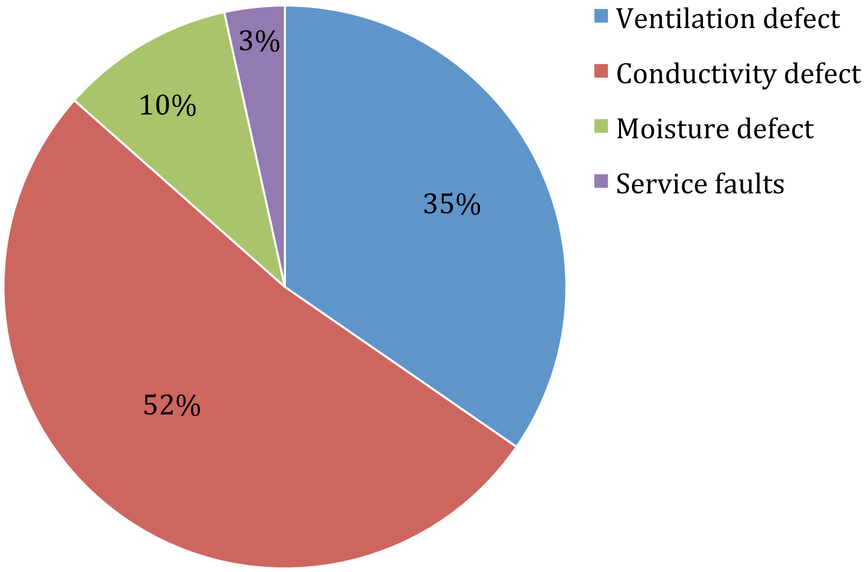


Figure 35. Proportion of thermally significant building defects (by overall defect group) detected in all case study dwellings.

After examining all of the case study thermal images, it became clear that certain patterns could be detected in defect locations. This also corresponded with the literature on defect types (chapter 3), where some defects such as ventilation losses are reported as being more commonly found around doors and windows than other areas (Nowicki, 2004). Therefore, the thermally significant defect groups were broken down into sub-categories so that a deeper investigation of the type of defect could be made. The sub-categories were:

- Ventilation defects
    - Windows
    - Doors
    - Other structural elements
- Conductivity defects
    - Windows
    - Doors
    - Walls
    - Roofs/ceiling
- Moisture defects
    - Penetrative
    - Condensation/damp
- Service faults

Example thermal images of the defect sub-categories discovered throughout these case studies can be observed in figures 36 - 42.

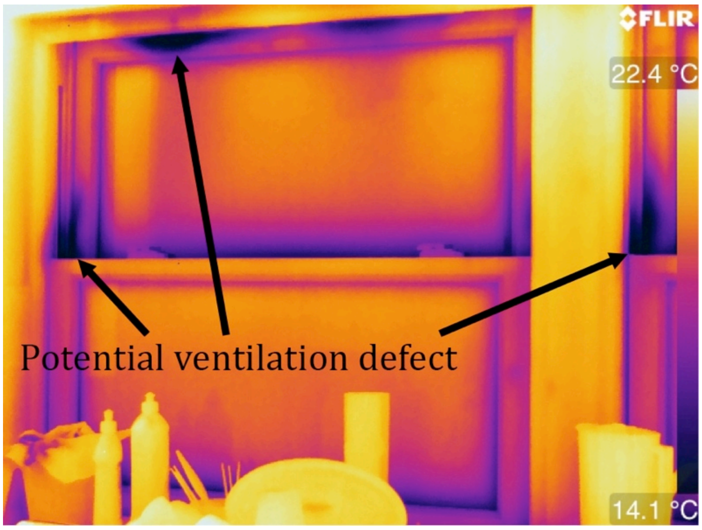


Figure 36. Potential ventilation loss around a window frame

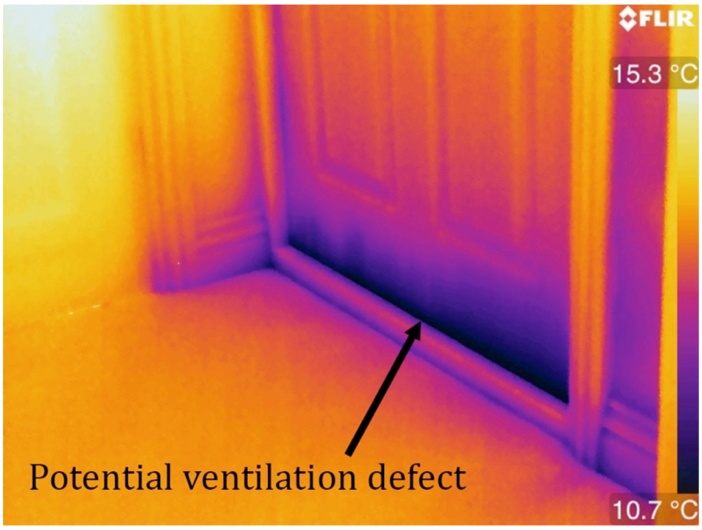


Figure 37. Potential ventilation loss under a door

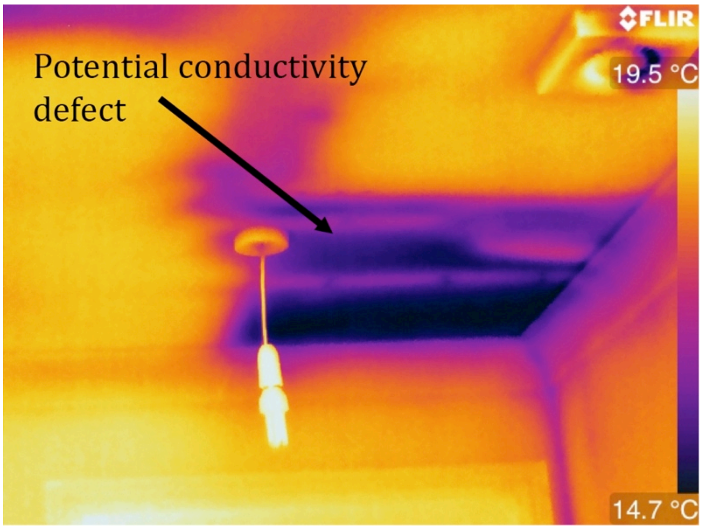


Figure 38. Potential conductivity heat loss from missing loft insulation.

Figure 39. Potential conductivity heat loss through external wall. Dotted box corresponds with figure 40 below.

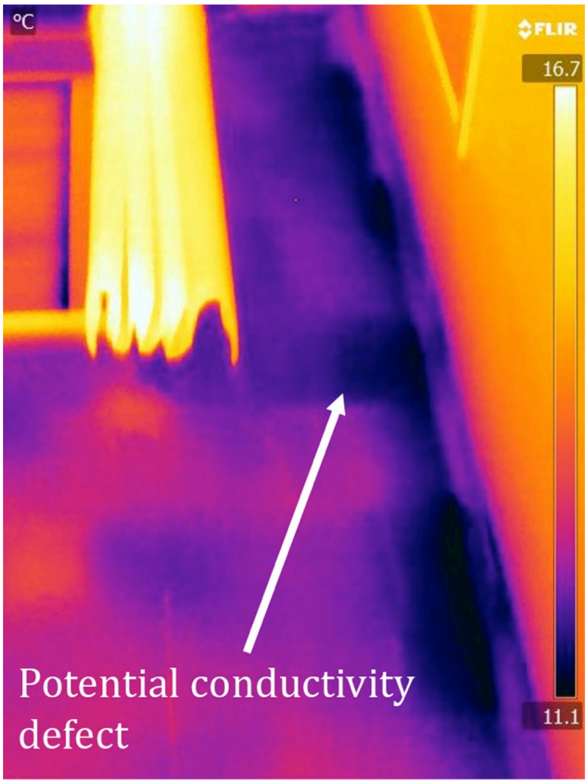


Figure 40. Internal view of figure 39. Potential conductivity heat loss.

Figure 41. Potential conductivity heat loss through external wall.

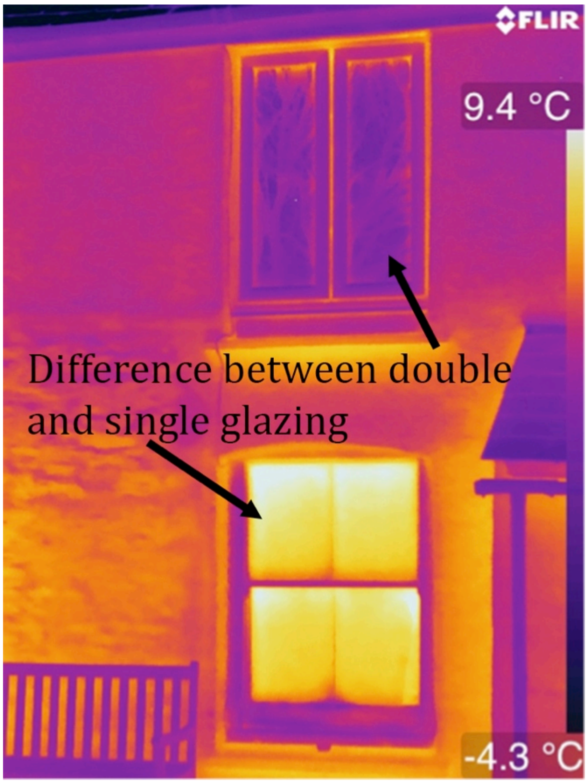


Figure 42. Illustration of conductivity differences between single and double glazed windows.

Assessing the detected defects by sub-category showed that the four most common sources of thermally significant building defect were conductivity loss through the roof (16%), ventilation loss from doors (15%), ventilation loss from windows (14%) and conduction loss through walls (14%) as illustrated in figure 43. The four least common were moisture penetration (2%), service faults (3%), ventilation losses through other parts of the structure other than the windows and doors (5%), and moisture condensation / damp defects (9%).

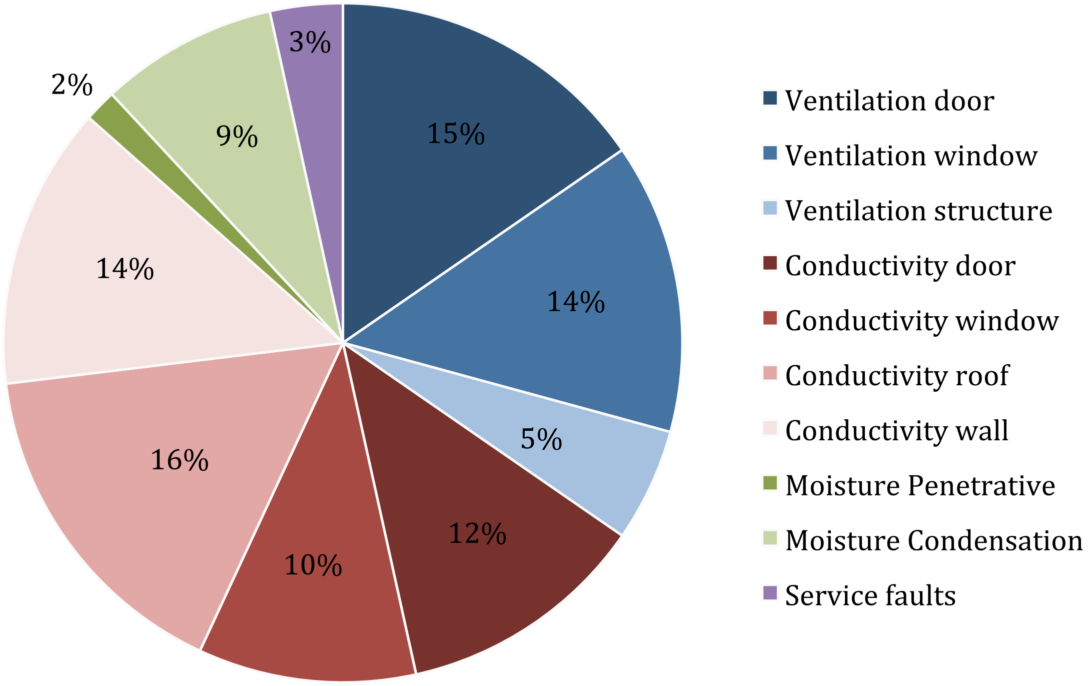


Figure 43. Proportion of thermally significant building defects (by defect sub-category) detected in all case study dwellings.

5.2.3 Results by location

Having performed external and internal thermography as part of the walk-through inspections, it was possible to further categories defects into those viewed from the outside, and those viewed from the inside. Figure 44 illustrates the percentage of dwellings where at least one potential defect was detected on either the internal, external or both surfaces of the same dwelling.

Of the 45 dwellings inspected, only 2% exhibited thermally significant defects that could be detected using external thermography alone. The only potential defects that could be detected externally were conductivity, ventilation and service anomalies/faults. Further analysis showed that 98% of all dwellings inspected presented defects that could be observed using internal thermography, while only 60% showed defects that could be detected using external thermography.

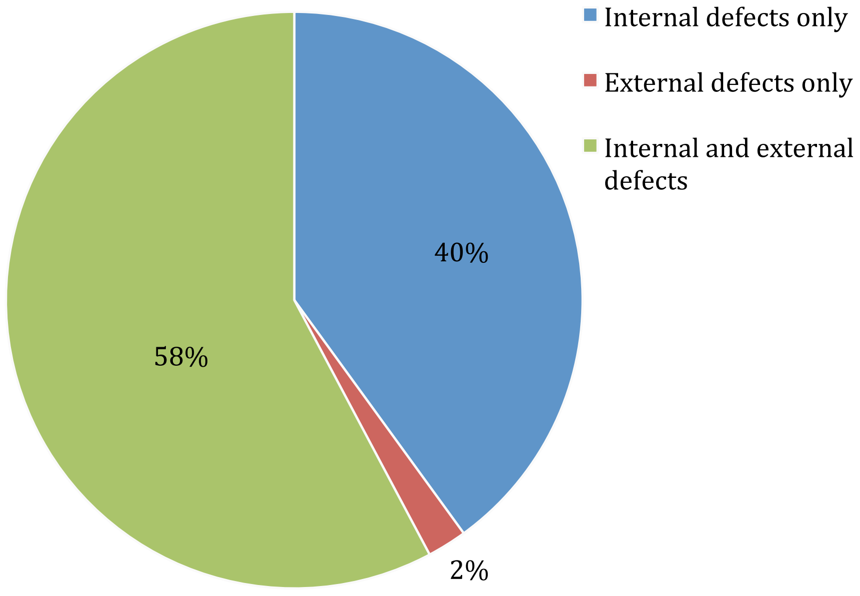


Figure 44. Location of detected defects (internally/externally).

Combining data on the location of potential defects with that of the different defect groups, figure 45 shows that for each overall group, defects were more likely to have been detected using internal thermography compared with external thermography. Other observations included noticing that conductivity defects were almost as commonly detected externally as they were internally, also there were no instances of moisture defect detection using external thermography.

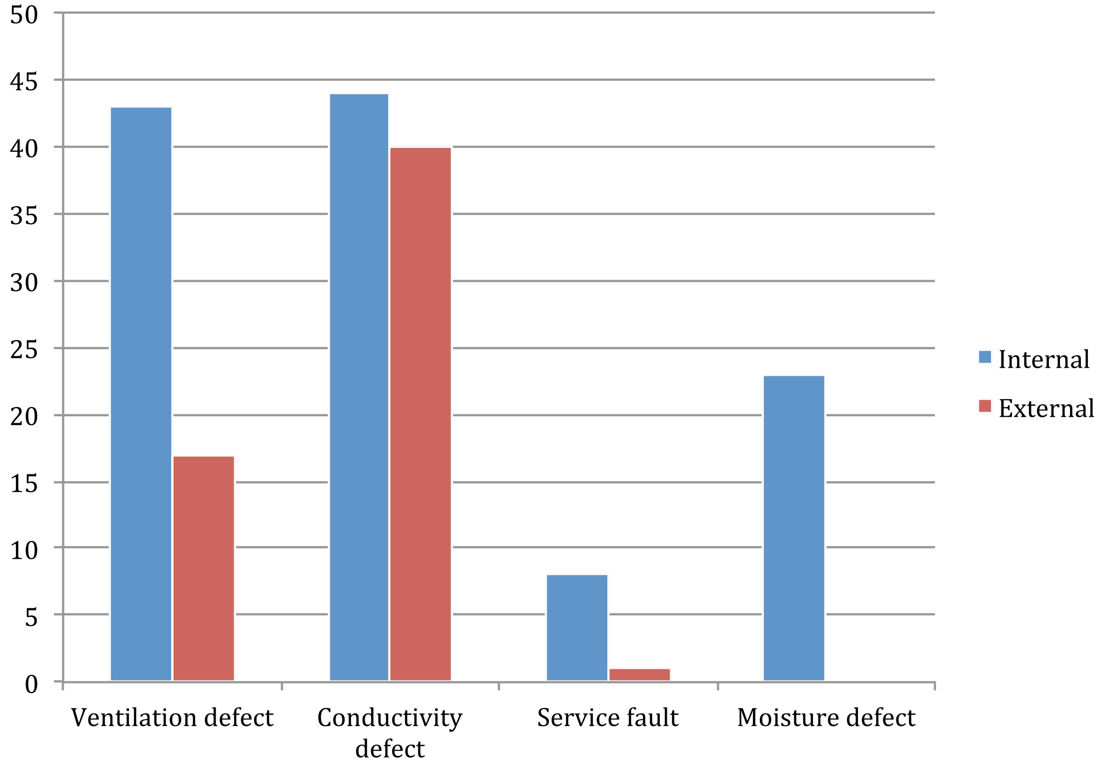


Figure 45. Incidence of thermally significant defect by location and overall group.

Breaking down figure 45 into the defect sub-categories delivered results that specifically showed where internal and external thermography proved most successful. This is illustrated in figure 46.

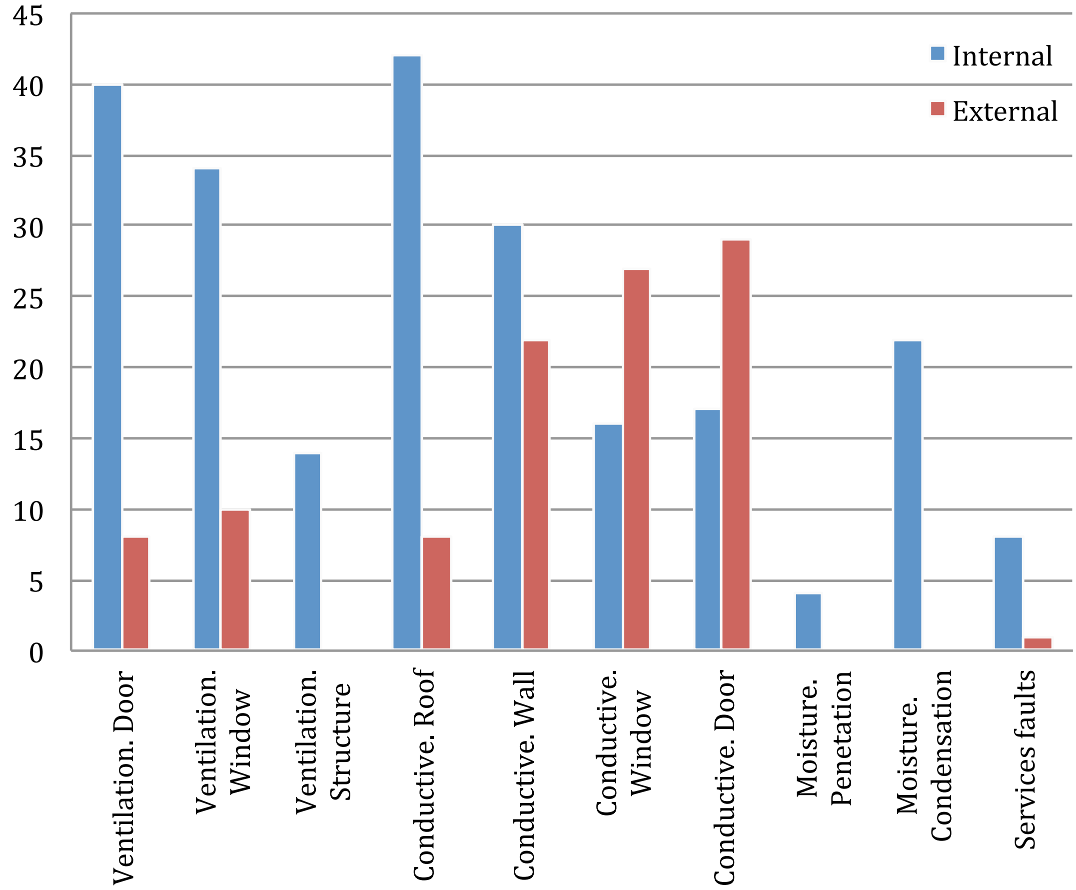


Figure 46. Incidence of thermally significant defect by location and sub-category.

From Figure 46, the following observations were made:

- While few ventilation defects were detected using external thermography, none were detected that came from sources other than windows and doors.
- Whilst conductivity defects illustrated in figure 45, appear to be almost as commonly found outside as inside, figure 46 shows that one sub-category, conductivity losses from roofs, performed significantly poorer under external thermography when compared with internal thermography.

- The only two defect sub-categories that were more commonly detected using external thermography compared with internal thermography were conductivity defects from doors and windows.

5.3 Discussion

This section of the chapter seeks to discuss some of the key findings from this research, which include: Practical benefits and limitations, difficulties in characterising defects and internal versus external thermography.

5.3.1 Practical benefits and limitations

The work in this chapter has successfully investigated the use of a traditional, walk-through thermography methodology for building defect detection. By conducting multiple case studies, a more robust practical methodology has been presented, which has drawn upon past experience and literature.

The practical application of this methodology was very dynamic, enabling the thermographer to move relatively quickly around a dwelling inspecting building features from different angles and distances dependant on the situation. This approach was made even more effective through utilisation of the camera's ability to provide real-time feedback and analysis (ITC, 2006). The real time feedback offered also enabled, on occasion, real time discussions on potential defects with householders, as they shared in viewing the live thermal image displayed through the VDU.

One of the most challenging aspects of this methodology was predicting the weather before and during a thermographic survey. Although for most of these case studies close to optimal weather conditions were targeted and achieved, some were not conducted under ideal conditions. Furthermore, some weather conditions (such as cloud cover or temperature) changed from one survey to the next or even during the survey of one dwelling. The effects of weather changes may have had an impact upon the results, particularly with external thermography.

In light of the changes that weather conditions can have on construction materials (Pearson, 2011) as discussed in chapter 2. Unless the weather had been/was constant, which is unlikely, it was often unclear while conducting the surveys whether this methodology worked in isolation from the weather conditions and adequately captured potential defects in variable external weather conditions, which might have diminished or over exaggerated the intensity of the defect. This factor was particularly concerning since the nature of walk-through thermography was to capture only single-moment-in-time thermal images.

5.3.2 Difficulties in characterising defects

This methodology was found to be very successful at detecting a broad range of thermally significant building defects. Defects included: conductive heat loss, ventilation heat loss and moisture related defects. However, results (Figure 45) indicate a disparity between the detectability of defects observed internally compared with those detected externally.

This last point requires careful consideration, because there is a difference between the activity of detecting a thermal signature of a potential defect and understanding the nature of the potential defect from the pattern characteristics. This dilemma poses the following question:

> *How is it possible to ensure that the* ***thermal signature*** *being read by the camera is presenting a* ***recognisable pattern characteristic*** *that can be accurately interpreted as being a particular defect?*

For example, how can it be known for certain that the increased heat being lost through the solid stonewall in figure 41 is due to missing insulation? What is on the other side of the wall? Have climatic conditions during the days leading up to the survey caused this? This external thermal image simply does not make it easy to guarantee an accurate diagnosis without further investigation. Such difficulties in image interpretation were common throughout the case studies in this work; however coming back to the discrepancy in results between internal and external thermography, this work found it much harder to not only detect, but to distinguish defect types from external thermography.

This is significant because when reviewing an external thermal image of a case study dwelling, such as that presented in figure 41, it might be too simple to categorise this hot spot as a wall conductivity defect. While initial thoughts may instinctively suggest missing insulation or thermal bridging, an alternative underlying cause could be moisture related, since penetrative damp is known to adversely effect material conductivity (Chown & Burn, 1983; Vollmer & Möllmann, 2010). Therefore, although categorised in this study as wall conductivity defects, some external thermal signatures might have been related to moisture defects.

One explanation for the difficulty in distinguishing between cold bridging / missing insulation etc. and moisture-related defects could be due to the transmission of heat through a material. The heat loss from these defects is likely to have an impact upon the entire thickness of the construction region. The effect of this will therefore result in heat conducting away from the epicentre and dispersing throughout the material dependant on the material properties for conduction and thickness. As the heat spreads out, it will likely start to blur the overall signature of the initial cause making it increasingly difficult to distinguish the nature of the anomaly.

Unlike these two defect types, ventilation heat loss appeared to be much easier to distinguish/characterise throughout this research. This was because such heat losses typically affected the surface adjacent to the defect source as opposed to having an impact upon the thickness of the material. With an easily identifiable gradated fan pattern, these stood out more distinctly than other defects. One of the reasons that ventilation losses were less detectable outside than inside might have been due to the effects of increased air (wind) movement compared with that experience internally. This might have disrupted the exfiltration warm air from the building, which could have lessened the thermal signature to a point that the thermal camera might not have been able to detect the anomaly. Another potential difficulty encountered with ventilation defects may have come from the presence of cavity walls. Unwanted excess air movement within ventilated cavities might lead to increased surface conductivity of the inner wall leaf, which could in turn lead to higher heat losses within a wall. Given the depth and nature of such a defect, this would have been very difficult to detect using this methodology alone. It would also seem remiss to deem this a limitation of external thermography alone, since throughout the walk-through surveys, difficulties in defect characterisation were also a concern for internal thermal images.

Attempting to mitigate the problem of defect characterisation due to the effects from other known limitations (such as climatic conditions), two level 2 thermographers analysed the thermal images for this work (one would confirm, dispute or question/discuss the other's assumptions) as explained in the methodology section of this chapter. Using past experience of thermographic image analysis and knowledge of building physics and construction, the ability for defect detection and differentiation in this project will likely be improved when compared with thermographic analysis by unskilled assessors. Although not included within the analysis of this thesis, as part of the broader Cornwall Together project a further 155 dwellings were thermally imaged by other thermographers. The concerns over quality of detection were verified when some of these reports (by unskilled thermographers) were reviewed alongside those reports produced by trained thermographers. Within the 45 dwellings inspected as part of this research, every effort was made to ensure each defect was correctly counted as a particular defect. However, regardless of experience, knowledge or education, there were times when thermal anomalies detected internally were found to be difficult to distinguish/categorise. Therefore, defect characterisation remained a limitation, which could only realistically be mitigated through knowledge and experience when using this methodology.

5.3.3 Internal versus external thermography

While Holst (2000) argued that internal inspections should only be conducted to verify results of external thermography, this work has shown that even when some thermal signatures are detected internally, they do not always show up on external thermography. By comparing the results from figure 46, it can be seen that by analysing the occurrence of conductivity losses through a roof, of 45 dwellings, 93% displayed signs of this defect when viewed using internal thermography, while only 18% showed such defect losses under external thermography. This resulted in a significant 75% of dwellings with roof conductivity losses, which would have had their defect, missed if a walk-around methodology had been employed alone. Similar scenarios could be seen from door and window ventilation losses, service faults and wall conductivity defects. The likely reason why conductivity losses are more difficult to detect externally compared with internally is that most roofs inspected were pitched and comprised of slate. When viewed at an angle, where the camera is at street level, the relatively low emissivity (0.85 compared with many building materials that are in the 0.90s) and specular finish of slate reflects the sky more noticeably than other materials and will degrade the thermal signature of potential defects. Also loft insulation is often placed along the top floor ceiling rather than lining the pitched roof, so small defects in insulation were more difficult to detect. The only way to truly mitigate the limitation of the acute roof angle would be to position the camera at a less oblique angle to the roof surface. To achieve this in practice would likely involve raising the camera up to be level with or slightly above the roof, for example viewing the roof from a taller neighbouring building. This is not always possible to achieve and might require additional equipment such as an extendable/telescopic mast or aerial/UAV thermography. Therefore this limitation is sometime impossible to eliminate.

Adding to this, Pearson (2011) suggested that defects detected using external thermography almost always show more clearly on internal thermography. This was proven to be the case in some circumstances, such as shown in figures 43 and

44, where the defect could be more clearly observed internally as opposed to externally. However, there were many more circumstances where external and moreover internal defects were not observable on the other side of the wall / feature. A number of reasons could explain why it might have been difficult to view the same defect on more than one side. One possibility is that it is due to the thickness of construction, which might hinder the conductive flow of heat from inside to outside. For example, the internal heat from a solid stone wall construction dwelling will take longer to manifest a corresponding thermal pattern on the outside when compared with an un-insulated timber frame construction, which will probably show signs of heat loss a lot faster. This might have been compounded by the length of time the internal heating system had been on prior to the thermographic survey, and because this methodology records one moment in time, this issue might have led to misinterpretations or defects being completely missed.

Another explanation is that it might have been due to climatic conditions prior to the walk-through survey. Whilst the conditions were favourable for most of the thermographic surveys, conditions leading up to (hours prior) some were not ideal, and were a limitation to this work. Some dwellings experienced high levels of solar exposure, wind or precipitation during the day or several days leading up to the survey and this might have had an impact upon the external elevations, which could have masked or diminished the thermal signature from defects that were identified internally, though not externally. This assumption is supported through literature by Vollmer & Möllmann (2010) (effects of wind), Brady (2008) (effects of moisture), BSi (1999), Hart (1991), and Snell and Spring (2008) (effects of solar exposure), which makes it plausible. However, like the first suggestion on construction thickness, it is very difficult to definitively ascertain what might be adversely affecting the thermal signature of defects when viewed externally. This research supports arguments by others (Pearson, 2011) against the use of quantitative analysis for external thermography, in particular when using a single moment thermograms methodology, such as walk-through thermography.

Whilst most defects were found to be more detectable using internal thermography, there were two that proved more detectable with external thermography. These were conductivity heat losses from doors and windows (Figure 46). Although not necessarily falling under the term ‘building defect’, excess heat loss from doors and windows could significantly contribute to overall dwelling thermal performance and occupant thermal comfort. The ability to qualitatively compare (Beard, 2007; BSi, 1999) one window with another window or adjacent building elements using external thermography made it easier to determine whether a door or window was likely to be generating excessive heat loss. Figure 42 shows an example, in which a single glazed window was compared with a double glazed window. It helps in such instances to know:

- Whether the internal temperature is the same in both rooms. This was the situation in this case study.
- What the likely sources of reflected radiation might be and whether these might be adversely impacting results. In this case study the reflective radiation sources were trees and cloud cover, which did not significantly affect the qualitative results.

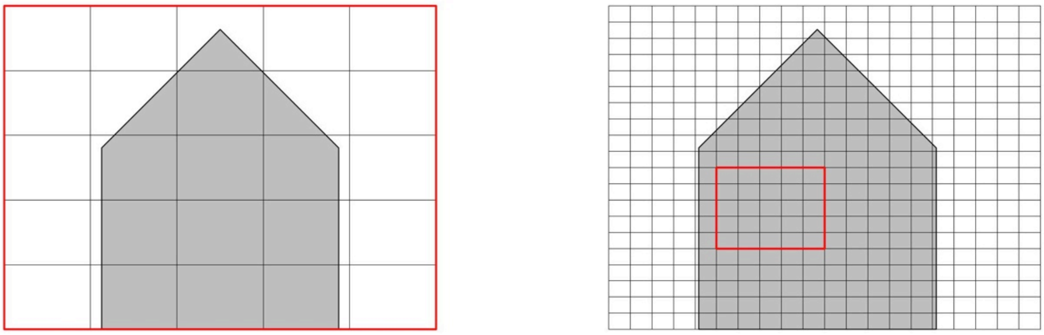
5.3.4 Spatial resolution verses adequate FOV

Another issue identified during the walk-through surveys of these dwellings was the balance between spatial resolution and capturing entire scenes/elevations within one thermal image.

As discussed in chapter 2, spatial resolution refers to the smallest discernable target that can be detected by the camera's sensor (Jensen, 2000). In summary, the closer the camera is to a target, the smaller the defects that can be detected. As the camera moves away from the target being viewed, some of the small defects become indistinguishable/missed by the thermal camera. To assess the size of defects, the measuring instantaneous field of view (MIFOV) is used (Holst, 2000). This is normally two to three times the IFOV and determines the smallest target that can be accurately measured using the thermal camera. Based on the thermal camera used for these experiments, at 20m from the target and with an IFOV of 0.69mrad (MIFOV of 2.07mrad), the smallest defect that could be detected would be 42×42mm in size. As some hairline cracks or ventilation losses might be smaller than 42mm in any dimension, these might have been missed at such distances. This becomes an issue, particularly when trying to capture as much of the subject within the FOV, as discovered in some of these experiments.

A.
Camera to target distance >20m
Standard aspect lens
Single image

B.
Camera to target distance <5m
Standard aspect lens
Single image



C.
Camera to target distance <5m
Wide angle lens
Single image

D.
Camera to target distance <5m
Standard aspect lens
Multiple images

Figure 47. Different options available for viewing a building. Red box denotes single FOV.

Figure 47 illustrates four options for viewing a building with a thermal camera. To begin with, the thermographer might stand about 20m from a building and use a thermal camera such as the FLIR T620bx (FLIR, 2013a), with a standard aspect lens (e.g. 25° x 19°) used in this chapter to take an image. As shown in figure 47A, the entire elevation might be captured, though each pixel covers a very large area, and with an MIFOV of 2.07mrad, might miss some of the surface detail. The next option (B) is to move much closer. Although the spatial resolution has been improved, because each pixel needs to cover a much smaller area, the whole elevation is not captured. To help overcome this, a wide-angle lens could be used (option C), which would permit the whole elevation to be viewed at a close range. However this does not deal with the spatial resolution issue because with a wide-angle lens, each pixel is covering a larger area of the view. To optimise the spatial resolution (measure small scale defects), whilst capturing entire elevations, the most appropriate methodology was found to be the use of multiple images captured over a grid (option D), taken close to the subject. These images were then placed together into a single large format panoramic image.

Figures 48 and 49 show the difference in spatial resolution between two internal and external scenes recorded using options C and D from figure 47. Comparing a single, wide-angle lens image with multiple (standard aspect lens) images of the same scene, it became clear that having greater spatial resolution provided more accurate images. This was particularly noticeable between the two images in figure 49, which captured an external elevation where the image on the right appears much brighter/warmer than the image on the left. The pixels in single image on the left of figure 49 were less able to detect the same radiation signal that the (multiple) closer-up images were able to detect in the image on the right. As such, multiple image panoramic images were preferred to wide-angle lens use, when seeking to capture entire elevations in one image scene.

Figure 48. Single, wide-angle thermal image (Left). 16 individual thermal images pieced into one panoramic view (Right).

Figure 49. Single, wide-angle thermal image (left). 20 individual thermal images pieced into one panoramic view (Right).

Figure 49 (right) comprises of 4(Wide)×5(High) thermal images, so instead of being 640(W)×480(H) pixels in resolution, this image will comprise of up to 2560(W)×2400(H) pixels. Also being captured at about 5m from the target surface, the smallest defect detectable using the same MIFOV would be 10×10mm in size. This is much better than would be expected from a similar image taken at distances in excess of 20m from the elevation.

The wide-angle panoramic images in this work have also shown that while a singe image might capture a particular defect or issue, it was sometimes difficult to discern the nature or location of this defect in relation to other parts of the building or other/similar defects. By capturing a panoramic image of an entire view, post survey analysis was made easier to undertake. This was because a detected defect or defects were placed in context with their surroundings and made it easier to make assumptions on defect cause, common patterns, impact on other areas and overall extent. An example of this can be seen when comparing Figure 50 (single thermal image) and Figure 51 (35 image panoramic thermal view).

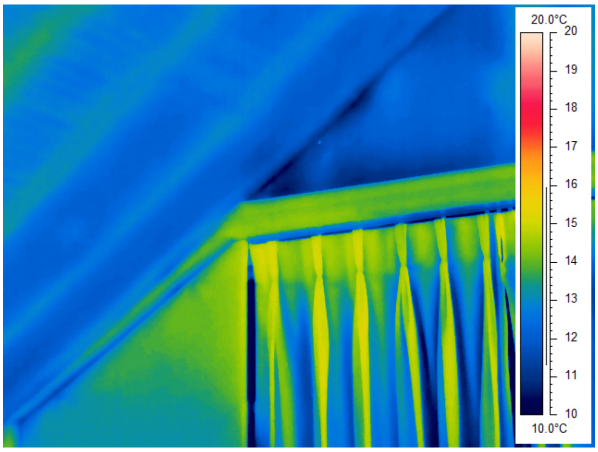


Figure 50. Single thermal image of internal room elevation.

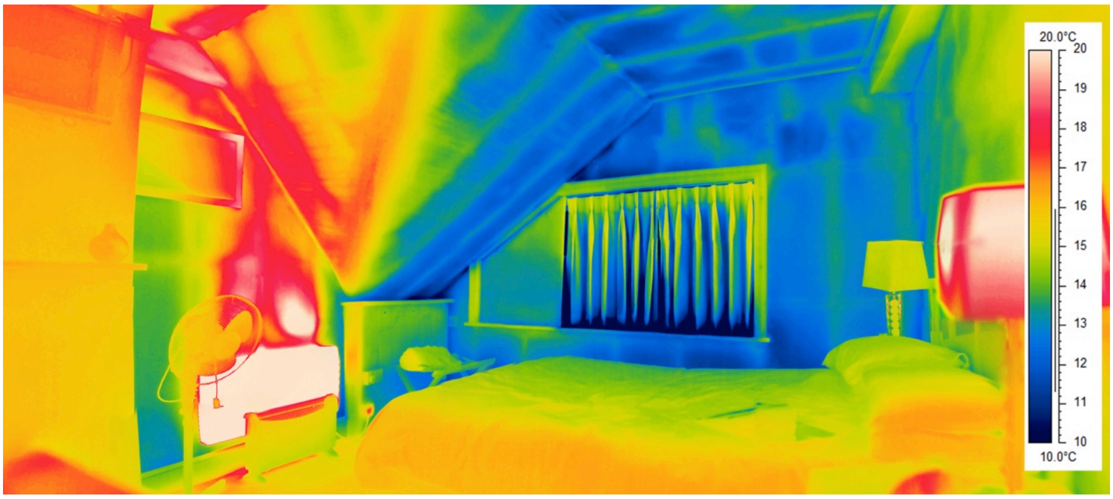


Figure 51. 35 thermal image panoramic view of internal room elevation.

The wide-angle panoramic images in this work have also shown that while a singe image might capture a particular defect or issue, it was sometimes difficult to discern the nature or location of this defect in relation to other parts of the building or other/similar defects. By capturing a panoramic image of an entire view, post survey analysis was made easier to undertake. This was because a detected defect or defects were placed in context with their surroundings and made it easier to make assumptions on defect cause, common patterns, impact on other areas and overall extent. An example of this can be seen when comparing figure 50 (single thermal image) and figure 51 (35 image panoramic thermal view).

The single thermal image (Figure 50) shows an apparently cold roof over a window. However it is impossible to understand the extent of this cold roof, or how it compares with other parts of the room. Figure 51 though presents a much wider scene, which shows heat being given off from a radiator, warming a section of ceiling. It also shows the internal wall surface and furniture temperatures, which gives an indication of air temperature at different parts of the room. Although much more time-consuming than a single image, on reflection, capturing panoramic views was found to be much more informative for image analysis using a walk-through methodology.

5.3.5 Assessment of time-scales/quantity of dwellings per survey

As discussed in the methodology section of this chapter, each dwelling survey took approximately 40 - 60 minutes to complete. This correlates with the lower time scale proposed by Smale (2014), though Smale has an upper limit of 150 minutes. As expected, time-scales were dependant on the size of the dwelling being inspected, which would increase (large dwellings) or decrease (small dwellings) the time needed to inspect a dwelling.

In addition to the time needed to inspect a dwelling, was the time needed to travel between different dwellings. For this research project, dwellings had been selected in close proximity to each other as part of the survey planning. Nevertheless, this contributed to the quantity of dwellings, which could physically be surveyed in one evening. The maximum number of dwellings surveyed in any one evening was 6. This figure relates to one thermographer imaging a standard 2/3 bedroom dwelling (45 minute survey), with 15 minutes allocated for travelling to the next dwelling, starting the first inspection at 6pm and finishing at midnight. Should the dwellings take longer than 45 minutes to survey, or be longer than 15 minutes travelling distance between consecutive dwellings, fewer than 6 dwellings could practically be surveyed in one evening.

5.4 Concluding summary and rationale for a new methodology

The objective (Objective 3) of this chapter was to explore the use of a traditional walk-through methodology. Having completed 45 dwelling case study surveys, the findings from walk-through thermography have been organised into a diagram (Figure 52), which highlights the benefits and limitations encountered during the case studies.

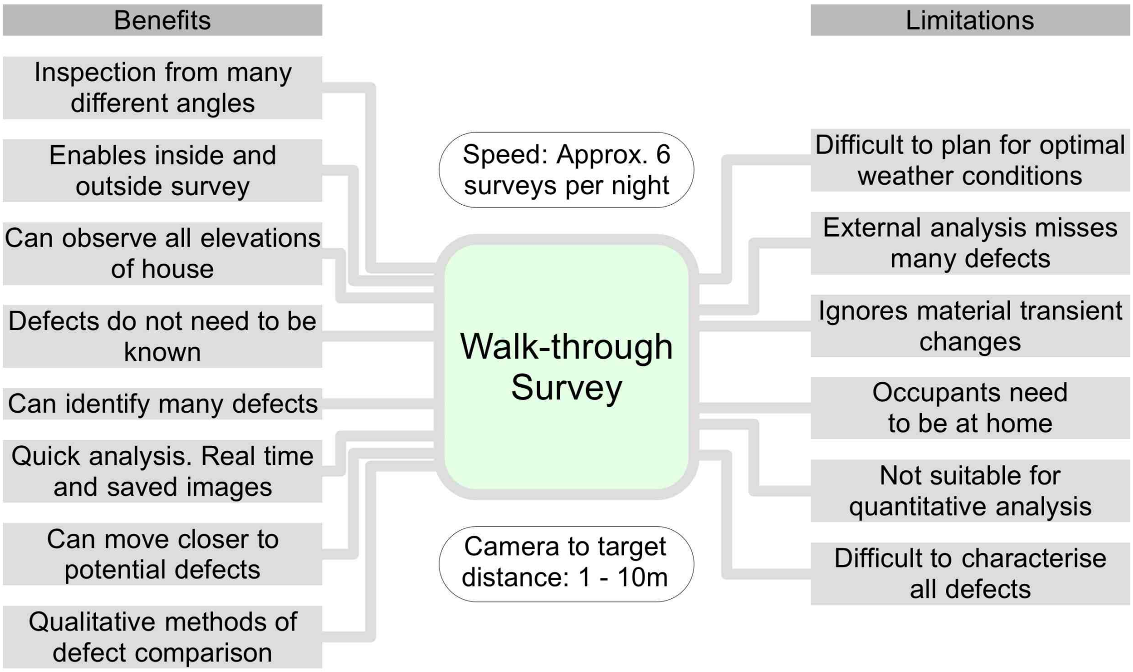


Figure 52. The benefits and limitations to walk-through thermography.

A maximum of 6 surveys could be conducted per night (60 minutes per survey including travel time). Although this is depended on dwelling size and proximity to each other, it matches the survey duration proposed by Smale (2014).

The potential defects that were detected using walk-through thermography included: conductivity heat losses, ventilation heat losses and moisture related defects. This methodology also enabled the detection of buried service faults, which could help to indicate deficiencies in pipe insulation lagging.

Whilst it appeared easy to detect the qualitative thermal signature of unexpected heat loss areas, ventilation defects were the only defect group that could be easily characterised using this single-moment-in-time image methodology. Although few unexpected hot and cold spots (potential defects) would be missed using this methodology, conduction and moisture related defects were sometimes found to be difficult to successfully characterise. Because of this, some of these defect types might have been misinterpreted due to a variety of situations observed in this research, such as unknown construction build-ups/thicknesses, and transient internal and external atmospheric conditions.

Comparing the detectability of defects between inside (832 total defects detected) and outside (377 total defects detected), this chapter has shown that internal thermography is much more successful at detecting defects than external thermography. Results illustrate that whilst every defect sub-category was detected using internal thermography, some were completely unobserved using external thermography. This was acknowledged as resulting from the climatic conditions experienced outside, which had a greater impact on results and were less controllable than the conditions indoors. These findings correlate with similar statements found in other literature sources, and highlight the ineffectiveness of using an external thermography methodology alone (such as the walk-around survey). Therefore, if a comprehensive review of building defects is to be made, it is imperative to conduct internal as well as external thermography.

Having completed the research for these case studies, it has become clear that through recording single thermal images that capture one moment in time (snap shot), the thermal patterns displayed cannot be relied upon to guarantee the accurate characterisation of building defects. Although this statement relates more to external thermography, there are some internally detected defects, such as moisture problems, that also prove challenging to discern under snapshot thermal images. In light of the issues resulting from the use of qualitative analysis, this research also questions the ability to accurately investigate defects using quantitative measures, particularly if the thermographer is not completely sure what the defect is that they are quantifying.

To improve spatial resolution, whilst capturing entire elevations, a method of capturing multiple images to be pieced together later into a large format panoramic image (of an entire scene) was used. This also proved to be more useful than single images of small details as they enabled the analysis of potential defects in context with other features and helped to portray the extent/pattern of defects.

As discussed, the primary reason for the difficulties in characterising defects has been attributed to transient weather conditions and material properties. This, therefore, suggests that an alternative thermography methodology might be required, which observes transient conditions and material properties over a prolonged period. By better understanding transient changes, defect characterisation can become more accurate, particularly for those defects that have been acknowledged as hard to characterise, or for potential defects that are observed using external thermography. Seeking to better understand the aforementioned transient changes, the next chapter will develop and explore a time-lapse thermography methodology on buildings and materials to determine whether this theory is correct, and that a slower, more detailed thermography methodology can indeed better characterise building defects than traditional thermography.

6.0 Time-Lapse Thermography

In chapter 5, a walk-through thermography methodology was explored to better understand the benefits and limitations of this as a methodology for defect detection. One of the main difficulties/limitations with this methodology was found to be the characterisation of defects based on a single point in time thermal image. One theory for this was the impact that transient conditions have on thermography and building material properties. Despite every effort taken to minimise the effects of transient conditions, the work in chapter 5 suggested that a walk-through thermography methodology was still prone and did not adequately factor in the effects of transient conditions when reviewing thermal images of potential defects. One method proposed to address this was the application of time-lapse thermography, which is the focus of investigation through this chapter (**Objective 4)**.

Applying qualitative and quantitative time-lapse thermography over a series of laboratory and in situ case studies, this chapter explores the use of apparent surface temperature changes over prolonged periods of time in order to draw conclusions from transient changes. Although building thermography can also be used to observe the behaviour of and defects within HVAC systems, this work primarily focuses on observing the building fabric.

This chapter has been split into three parts:

Part 1. A study of time-lapse thermography in real buildings is complicated by their multi-layered and three-dimensional envelopes, which behave dynamically within a constantly changing environment; therefore, before embarking on this, part one will report on an experiment that studies the dynamic behaviour of simple monolithic material samples under more controllable laboratory conditions than can be achieved with real buildings.

Part 2. The second part specifically explores and reports on the use of a time-lapse thermography methodology for defect detection in real buildings (full complexity). Case study experiments on two dwellings are conducted to ascertain limitations with a time-lapse methodology and to start drawing observations from building surfaces over prolonged periods of time. A review of the temporal resolutions needed for time-lapse thermography is also explored.

Part 3. Continuing with real life building case studies, part three observes three different wall constructions using time-lapse thermography in combination with Madding's (2008) U-value equation to determine in-situ values over a prolonged period of time. These are then compared with U-values that are measured using heat flux sensors to determine the success of time-lapse thermography for quantitative analysis such as in-situ U-value assessment.

For the longitudinal application of thermography, the terms 'transient' and 'time-lapse' are important. According to the Oxford Dictionary ('Oxford Dictionaries,' 2014), 'transient' is defined as *'lasting only for a short time; impermanent*'; 'time-lapse' is defined as *'denoting the photographic technique of taking a sequence of frames at set intervals to record changes that take place slowly over time; when the frames are shown at normal speed the action seems much faster'.*

Accordingly, the work in this chapter/thesis defines time-lapse thermography as a passive (only relying on heat transfers taking place as a result from 'normal/typical' heat sources, such as solar gain and domestic heating systems etc.) thermal imaging methodology, which aims to better understand transient heat flow within a building's fabric by recording a sequence of images. Given the slow nature of transient changes in building materials, time-lapse image recording appears well suited to thermographic investigations.

6.1 Time-lapse photography

Before proposing a time-lapse thermography methodology, it is important to understand the context behind time-lapse photography, the field where this technique started.

Time-lapse image capturing is a filming technique whereby a series of images of the same scene are recorded over a prolonged period of time, before being placed together into a motion sequence. This technique is commonly attributed to photography (Allen, 2009) where typically slow or fast events can be accelerated or slowed by saving image frames at different temporal spacing's to that of traditional film speeds, which are 24 frames per second (Kinsman, 2011). This means that events, which might take many minutes, hours or days, can be replayed in a matter of seconds (Chylinski, 2012). Hawkins (2014) argued that one of the main advantages of using sequential still images rather than accelerated filmed footage, is that still images offer an improved resolution/quality over compressed film.

The first applications of time-lapse photography were undertaken towards the end of the 1800s / early 1900s by Eadweard Muybridge, who devised a method of capturing motion through a series of photographs (Persohn, 2014). Together with Etienne-Jules Marey and Leland Stanford, Muybridge took a sequence of closely spaced photographs (from 24 individually spaced cameras (Chylinski, 2012)) of galloping horses. These were then viewed frame-by frame to see whether horses ever had all four hoofs off the ground during a gallop (Dagognet, 1992). Subsequently, others have used this photographic technique to observe lengthier processes, such as moving clouds, flowers budding and the construction of buildings (Sunkavalli et al., 2007).

Kinsman (2011) discusses the temporal resolution (spacing's between recorded images) preferred for time-lapse photography as being one of the most challenging aspects to get right. The methodology that Kinsman (2011) uses for determining the temporal resolution is to divided the total process time by the total number of frames, which will give the image spacing time (EQ. 1). However Kinsman goes on to suggest that photographers should plan to capture 20% more photos than calculated through EQ. 1.

$$\frac{TPT}{TFS \ x \ 24 \ \ frames/second} = IST$$

EQ. 1. Equation for determining temporal resolution (Kinsman, 2011).

Where TPT = Total process time in seconds

TFS = Preferred duration of time-lapse film sequence in seconds

IST = Image space time in seconds

However EQ. 1 seems a little too simplistic in approach, since it is not always known how long an event will take, nor is the duration of a time-lapse film sequence an accurate parameter for deciding upon temporal resolutions. Kinsman (2011) acknowledges this, suggesting that dynamic environmental effects, such as how shadows will fall, or how clouds might impact on the lighting, which will impact upon the temporal resolution.

With the introduction of digital camera technology, time-lapse photography has become more accessible and efficient and hundreds and thousands of digital photos can now be captured and combined into a lengthy time-lapse sequence (Persohn, 2014).

As discussed in chapter 3, some thermal cameras have adapted the time-lapse technique to enable the recording of thermogram sequences, thereby presenting new opportunities for prolonged building thermography (Lucier, 2002) to observe the transient flow of heat through construction over a much longer time. However, to date, only limited (see chapter 3) academic application of passive time-lapse thermography has been made.

6.2 PART 1. Time-lapse laboratory validation

6.2.1 Introduction

To start exploring time-lapse thermography for building inspections, it was first important to develop/validate a simple time-lapse methodology under controlled/known laboratory conditions. The specific aim of this experiment was learn whether time-lapse thermography could observe transient changes in materials. This experiment compared time-lapse thermographic images of four material samples under two different simple scenarios (dry and wet), and helped to pave the way for more complex investigations using real world building case studies.

6.2.2 Detailed Methodology

In order to begin examining transient changes between dry and wet samples using time-lapse thermography, a relatively simple experiment was devised, which enabled materials to warm up over a period of time and results then compared between the two conditions.

Materials were chosen that are representative of materials commonly found in UK buildings. These were (Figure 55):

- Brick
- Concrete Block
- Delabolle (Cornish) Slate
- Sanded softwood

Thin slices of the sample materials were positioned within a purpose built timber frame, which allowed the materials to be uniformly heated from behind with a

31W electric heating mat and copper plate to ensure even distribution as shown in figure 53. This provided a sufficient temperature difference across the samples as is required for thermographic investigations (BSi, 1999).

In order to minimise any adverse environmental conditions that the building materials commonly face, the experiments were conducted in a semi-controlled internal environment, i.e. a room held at a constant temperature of roughly 16°C.

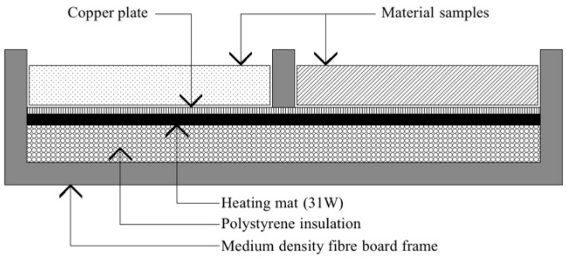


Figure 53. Section through the experimental set-up

Initially all the material samples were at a stable temperature in the 15 – 17°C range. The heating mat was then switched on, providing a continuous power of 31W during the experiment, and a series of thermal images were recorded every 5 minutes to record the warming up of the materials. After a period of 4 hours, the heating mat was turned off and left for a further hour to record the cooling down of the materials.

A FLIR ThermaCam S65 (FLIR, 2006), calibrated by the UK's National Physical Laboratory in December 2010 across the temperature range of -5 to 100°C, with a built-in 36mm lens (specifications listed in appendix B) was positioned 500mm from the experimental setup. The internal temperature was recorded at 16°C with a relative humidity of 60% and a reflected apparent temperature of 17°C. To minimise the impact of reflected IR radiation from other sources, the experimental setup was angled slightly so that the IR radiation from the camera (and operator) would not be reflected in the materials, and a fabric curtain was used to cover other potential sources of reflected IR radiation.

Figure 54. Photo of the experimental setup, thermocouples and IR camera.

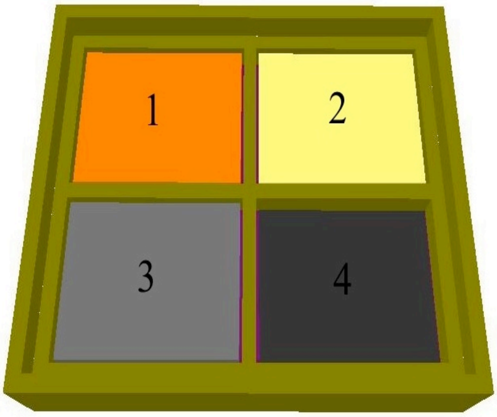


Figure 55. Order of samples within hot plate grid. 1. Brick, 2. Sanded softwood, 3. Concrete block, 4. Delabolle slate.

To analyse the samples using the IR camera, a box measurement tool was used for each material to obtain an average temperature over the area of the box, which was close to (but not over) the area covered by the duct tape.

In addition, thermocouples were attached to the surface of each material with insulation tape to measure the actual surface temperatures (Figure 54). To aid the accuracy of the thermocouples, a heat sink compound was used between the surface and the tip of the K-type thermocouple.

Each material had its emissivity measured in accordance with the ITC measurement procedure (ITC, 2006). These were recorded and inputted into the QuickReport analysis software (FLIR, 2009a).

The emissivities recorded for each material were:

- Brick (emissivity 0.97)
- Concrete Block (emissivity 0.98)
- Delabolle Slate (emissivity 0.86)
- Sanded softwood (emissivity 0.95)

The dimensions of the samples were 100x125mm. Each had a thickness of 20mm, apart from the slate, which had a thickness of 5mm. These dimensions were based on practical considerations, with brick, concrete and wood cut to a relatively thin slice, whereas the slate was supplied at the given thickness.

Where the first experiment observed the heat transfer through naturally dry materials, a second identical experiment was undertaken using the same materials which had been moistened for an hour.

The comparison between the wet and dry materials samples was undertaken in order to explore the generic assumption that thermal imaging of buildings should not take place when the materials are wet due to changes in material properties.

Following the experimental phases, images and numerical data was collected. The numerical data was then plotted on graphs, to illustrate the warming up and cooling down phases of the material samples.

6.2.3 Results

The dry experiment was undertaken initially and provided an indication of the thermal performance for each material sample. Figure 56 shows the results from the dry sample experiment. Within this figure, a difference in apparent surface temperature can be observed between the four material samples. Each sample however takes a very similar warming up and cooling down curve pattern.

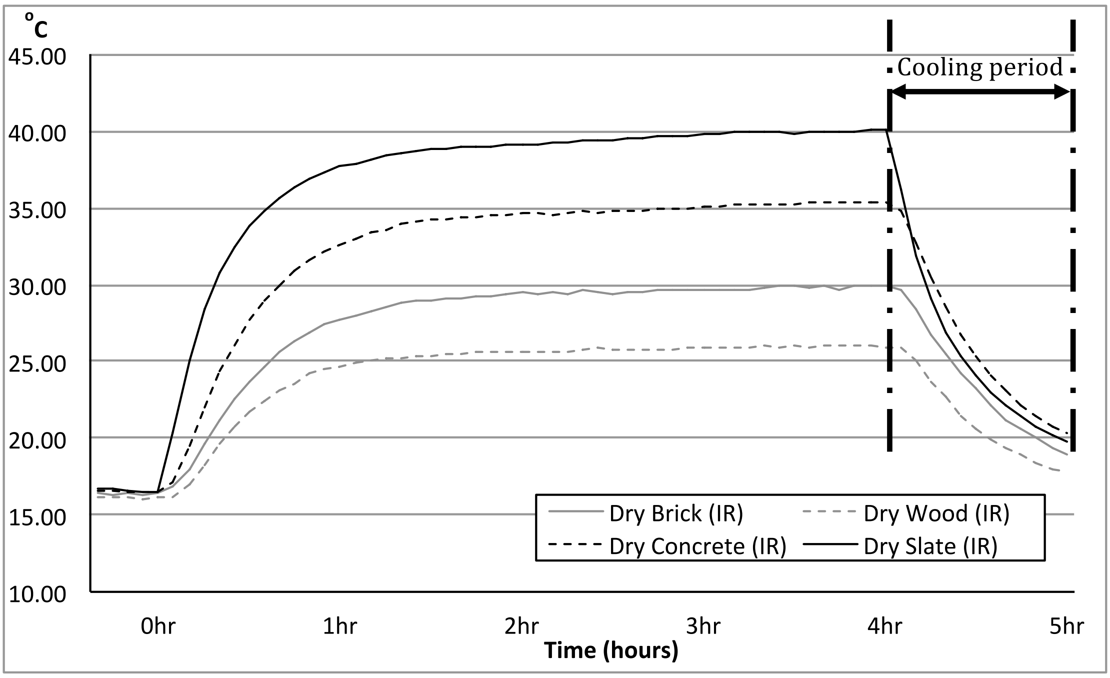


Figure 56. Experiment 1. Dry samples. Showing apparent surface temperatures obtained from the thermal camera (IR).

To explore the effects of moisture within the selected materials, a second experiment was conducted once the material samples had been moistened for an hour. Figure 57 shows the results from the wetted sample experiment.

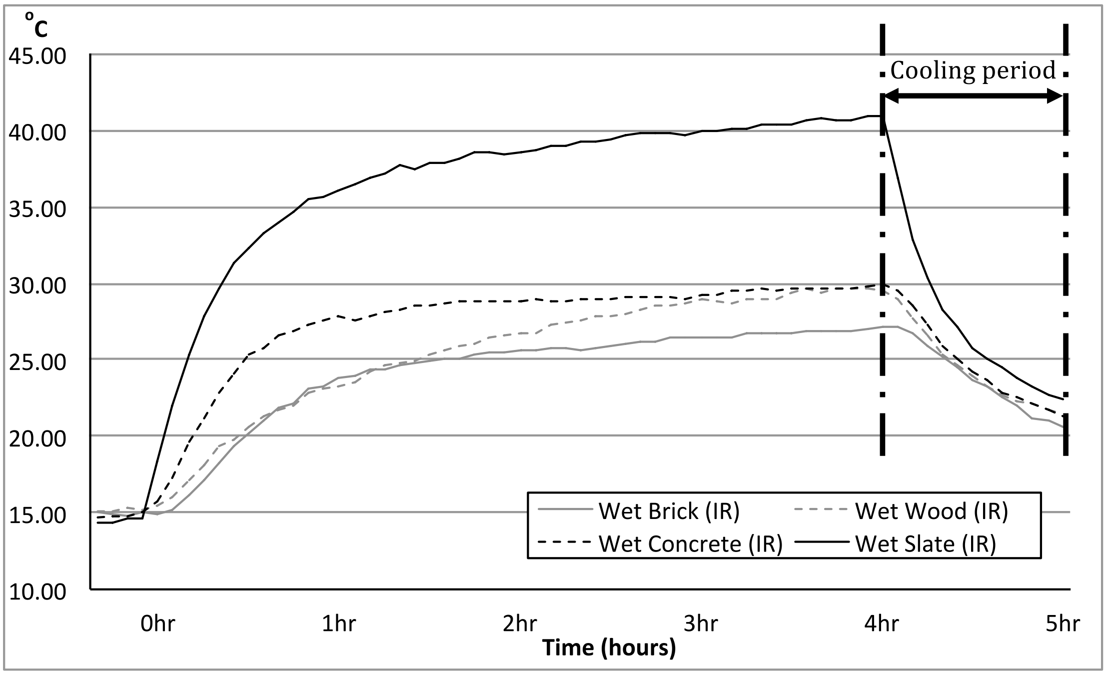


Figure 57. Experiment 2. Wetted samples. Showing apparent surface temperatures obtained from the thermal camera (IR).

While quantitative temperature data was the primary means of analysis during this experiment, figure 58 presents thermal images from the dry experiment and wet experiment. The top line shows results from the dry experiment. The bottom line shows wetted sample experiment. For material sample locations, refer to figure 55.

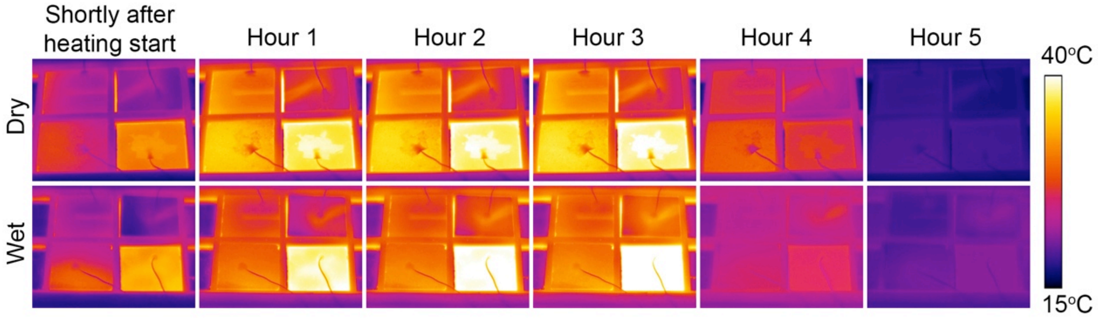


Figure 58. Thermal images from the experiment 1 (dry) and 2 (wet).

As a benchmark for the thermal camera measurements, surface temperature data was also obtained from surface mounted thermocouple. For each sample (wet and dry), the thermocouple measured temperatures correlated with the thermal camera measured surface temperatures.

Having completed the two experiments, key differences could be drawn from comparing the wet and dry sample experiments over time. To aid in assessing these differences, a graph was created for each sample that included data from both wet and dry experiments. These are presented below through figures 59 – 62. In these graphs, the codes 'IR' stands for 'thermal camera' and 'TC' stands for 'thermocouple' measurements.

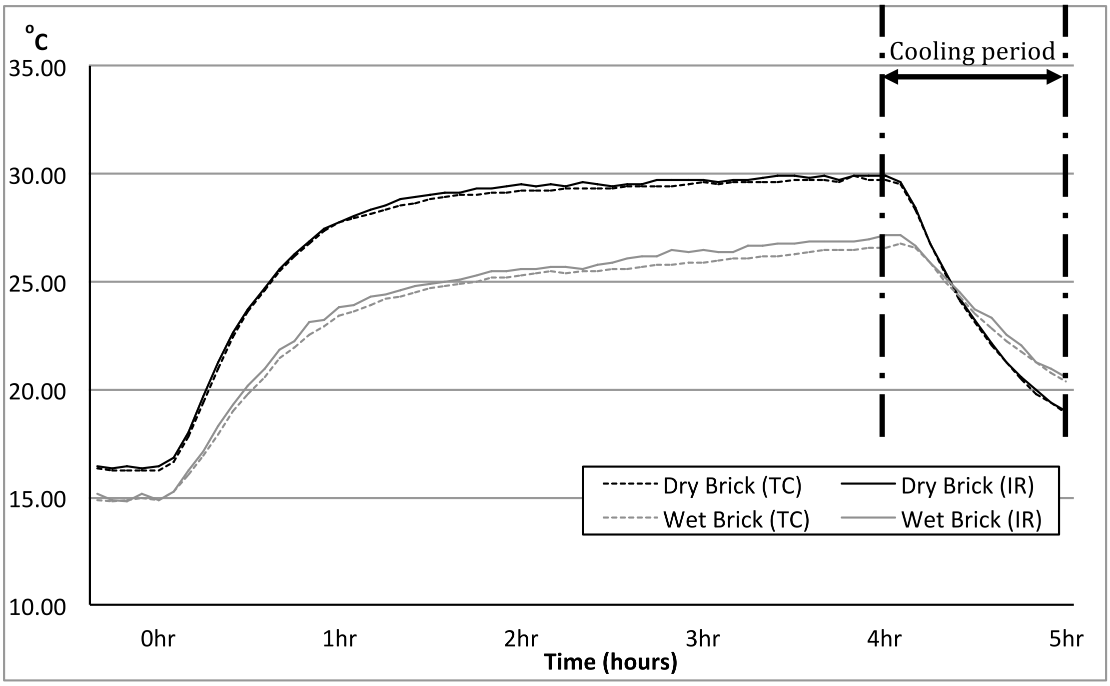


Figure 59. Dry and wet experiment results for the brick sample.

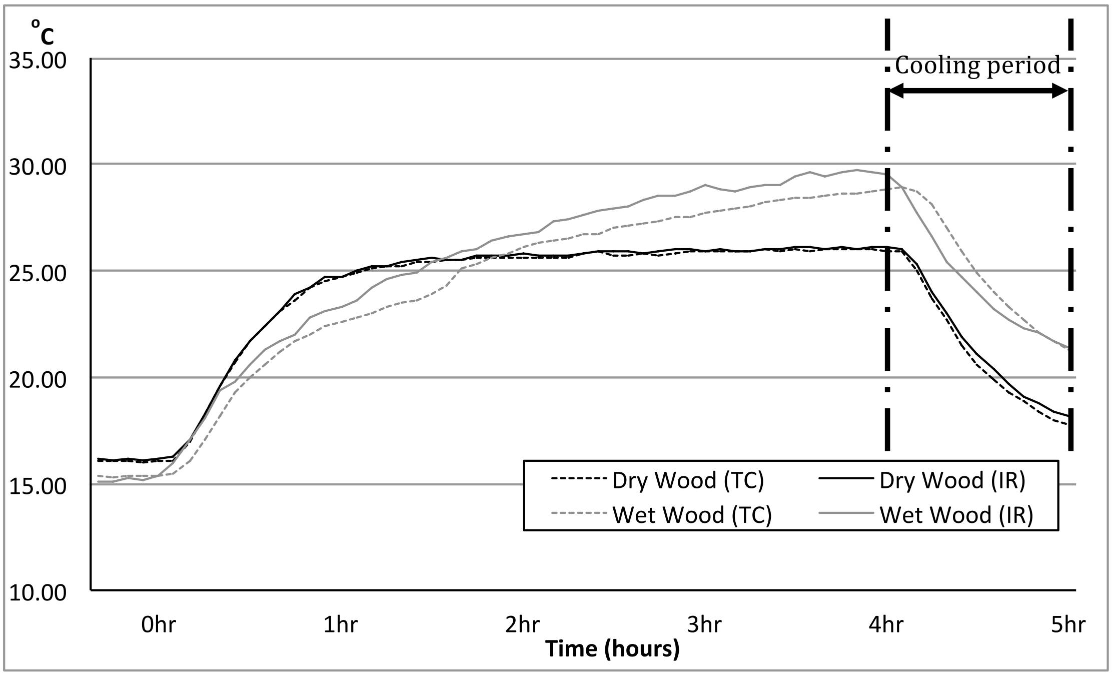


Figure 60. Dry and wet experiment results for the softwood sample.

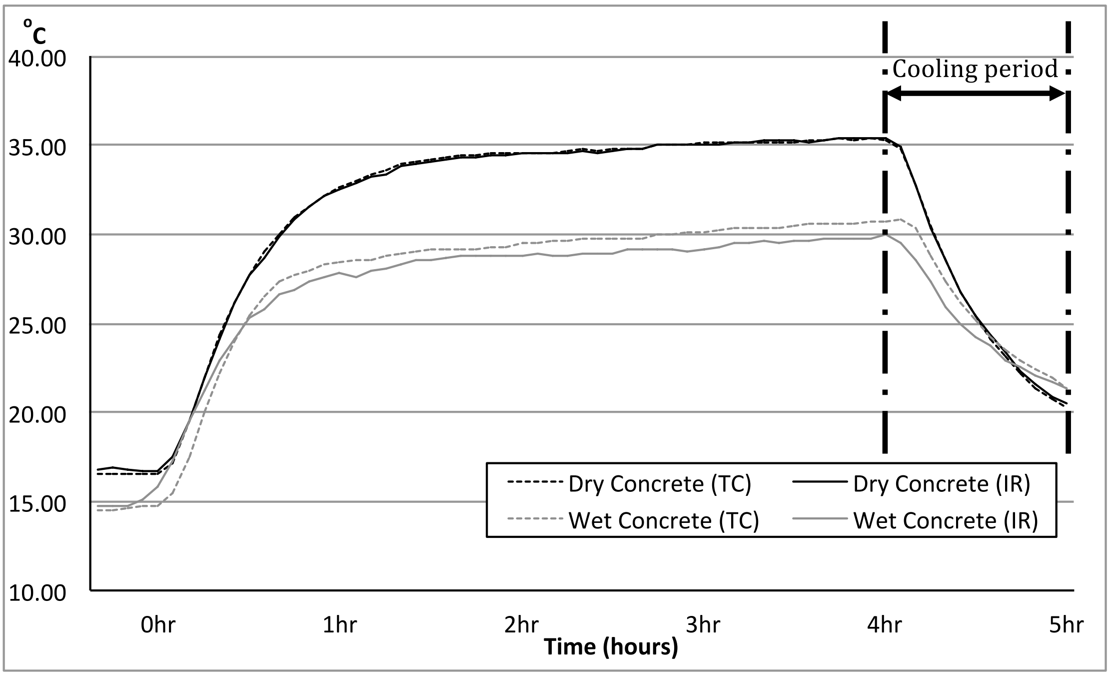


Figure 61. Dry and wet experiment results for the concrete block sample.

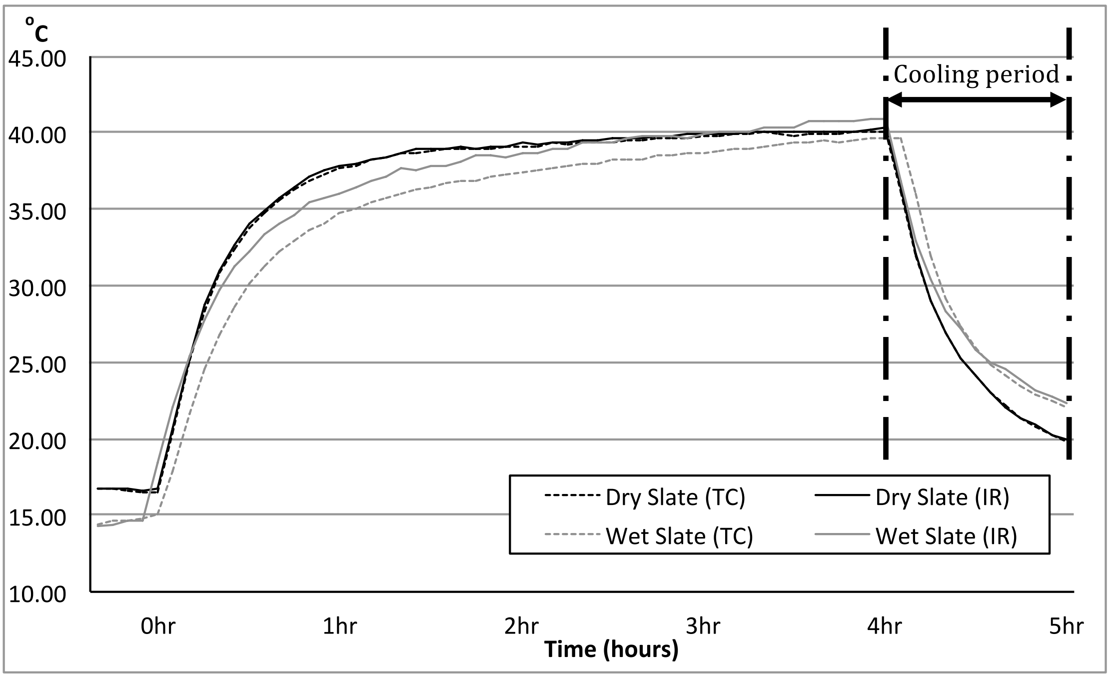


Figure 62. Dry and wet experiment results for the delabolle Slate sample.

6.2.4 Analysis

Reviewing the data from the wet experiment, it can be observed from figures 59 - 62 that when the samples were damp, the initial heating phase took longer than the dry experiment. Actual results depended on the amount of water present in the sample, with brick and concrete showing a different pattern from wood and slate. Following this phase, the wet samples showed a sharper rise in temperature over the 4-hour heating period than the dry samples. This was due to the materials drying out over the heating period.

Brick (Figure 59) and concrete block (Figure 61) show a lower temperature over the duration of the heating phase for the wet experiment. It was observed that these materials were still damp at the end of the heating phase and account for this lower temperature.

Although having a longer initial heating phase, the wet delabolle slate sample (Figure 62) showed a temperature profile that ultimately matched the dry data, which would suggest that the moisture on top of the slate had evaporated. Due to the impervious nature of slate, this seems plausible.

The wet softwood sample (Figure 60) showed a much slower initial rise in temperature than the dry sample, though continued to rise until the point when the hot plate was turned off. In contrast, the dry sample had reached a plateau like the other dry samples by about the first hour. Had the hot plate been left on for longer, the wet timber sample might have become even hotter. Observing the difference that water had on the concrete, brick and wood samples, highlights the challenges present when inspecting real world wet materials/constructions with a thermal camera.

The cooling down phases for all of the wet samples were shorter and had a steeper gradient, which would be expected from damp materials in comparison with their dry counterparts.

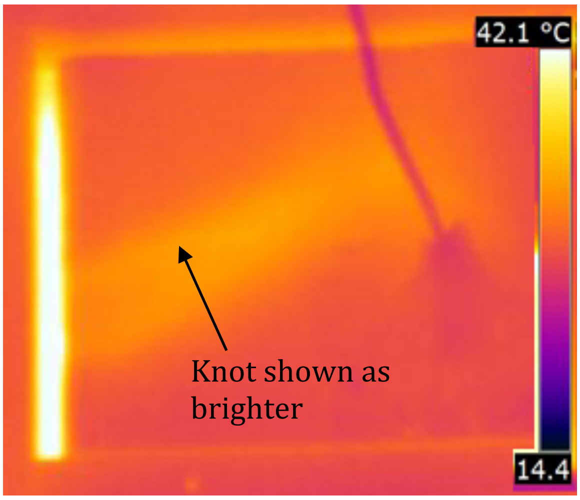


Figure 63. Softwood sample showing anomaly due to presence of knot.

Another observation related to the softwood timber sample. As the sample reached a higher temperature, the thermal image (Figure 63) showed a brighter patch within the sample.

6.2.5 Part 1 Conclusion

The work in this section of chapter 6 presents a comparison of dry and wetted material surface temperatures using time-lapse thermographic images. In both wet and dry experiments, four simple material samples were heated. This enabled the warming-up and cooling-down behaviours to be observed. This work has enabled a better understanding of thermal images, and established some benefits from time-lapse thermography, such as identifying potentially hidden details as found in the timber sample (Figure 63), and raising awareness of the effects moisture can have on material properties. These findings can be translated through to further work exploring potential defects and transient changes in actual buildings and in-situ materials, and will be explored through the next parts of this chapter.

From the perspective of a thermographer, the level of information that can be gained from thermal images is important. Much of the industry perceives thermography as a relative tool (Pearson, 2011), observing colour gradients through the thermal camera on a single point in time method of analysis. This often requires professionals to use past experiences and best judgements to interpret what they are seeing. However, the work presented here hints that it might be possible to use thermography on a time-lapse basis to quantify thermal behaviour more accurately than this.

From the perspective of time-lapse analysis, this study demonstrates the importance of longitudinal investigation of material behaviour under changing conditions. The study’s thermographic experiments proved successful in demonstrating the transient heat flow from both the dry and wet samples, and therefore paves the way for more complex investigations with multi-layer samples and real buildings. Caution is needed however when scaling this experiment up to real life building examples, since other parameters might begin to feature that are not present in semi-controlled conditions. Conditions such as changes in occupancy and weather might cause complex effects on image results. Also multi-layered structures could respond variably in response to such changes in conditions.

6.3 PART 2. Time-lapse thermography for qualitative defect detection

6.3.1 Introduction

Whilst it is appropriate to explore new thermography methodologies such as time-lapse thermography under laboratory environments, where a greater likelihood of achieving close to steady state conditions can be made, for practical application on real in-situ buildings, experiments need to be undertaken in the field. The next two sections of this chapter therefore specifically focus on real building analysis using time-lapse thermography.

As stated in chapter 3, the most commonly reported use of time-lapse thermography involved active thermography. This is exemplified by Hamzah (1996) whose work located structural defects hidden beneath material surfaces using forced heating phases prior to thermographic observation over periods no greater than 22 seconds. Avdelidis (2006) asserts that time-lapse thermography is in the realm of active thermography. However, work which explored the evaporation process from moistened plaster samples under laboratory conditions by Grinzato *et al.* (2010) is one example where a time-lapse methodology has been applied to passive thermography. Also, work by Lehmann *et al.* (2013) applied a passive time-lapse methodology to determine the most influential environmental conditions to external thermographic analysis. This study identified solar gain in combination with differences in construction composition (insulated versus un-insulated brick wall construction) as presenting the greatest impact on thermography. For quantitative analysis, Madding (2008) and Kato *et al.* (2007) have explored the determination of fabric U-values using passive time-lapse thermography by measuring apparent surface temperatures over a prolonged period of time. Lehmann *et al.* (2013), Madding (2008) and Kato *et al.* (2007) have captured thermographic images at intervals ranging from 5 to 20-minute. For qualitative analysis, Lehmann *et al.* (2013) reported using an image interval of 5 minutes; however, when publishing the image data in their paper, images were reproduced at a 60 minute intervals only, which suggests that the images between 60 minutes did not show a discernible difference in the displayed patterns to enable qualitative analysis.

While this existing work utilised passive time-lapse thermography for the study of some transient aspects of thermal building behaviour, there is no evidence in literature on the use of time-lapse thermography to identify building defects. Currently, there is no evidence in the peer-reviewed literature of a practical methodology for time-lapse thermography as applied to the study of whole buildings. Indeed, recommendations regarding temporal resolution for such studies are non-existent.

6.3.2 Detailed Methodology

Case study buildings

This research explores the application of time-lapse thermography for the study of transient building behaviour, with a view of identifying building defects. In order to compare in-situ time-lapse building thermography with traditional methodologies that only capture images at one point in time and to explore the practicalities involved with conducting time-lapse thermography, case study research was employed. For this, two residential dwellings in the south west of England were chosen using convenience-sampling methods described in chapter 4. Building 1 consisted of predominantly two main constructions. A 18th century solid cob construction and a 19th century solid stonewall construction. Building 2 comprised of an 18th century solid stone cottage with a 21st century concrete block cavity wall extension. Both buildings offered large back gardens, which enabled a thermal camera to be positioned so that entire elevations can be observed. Building selection was based on the need to find contrasting construction methods that reflect on existing UK housing stock and held the likelihood that defects would be present. By investigating a mix of construction types, a broader interrogation of temporal resolutions for time-lapse thermography of different scenarios could be studied.

Hardware

To perform time-lapse thermography a FLIR T620bx thermal camera was set on a tripod facing the target building surface and positioned far enough away so that as much of that surface could be captured within the Field of View (FOV). Climatic conditions were monitored using a WH1080 wireless weather station. See chapter 4 for more detail on these two items of equipment.

Indicative surface temperatures were obtained using simple k-type thermocouples fixed to the wall at head height next to an openable window and readings were noted manually; these served as a benchmark check for the thermographic results.

Data collection

Images were captured every 20 to 30 minutes. This spacing was chosen as a mid point between the 5-minute image spacing used in part 1 of this chapter and the 60 minute displayed image spacing in the work by Lehmann *et al*. (2013). Following the survey period, all images were uploaded and assessed using the FLIR Tools software (FLIR, 2013b). This software enables image adjustment so that each had the same temperature span (between min and max temperatures). This enables a time-lapse sequence of multiple images to be created, covering the same temperature range, and hence that can more clearly show any transient changes.

Practical methodology constraints and controls

There has been no previous research detailing a time-lapse methodology for passive building thermography. This work therefore sought to introduce and explored a practical methodology for this form of thermographic investigation.

Through conducting time-lapse experiments using passive building thermography, practical issues were identified. Limitations to a time-lapse methodology have been encountered both internally and externally. External constraints encountered during studies 1 and 2 included:

- The safe and secure positioning of equipment;
- Challenges with monitoring environmental conditions (wind, rain, cloud cover);
- Maintaining power for equipment throughout the survey period;
- Balancing spatial resolution with FOV;
- Minimising human interference;
- Limitations on viewing different elevations.

Pearson (2011) suggests that there are fewer limitations to internal thermography than external thermography due to the presence of a more controllable environment. However the following limitations were encountered during study 3:

- Capturing entire elevations within narrow FOVs;
- Avoiding occupant interference;

- Avoiding unwanted foreground objects.

Once the practical limitations had been considered, a robust practical methodology for time-lapse thermography could be developed. Figure 64 illustrates the equipment set-up for an external time-lapse investigation, and the following aspects detail the practical approach to the acknowledged methodology constraints.

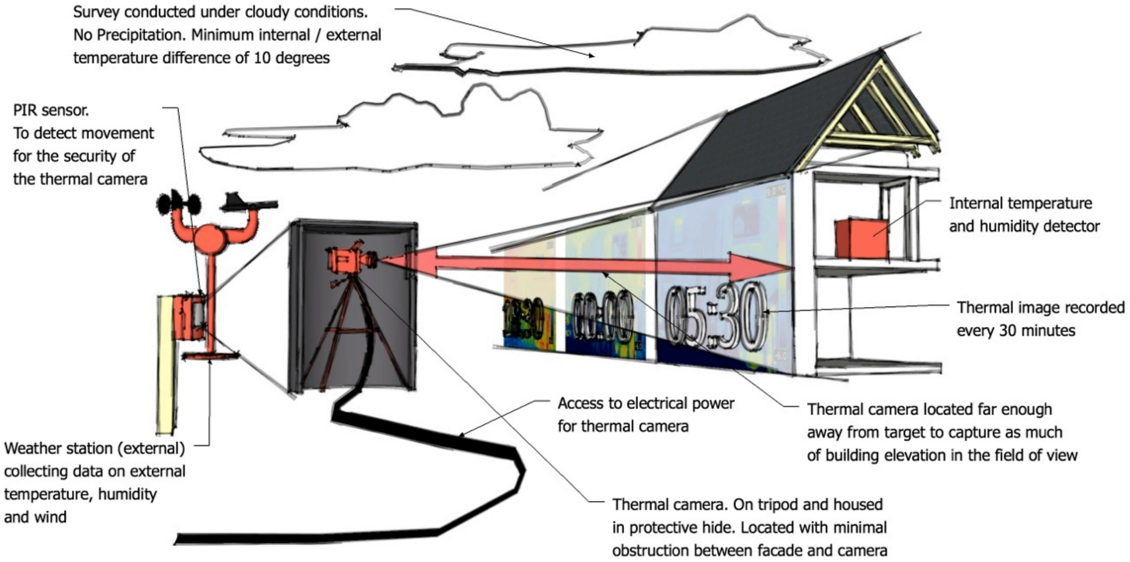


Figure 64. Experimental set-up for external time-lapse thermography.

Safety and security

Although less of an issue during internal investigations, when left outside unattended for prolonged periods of time, thermal camera (valued at approximately GBP £20,000) safety and security was a key concern. Despite positioning the thermal camera in back garden locations; away from public view, the security risk was not completely eliminated. To further aid security, a remote passive infrared (PIR) alarm security device was used to observe the vicinity of the thermal camera during the experiments (Figure 64). Weather protection was also paramount. While nights with a cold and dry weather forecast were chosen, care needed to be taken that the thermal camera did not get wet when left outside. To guard the camera against precipitation and frost damage, a simple shelter with a viewing hole was placed over the camera as shown on the left of figure 65. This proved invaluable during the unexpected snowfall experienced under study 2 as shown in the image on the right of figure 65. Also a water-filled watering can was used to weigh down/steady the tripod and shelter from movement/vibrations due to unexpected wind.

Figure 65. Tripod mounted thermal camera housed within a simple plastic shelter. (left). Snow covered experimental set-up (right).

Monitoring environmental conditions

Environmental conditions such as temperature, precipitation and wind were easily monitored using a weather station however monitoring the presence of cloud cover (which might reflect off the target surface) was very difficult due to the large expanse of sky and potential for fast moving and irregular density of cloud cover. Although forecasted cloudy nights were chosen, the actual presence and density of cloud was not observed, and might have impacted on the results of the external experiments. It is therefore important to note such factors and their potential for impacting upon time-lapse results, which might vary from image to image in a continuous sequence.

Prior to a thermal image being recorded, ITC (2006) recommend pointing the thermal camera away from the observed object to identify surrounding sources of infrared radiation (sky, other buildings, appliances etc.), which might reflect off the target surface and could impair measured results. This methodology might work for images captures at a single point in time, however for automated periodic image recording, a second thermal camera would be required. To obtain reflected apparent temperature (RAT) of the surrounding objects (sky, walls, foliage etc.), the aluminium foil methodology was used as set out by Fokaides & Kalogirou (2011).

Maintaining power for equipment

The battery operational time for the T620bx thermal camera is listed as being 2.5 hours long (FLIR, 2013a). To avoid reliance on battery power, it is essential to either maintain a mains electricity supply throughout the experiment. Alternatively, an additional battery would be required; for instance a typical 60Ah automobile battery (using a Buck-boost converter giving 97% conversion efficiency) would power a 3amp rated thermal camera for about 19 hours. Whist this is easy to address internal thermography with mains electricity, it is more problematic for external thermography, which requires long extension leads that place restrictions on camera location and distance from target surface. A source of external mains electricity was available for all studies in this paper, but future studies might not have this amenity. Furthermore relying upon mains electricity might limit the positioning of the thermal camera (to the garden), as it could be impractical to establish a power supply some distance from the property due to features such as roads. For studies 1 and 2, mains electricity was supplied via a 20m-extension cable.

Balancing spatial resolution with FOV

Traditional walk-by/ walk-through methodology permits thermographers to scan entire surfaces at relatively close proximities. Multiple views of the surface can then be captured and merged into higher spatial resolution single images of the elevation (Phan, 2012). Unattended automated time-lapse thermography however requires the thermal camera to be fixed on a tripod, resulting in only one view being captured. In order to capture as much of the surface within the FOV as possible, this means that the camera is often at a large distance from the target. As discovered from the findings in chapter 5 on walk-through thermography, the further the thermal camera is from the target, the more difficult it is to discern small detail accurately. The camera used in these studies held an IFOV of 0.69mrad, which at a 20m distance with a pixel size of 640 x 480, meant that defects smaller than 42 x 42mm could not be accurately measured due to falling below the MIFOV. For comparison, had the camera been 5m from the surface, defects as small as 10.4 x 10.4mm might have been detected.

Similarly, by attempting to capture an entire internal wall surface within the FOV, the thermal camera needed to be placed as far from the observed surface as possible. Given the small domestic room size for study 3 (4.5m x 2.5m), the thermal camera had to be located on the farthest opposite side of the room to the target. Based on the camera FOV (25^{o} x 19^{o}), this gave an observable area of 2m x 1.5m, which proved insufficient to capture the entire external wall surface of 2.5m wide x 2.8m high. Therefore only a portion of the wall could be observed at once using this camera / lens. To help provide a larger FOV, a wider angle lens could be used, though these can prove costly.

Minimising human interference

In addition to unwanted foreground obstructions (see chapter 4), it was important to instruct all occupants to avoid entering / using the survey room or garden whilst the experiment was being conducted as they might adversely impact on results.

Single elevation view limitation

Because of a combination of security, FOV and power supply issues, it became routine to locate the thermal camera in back garden settings. Whilst mitigating these known limitations, this factor also became a limitation itself, since the experimentation was largely constrained to observe rear elevations only. Therefore front and side elevations were more difficult to investigate and had defects been more prevalent in these locations, they may have been missed.

6.3.3 Results

Case study 1: External time-lapse study

Study 1 observes a Devon vernacular cottage that has been constructed using various materials throughout its history. Two construction types (Figure 66) were inspected as part of this case study. The original 18th century cottage was formed from cob construction. Cob comprises of sub-soil, water and straw mixed together and built up in layers to form a solid structural wall that sits on a stone foundation (Bee, 1997; Devon Historic Buildings Trust, 1992). In the 19th century a solid stonewall constructed extension was added to the cob cottage. Both constructions were covered with a cement-based render. Observing the rear (west) elevation, the camera was situated approximately 20m from the dwelling in the back garden.

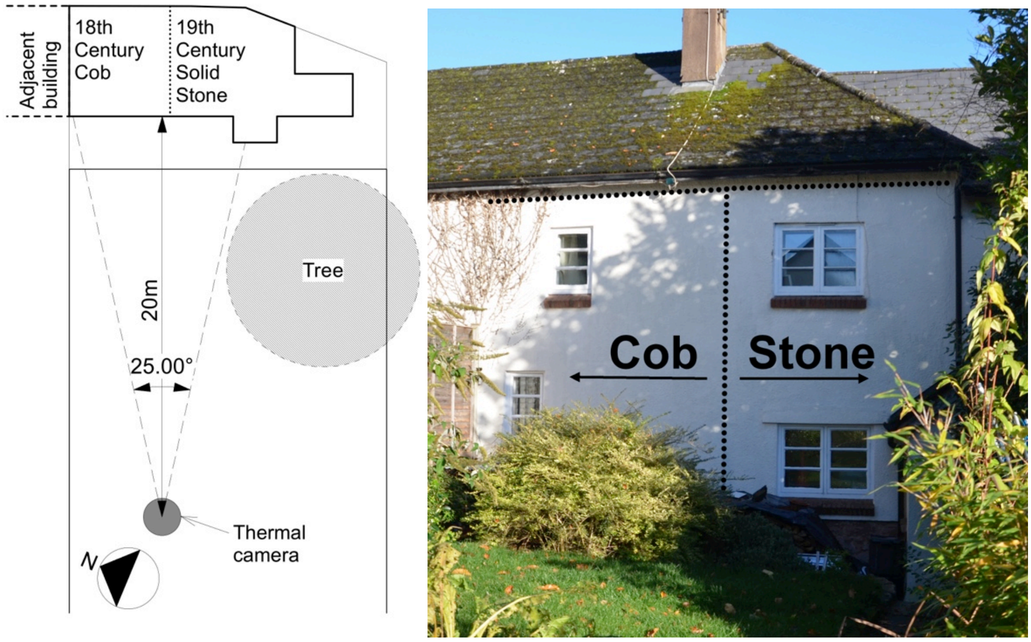


Figure 66. Plan and photo of case study 1 building

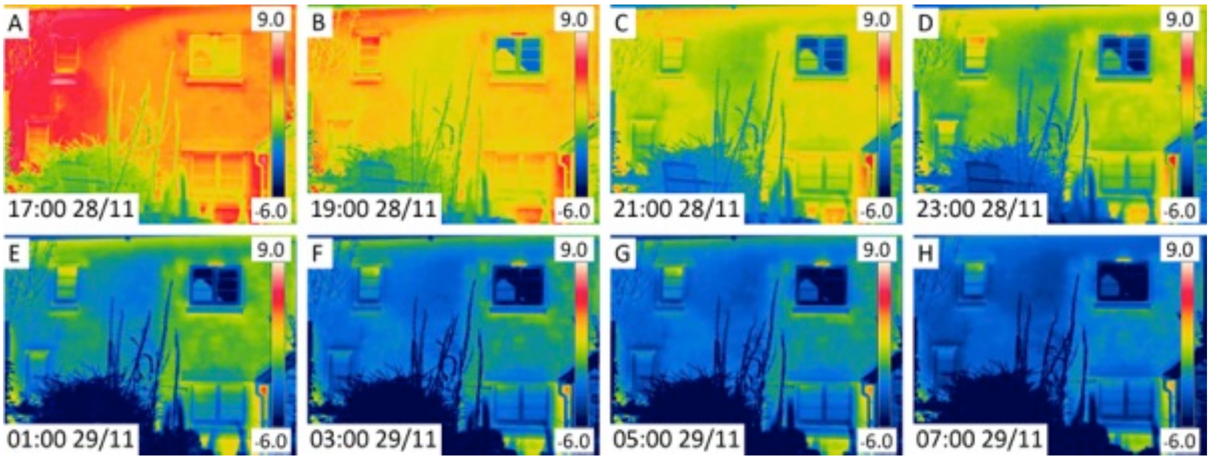


Figure 67. Top left to bottom right (A-H). Study 1. Displayed every 120-minute interval image only (every 4th image).

Table 12 in appendix G presents the parameters for case study 1. Differences in image colour patterns were analysed (Figure 67A-H), leading to the following observations:

a) The cob and stone portions of the dwelling show different thermal behaviour. Figure 67A shows the initial effects of solar exposure during the day, with higher surface temperatures for the cob walling (5.2^{o}C) noticed at the start of the survey that progressively cool down throughout the study into the morning, which ended at -3.5^{o}C. It is noted (Figure 67H) that the render over the cob overall had a lower surface temperature (-3.5^{o}C) to that of the render over the stone (-1.7^{o}C).

b) An approximately 1m diameter warmer patch became increasingly notable over time below a window in the cob walling (Figure 68). Although the specific detail of this patch could not be distinguished by thermography alone, at the start of the experiment, the temperature differential between the suspected cob defect and surrounding 'normal' cob was approximately 0.1^{o}C; this differential increased throughout the experiment to 1.0°C by the end, and suggests that the patch represents a defect rather than an image anomaly due to emissivity or climate.

c) Adjacent to this patch, a hairline crack (Figure 68) was observed as being cooler than the surrounding area and could be a related issue.

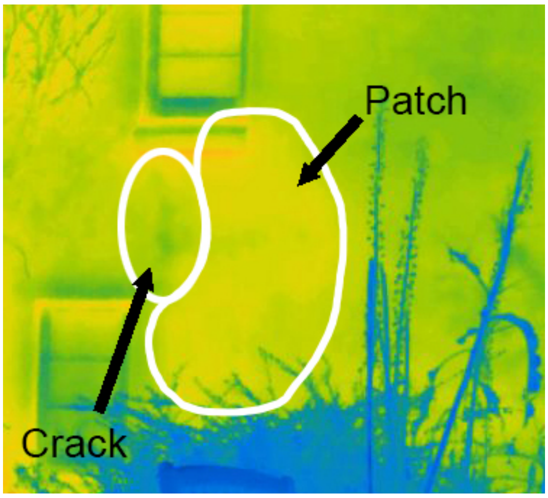


Figure 68. Locations of identified crack and patch

Case Study 2: External time-lapse study

The original cottage was formed of solid stone construction with a 20th century rendered concrete block extension towards the rear of the dwelling. Combining modern with traditional construction, this portion of the dwelling formed the focus of this study. Located in the back garden, 20m from the dwelling, the thermal camera was angled to observe the northwest elevation (see Figure 69). Table 13 in appendix G presents the parameters for case study 2.

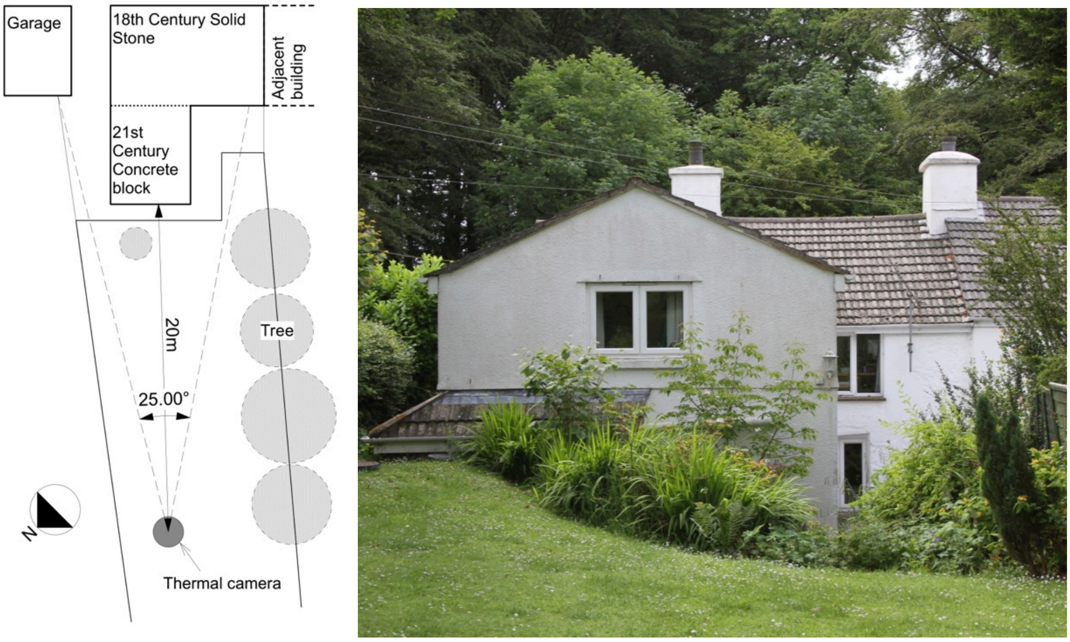


Figure 69. Plan and photo of case study 2 building

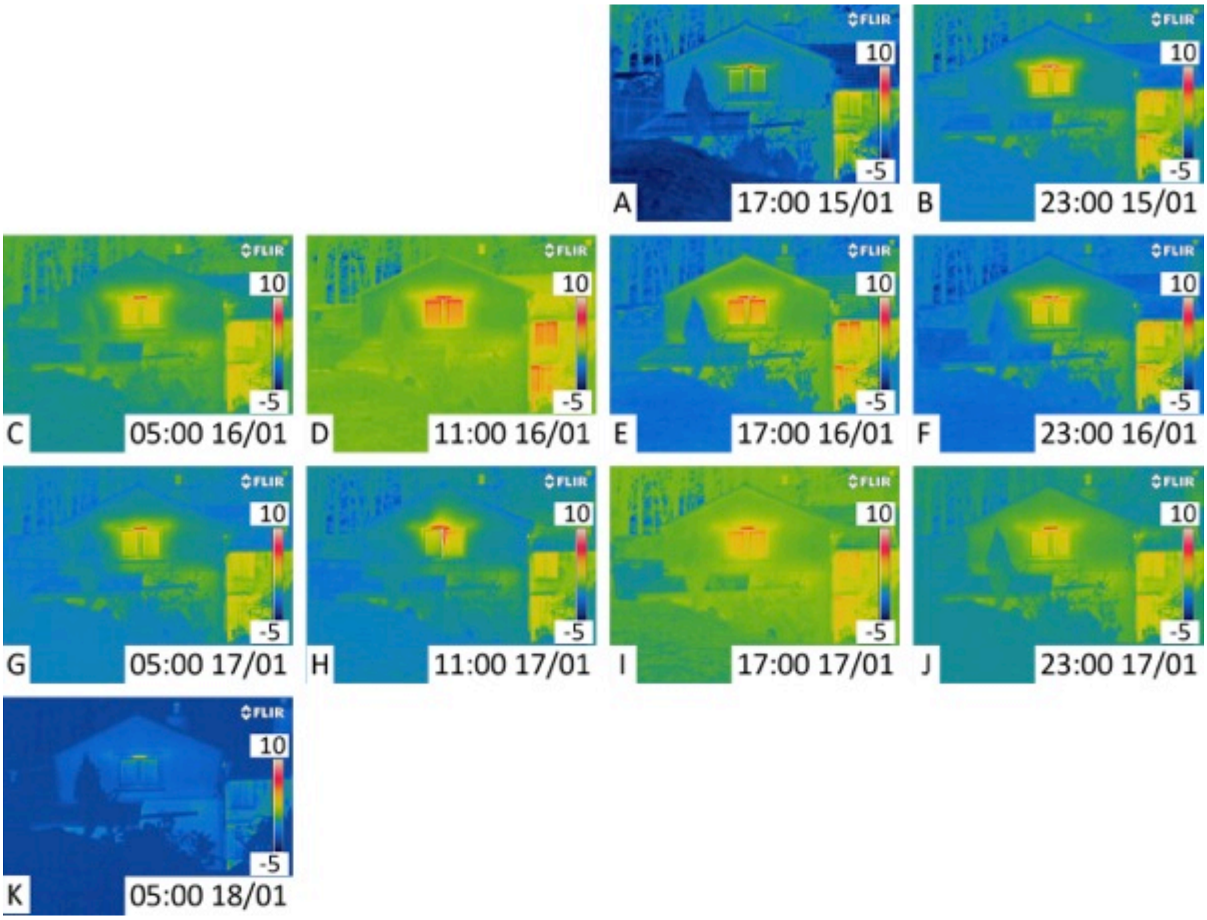


Figure 70. Top left to bottom right (A-K). Study 2. Displayed every 360-minute image only (every 12th image).

From Figure 70A-K, several areas of interest can be observed, including differences in surface temperature between the original stonewall construction (back right of images) and the newer rendered concrete block, cavity wall extension (foreground building). Above the window of the extension, a warmer patch is identified, which marks the location of a lintel. Within this patch is an even warmer feature, which shows internal heat escaping through air leakage from a trickle vent.

Recorded at 17:00 over three days, Figure 70A, E & I illustrate qualitatively how thermal patterns appeared to fluctuate from day-to-day during study 2. Measured apparent temperatures recorded at this time fluctuated from 0.1°C to 1.8°C. In order to minimise the effects of thermal mass from the day before, generic wisdom states that building thermography should be conducted in the morning, before sunrise (Eads, Epperly & Snell, 2000; Vollmer & Möllmann, 2010), yet further comparisons between Figure 70C, G & K recorded at 05:00 over three days again show discrepancies with measured apparent temperatures ranging from -1.1°C to 1.1°C. At both 17:00 and 05:00 time intervals, a temperature difference of about 2.0°C was experienced over three days.

Case Study 3: Internal time-lapse study

Using the same building as used in study 1, this experiment explored internal time-lapse thermography. Located in a bedroom to observe an east facing external wall (Figure 71), the construction observed was predominantly solid cob with a thinner section of brick infill above a window. Table 14 in appendix G presents the parameters for case study 3.

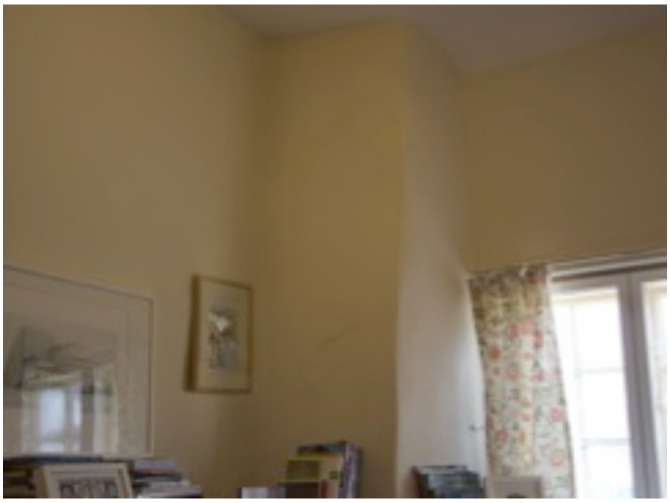


Figure 71. Photo of case study 3

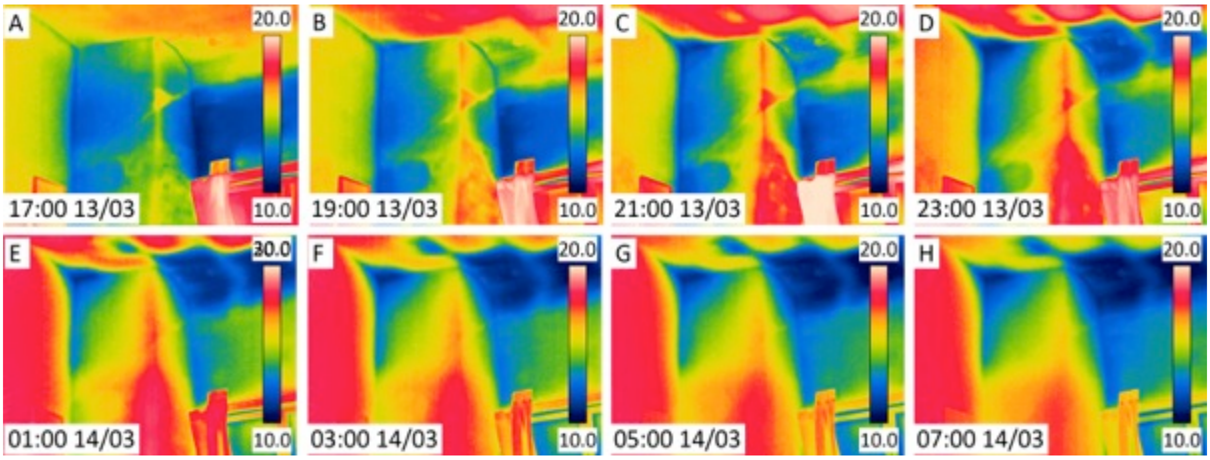


Figure 72. Top left to bottom right (A-H). Study 3. Displayed every 120-minute image only (every 4th image).

Qualitative interest included noticing unidentified features that were seen as bright markings within the cob. These patterns were clearly visible at the start of the investigation (Figure 72A–C), though diminished in clarity as the survey proceeded throughout the night, before becoming completely indistinguishable by the end (Figure 72H). Above the window was a patch of solid brick walling that appeared cooler than the adjacent cob. Above the brick was a patch located within a corner of the eaves and which appeared even cooler than the brick and other parts of the eaves.

Temporal resolution exploration

Seeking to investigate different time-lapse thermography temporal resolutions, a 20 to 30-minute image interval has been trailed for qualitative data collection over each study. This was based upon past research (Grinzato, Cadelano & Bison, 2010; Kato, Kuroki & Hagihara, 2007; Lehmann *et al.*, 2013; Madding, 2008), which employed time-lapse thermography at intervals of between 5 and 20-minutes for quantitative analysis of close-up fabric studies, U-value investigations and moisture analysis. Once the images had been collected, each had their environmental parameters (atmospheric temperature etc.) adjusted for the specific conditions at that time, measured by the weather station, and had their level and span settings equalised so that all images could be viewed side-by-side. The images were then placed together into a time-lapse movie sequence, which enabled the evolution of heat losses from the inspected elevations to be observed.

The movies used for this analysis can be observed in gif format. Movie 1 (case study 1), Movie 2, Movie 3, Movie 4 (case study 2) and Movie 5 (case study 3) can be found on the CD accompanying this thesis. These time-lapse recordings have been processed in the following way. Initially, the movie sequences consisted of each recorded frame, giving the full 20 or 30-minute temporal resolution. To begin with, these were reviewed using qualitative analysis techniques (Walker, 2004), including target signature, target symmetry and target comparison. From this investigation, it became apparent that some images in the sequence were very similar to subsequent images. This is best observed through Movie 2, which shows a 20-minute temporal resolution for case study 2. In this movie, very little colour change over the concrete block cavity wall between images was discernable. Seeking to address this, further movies at longer temporal resolutions were created for case study 2, which included 120 (Movie 3) and 360-minute (Movie 4) intervals. At 120-minute intervals, the colour change between surface temperatures was much more discernable than at 20-minute intervals, while at 360-minute intervals the spacing did not appear to offer greater contrast to the 120-minute temporal resolution.

Following qualitative analysis, quantitative analysis was used to measure the change in target apparent surface temperature between images. Figure 73 shows a thermal transect graph, which was plotted for the cob and stone portions of study 1. Measured using two lines, as indicated in the thermal image above the thermal transect, this graph was plotted for each 30-minute interval thermal images for building 1. The bold lines highlight 120-minute image intervals, and correlate with thermal images displayed through Figure 67A – H. The grey block within the graph indicates the presence of the crack defect. This is verified in Figure 74, which shows a photo of this crack and signs of bubbling paint/plaster either side of the crack.

The apparent surface temperature difference between 30-minute spaced images, for the cob gave an average of 0.3^{o}C, while for the stonewalling, the temperature difference was 0.2^{o}C. At 120-minute intervals, the average apparent temperature difference for the cob was 1.2^{o}C and for the stone, 0.8^{o}C.

Comparing the measured apparent surface temperatures of different constructions at 60-minute image spacing's, the average temperature differences between images were:

- Cob (study 1): 0.5°C
- Stone (study 1): 0.4°C
- Concrete block cavity wall (study 2): 0.2°C

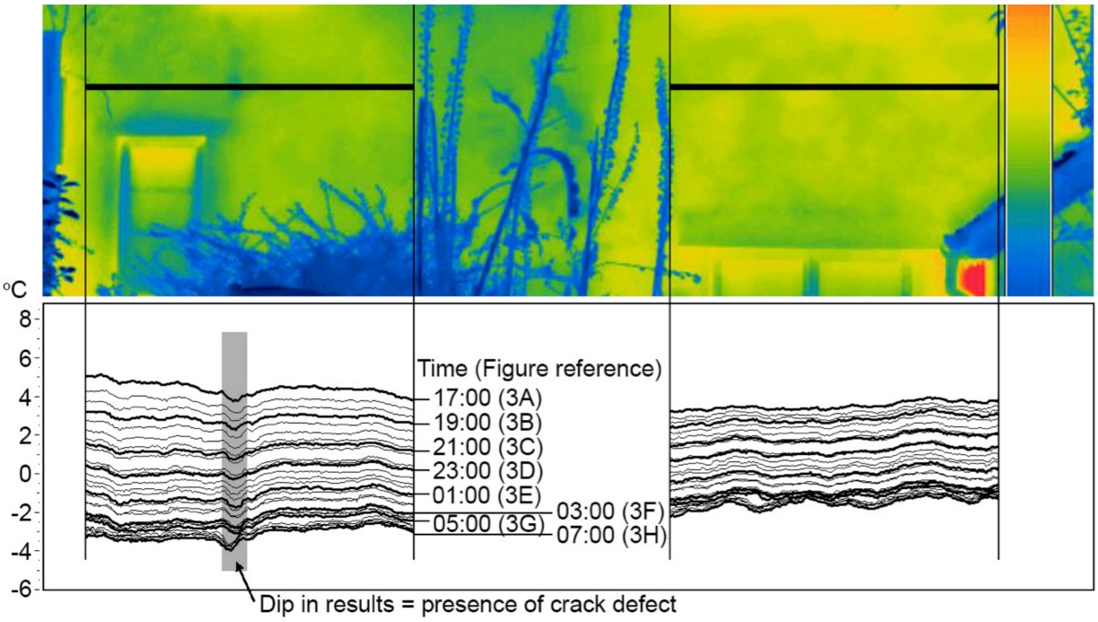


Figure 73. Thermal transect for building 1.

Figure 74. Photograph of crack defect.

6.3.4 Analysis

Results shows that time-lapse thermography offers deeper insights into how unknown constructions might be behaving compared with traditional analysis using thermal images taken at one single point in time. Once a better understanding of how a construction might be behaving (over time) is made, behavioural nuances can be factored in so that potential defects become more straightforward to identify and diagnose. See for instance study 1, where a warmer patch was identified within the cob walling. Following quantitative analysis of temperature differentials (Figure 73), clearer assumptions on the defect type could be made. In this specific case delamination was identified through gentle tapping of the identified area, which gave a dull hollow sound. It was unclear whether moisture was present beneath the cement render, though Keefe (1993) suggests a common failure with cob arises when moisture enters cavities behind cement render via hairline cracks (also observed in case study 1). The temperature effects captured through the time-lapse thermography could result from the presence of moisture, because water holds a higher specific heat capacity than other common building materials, and will retain heat longer than materials surrounding it (Jensen, 2000).

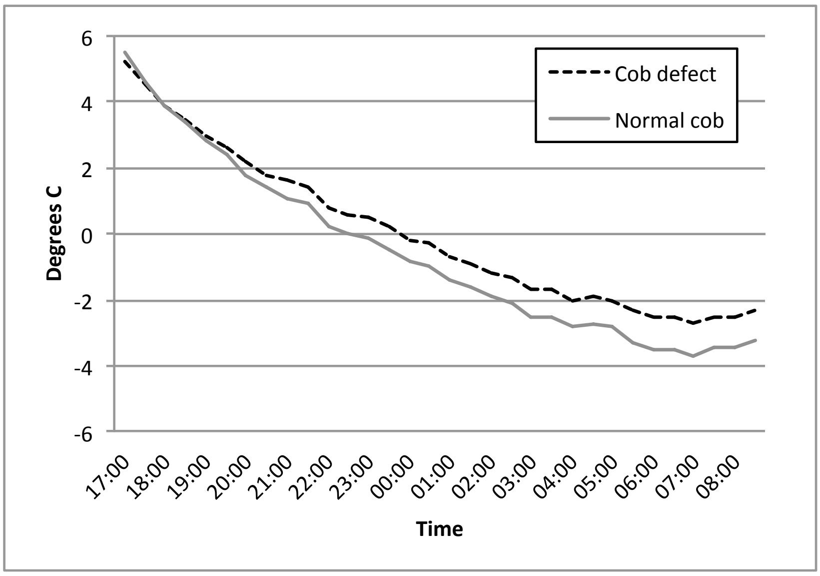


Figure 75. Temperature difference between normal cob and cob warm patch.

Although the defects identified in study 1 might have been detected using single point in time thermography (following a reduction in thermal mass stored from the previous day), what time-lapse thermography enables is assessment through image evolution, where thermal patterns transform from one state (temperature) to another to illustrate the unfolding/progressive behavioural changes in an observed target. Such evolution can be seen in figure 75, which displays the increased temperature difference between the normal cob and warm patch in the cob (potential defect). Furthermore, viewing the time-lapse images in a motion sequence helps to qualitatively review the evolution of heat losses, which also indicates how materials respond to changes in transient conditions. This extra layer of information is something devoid from single point in time analysis.

Study 1 showed that the effects of solar gain presented a significant limitation to thermographic results. This corresponds with findings by Lehmann *et al*. (2013), though largely depends on the elevation viewed, as study 2 was not subject to solar gain in the same way. Once stored solar energy had been released (study 1), the heat flow from inside to outside became increasingly apparent, leading to a clearer picture of potential defects later in the investigation. Conversely, the internal investigation (study 3) presented clearer images at the start, prior to the introduction of artificial domestic heating. As the wall surfaces warmed up through domestic heating the heat appeared to dissipate through the construction and led to a reduction in image clarity. Had study 3 been undertaken using a single point in time methodology following a period of domestic heating, potential subsurface defects might be missed or misinterpreted. It is therefore critical to consider the effects different heating sources might have on how a construction might behave, whether it is heating from the sun or from internal appliances.

Work to develop a time-lapse thermography methodology has shown that there are more practical limitations to overcome externally than experienced within internal investigations. In particular, attention needs to be taken over the security, weather proofing, monitoring of environmental conditions and power supply for the thermal camera. In light of these key limitations and methods for overcoming these, the time and effort required to setup and maintain a time-lapse investigation for prolonged periods of time are quite considerable and might prove prohibitive for commercial application.

Temperature variations between each of the observed construction types were seen as being quite different, when viewed at the same temporal resolution. This suggests that the temporal resolution selected will largely depend on the type of construction being monitored, where for example, more modern and highly insulated constructions will show a slower flow of heat (from inside to outside) compared with older solid masonry constructions.

Analysis of different temporal resolutions showed that apparent surface temperature differences between consecutive images could fluctuate significantly, as seen through the thermal transect in figure 73. For example temperature differences between 60-minute image spacing's for the cob in study 1 started at 1.4^{o}C between 17:00 and 18:00 before ending at 0.2^{o}C between 07:00 and 08:00 the following morning. This result of this was most likely due to transient changes in environmental conditions, such as the thermal mass experienced in study 1. The impact of this is significant because if a temperature difference of no greater than 1.0^{o}C is chosen between consecutive images, then a temporal resolution shorter than 60-minutes might be required to ensure that all temperature differences are below 1.0^{o}C.

This work has demonstrated how environmental conditions and building properties can fluctuate over multiple days (study 2), giving a surface temperature difference of about 2.0^{o}C between images recorded at identical times over three days. This was as a result of transient environmental conditions such as air temperature, precipitation and cloud cover, which had impacted on the apparent surface temperature results during the entire study period. Consequently if thermography were conducted externally on just one of these days, the results would be different to that undertaken on another day. This therefore questions the ability to obtain accurate results from relatively short time-lapse investigations and particularly from single point in time images, indeed Biddulph *et al.* (2014) recommend in situ investigations of at least 3 days for better estimation of U-values using heat flux sensors, therefore if quantitative analysis using time-lapse thermography were to be pursued, then it would be advisable to conduct investigations over at least 3 days before taking averages from the results and drawing conclusions on how environmental conditions are impacting on the results.

6.3.5 Part 2 Conclusion

The work in this part of chapter 6 has explored the practical application of a time-lapse thermography for building defect detection. Contrasting time-lapse thermography with traditional methodologies that capture one moment in time it was evident that although traditional studies might be useful in capturing particular defects at one moment in time, often this methodology is constrained by physical limitations such as reflected radiation and the interaction between transient weather conditions and materials (solar gain and moisture). This makes assumptions on defect behaviour or thermal transmittance using single point in time images particularly challenging. Passive time-lapse thermography however has been shown to enable the evolution of heat loss to be observed and thus better understood.

Through the application of time-lapse thermography in this work, a methodology for such an investigation has been developed. This addresses practical limitations, comprising of safety and security concerns, spatial resolution / FOV limitations resulting from camera distance to object surface, unwelcome foreground objects, difficulties observing front elevations, and challenges involved with supplying continual power to the thermal camera.

This chapter also investigated the different temporal resolutions required for time-lapse analysis of different building constructions. Qualitative analysis of the time-lapse movies recorded at 20 – 30 minute image intervals showed that some images in the sequence were visually identical to consecutive images, not helping to discern variations within thermal patterns. With regards to the selection of temporal resolution for time-lapse analysis, results from the three studies showed that a greater accuracy in surface temperature difference (lower temperature differences between consecutive images) was gained from shorter temporal resolutions. Whilst a high degree of temperature accuracy such as 0.2^{o}C between images intervals might be required for quantitative analysis (such as U-value determination), for qualitative analysis such low differences were not visually discernable. Instead temporal resolutions that gave approximately a 1.0^{o}C surface temperature difference between images seemed more appropriate. Also findings from part 2 of this chapter indicate that periods lasting longer than one day might be preferable for time-lapse quantitative analysis.

6.4 PART 3. Time-lapse thermography for quantitative U-value measurement

6.4.1 Introduction

U-value measurement is seen as one of the main methods for quantifying the success of building insulation/thermal transmittance (Young, 2014). In-situ U-value measurement by thermography is becoming more commonly requested (Red Current, 2012b). Although U-value analysis is not directly related to building defects (which is the focus of this thesis), because of the increased application of time-lapse thermography for quantitative U-value analysis over other forms of defect detection (as identified in chapter 3), it would be remiss if this application was not explored as part of this methodology investigation. As discussed in chapter 3, conductivity heat loss defects will also impact upon fabric thermal transmission. Therefore, whilst not specifically addressing building defects, by measuring in situ U-values, a deeper understanding of defect severity could be made. Based on these arguments, an investigation of U-value measurement by thermography became the focus of this part of chapter 6.

Early work by Vavilov *et al*. (1997) explored the use of building thermography for quantitative analysis over prolonged periods of time. Their conclusions recommended the use of a methodology, which consists of multiple images that could better capture transient environmental changes for more informed defect detection. This recommendation is significant, since as observed in part 2 of this chapter, changing climatic conditions can have a significant effect on the ability for the thermal camera to accurately measure apparent surface temperatures, due to the effects on building fabric, where material properties change on a transient basis (Lehmann *et al.*, 2013), particularly when subject to environmental stimulus such as moisture or solar gain. Baker (2011) suggested that an in situ sand stone example would have had a U-value of 1.5W/m^{2}K if dry, while 2.4W/m^{2}K if it was saturated.

Because of these transient changes, some thermography commentators such as Pearson (2011) caution against the accuracy of in situ construction thermal transmittance results, in particular when relying upon single images for quantitative analysis (Johansson, Hagentoft & Kalagasidis, 2014; Young, 2014). Red Current (2012b) highlight the need for steady state conditions when seeking to conduct U-value calculations with thermography, particularly as typical thermographic surveys record single images, which will not capture the effects of a constantly changing environment and therefore make obtaining accurate U-values more difficult.

In the 2008 paper, *Finding R-Values of Stud Frame Constructed Houses with IR Thermography* by Madding (2008), the use of periodic image recording was applied to observe both in situ and lab-based examples of wall build-ups. From this information, Madding was able to assess construction thermal transmittance. To do this a thermal camera was positioned to record thermal images of the wall sample every 15 minutes over a 24-hour period, which were then processed using an equation (EQ. 2) developed by Madding to measure in situ U-values.

$$U=1/R=\frac{\Delta Tio}{4\varepsilon\sigma Tm^3\Delta Tr\ +\ h_c\Delta Ta}\,W/m^2K$$

EQ. 2. Equation for determining in-situ U-values by thermography (Madding, 2008).

Where:

U = U-value (W/m^2K)

R = R-value (m^2K/W)

ΔTio = Temperature difference between inside air and outside air (K)

ΔTr = Temperature difference between surface and reflected apparent temperature (K)

ΔTa = Temperature difference between the surface and inside air (K)

Tm = Mean temperature (K)

ε = Emissivity of the surface

σ = Stefan-Boltzmann constant - 5.67×10^{-8} ($W(m^2K^4)^{-1}$)

h_c = Convective heat transfer coefficient (W/m^2K)

Fokaides and Kalogirou published another paper, '*Application of infrared thermography for the determination of the overall heat transfer coefficient (U-Value) in building envelopes*' (Fokaides & Kalogirou, 2011), which used a similar calculation method to Madding's to determine fabric U-values through the application of thermography. Working with real building cases, they captured thermal images every 20 minutes over 3 hour periods for each observed building element. U-values were calculated for the observed surface in each image before being averaged. Both Madding's and Fokaides & Kalogirou's studies utilised internal thermography. Conclusions from these suggested that although quantitative data was not completely accurate, the absolute deviation values for both studies were between 5 and 20% from an acceptable level for the thermal transmittance of sample.

While work by Madding and Fokaides & Kalogirou measured fabric U-values from the inside only, Nardi *et al.* (2014) explored external U-value determination using thermography, which was compared against heat flux measurements. From single thermal image U-value analysis on two different days, results ranged from about 2% to 37% in accuracy compared with design based U-value results for the construction sampled. Others using external thermography for U-value measurement were Albatici & Tonelli (2010). They explored external U-value determination using thermography of three in situ case studies in Italy. Observing two timber frame dwellings and one insulated brick block dwelling, their work captured thermographic data over a 2 – 3 hour period starting at 3 or 4am in the early morning. This was described as a limitation imposed so as to minimise the effects of solar radiation gained during the previous day. They also highlight wind as a key limitation to external quantitative thermography, suggesting speeds lower than 0.2m/s as the most desirable conditions with results potentially varying by up to 80% when wind speeds exceeded 1m/s across surfaces. Fabric U-values were equated from the quantitative data within thermal images. Results found that measured in situ U-values ranged from 27% to 31% higher than theoretical/predicted U-values using technical standards (Albatici & Tonelli, 2010) for the same constructions. This range correlates with Pearson (2011), who states that the accuracy of calculated U-values from thermography will be at best ±25%, though could be worse for well-insulated walls. Furthermore Doran (2000) argues that actual U-value results are often 20% higher than predicted values.

Analysing the work by Madding, Vollmer & Möllmann (2010) delve deeper into the subject of the convective heat transfer coefficient, which is suggested as being one of the most critical inputs to Madding's calculation. This is deemed fundamental to

U-value measurement, since the effects of air movement across a surface will impact on the surface boundary layer of air, which could be changing on a frequent basis. For instance, too little air movement and the surface boundary will act as an insulator, while too much air movement and the surface boundary layer will be removed, and the effects of forced convection are more likely (Balaras & Argiriou, 2002; Vollmer & Möllmann, 2010). It could therefore be argued that seeking to conduct U-value calculations using thermography on the external face of an external wall will poses a significant risk to the accuracy of results.

Wind is not the only external environmental factor that can significantly impact on results. Möllmann & Vollmer (2008) state that night sky radiant cooling as being potentially significant to the successful interpretation of thermal images. As temperatures in the region of -60°F (-51°C) (Madding, 2008) from a clear sky can be reflected off surfaces, particularly those that have a low emissivity (ITC, 2006). Consequently thermographers such as Asdrubali *et al*. (2011) argue that it is very difficult to conduct accurate external thermography due to such difficulties in achieving a steady state external environment. Further comments by Madding (2008) suggest that quantitative thermography should only be conducted internally so as to minimise the effects of environmental conditions.

Based on past literature and the work undertaken during part 2 of this chapter (specifically building 2, case study 2), it is undeniable that external environment conditions pose greater transient challenges/limitations to thermographic analysis compared with internal thermography and more steady state laboratory conditions as found in part 1 of this chapter. Because climatic factors such as wind, solar gain and moisture have been shown to significantly affect the way that thermal cameras perceive construction materials, it is not appropriate to conduct external quantitative analysis using thermography. Internally materials are less prone to fluctuation and present a better opportunity for in-situ quantitative analysis. Because of this, the work in this part of chapter 6 will only seek to measure U-values from the inside.

For more accurate heat loss measurements of existing buildings, Hart (1991) suggests that it might be more appropriate to use thermography in combination with a heat flux meter to better determine the thermal performance of a wall. Indeed, heat flux measurement is acknowledged as one of the primary methods for in-situ U-value determination (Asdrubali et al., 2014; Desogus, Mura & Ricciu, 2011).

Because of the doubts (Hookins, 2009; Pearson, 2011; Red Current, 2012b) surrounding in-situ U-value measurement using thermography and the newness of the time-lapse/measurement methodology compared with the more established heat flux measurement methodology, this part of chapter 6 seeks to directly compare the two measurement methodologies. By undertaking this, a clearer understanding of the accuracy that thermography U-value measurement can achieve will be made. Although work by Nardi *et al.* (2014) compared thermography measured U-values with heat flux U-values, their thermography results were based on single images, which as discussed earlier, is not deemed appropriate for U-value measurement (Young, 2014). Therefore, this work is unique in blending time-lapse thermography with heat flux measurement for U-value estimation.

6.4.2 Detailed Methodology

To explore the success of time-lapse passive thermography for U-value determination, three case study experiments were conducted using the following wall constructions:

1. Cob wall construction (18th century)
2. Stone wall construction (19th century)
3. Present day concrete block, insulated cavity wall construction (21st century)

Constructions 1 and 2 formed part of the same dwelling. This was the same dwelling as building 1, which was inspected in part 2 of this chapter. A number of reasons led to this building being used again. As previously mentioned, this dwelling comprised of an original 18th century cob construction dwelling, which had been extended in the 19th century with a stonewall extension. These two wall build-ups were deemed to represent vernacular constructions that were commonly found within the South West of England, and aligned with the focus area of this thesis. Convenience sampling also played a part in the re-use of this building. Because lengthy surveys were planned for these case studies, it was deemed important to choose a building, which offered familiarity to the author, suitable case study constructions and enabled flexibility in survey period (to coincide with the most appropriate weather conditions forecast).

Construction 3 formed part of an existing late 20th century dwelling, which had recently been extended using a concrete block, insulated cavity wall construction. Since this construction was designed to conform to current building regulations, and the cavity had been nearly fully filled (a 5mm unventilated cavity was present), this construction presented the opportunity to compare the two in situ U-value measurement methodologies on a more insulated example.

Another factor that influenced the selection of these case study wall samples was based on convenience sampling, where previous access and knowledge of these dwellings made it easier to re-visit for further inspection.

Details of the three construction build-ups are illustrated in figure 76. While the precise construction of the 21st century concrete block, insulated wall was fully known due to design-based information; the stone and cob constructions could only be based on assumptions. This was because of the uniform surface finishes making it impossible (without destructive investigations) to ascertain for certain the construction build-up by visual analysis alone. These constructions were assumed, based on past knowledge of similar constructions, the overall wall thicknesses and literature documentation (Baker, 2008; Baker, 2011; Rye & Scott, 2012).

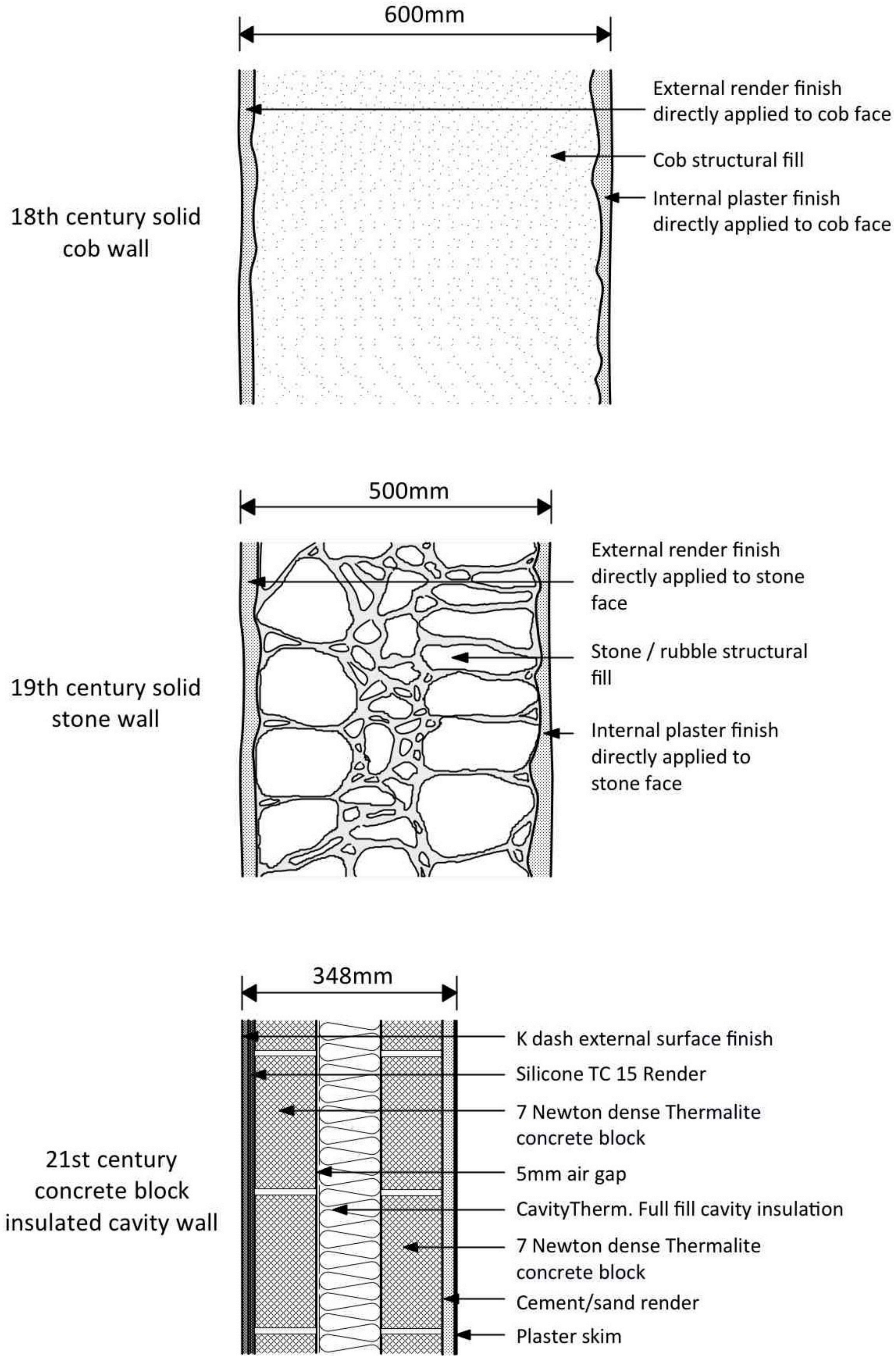


Figure 76. Cross-section details through the three construction case studies.

The following sections describe the detailed methodologies used for measuring the in-situ U-values of the three wall constructions. The same methodology was applied on each occasion and comprised of two primary aspects:

- Heat flux measurement
- Thermography measurement

Heat Flux measurement methodology

The first aspect of these case study experiments was to measure in-situ fabric U-values using heat flux sensors. Heat flux (Q) is the measurement of heat energy flowing through an area of a defined body (Szokolay, 2008). The methodology for this part of the experiment was developed in accordance with previous work by Asdrubali *et al.* (2014) and Baker (2008; 2011).

Two calibrated HFP01 heat flux sensors were used for these experiments. The sensor within the heat flux sensor pad is a thermopile, which uses a small voltage (relative to the objects heat flux) that measures temperature differentials across the ceramic/plastic composite pad material (Hukseflux, 2006). Figure 77 shows a photo of one of the heat flux sensors used. A thermal camera was used to help determine the most appropriate location for measurement (Asdrubali *et al.*, 2014), which avoided thermal bridges and known defects. Sensors were also placed equidistance between room corners and window jambs to minimise the effects of thermal bridging (Baker, 2008). Once the location was selected, the heat flux sensors were positioned within (but at opposite sides of) the thermal camera's FOV. The heat flux sensors were fixed to the internal face of the wall to be measured using a heat sink compound applied between the sensor and wall. An average between the two sensors was used for U-value equations.

Figure 77. Hukseflux Heat flux sensor and K-type thermocouple.

Figure 78. Campbell Scientific CR1000 data logger.

In addition to the two heat flux sensors, two K-type thermocouples were used. One was fixed to measure the internal surface temperature, while the other measured the external surface temperature. Both used a heat sink compound to aid conductivity/accuracy. While the internal sensors were fixed to plastered surface using highly adhesive tape, externally the risk of damage to the cement render meant that the external thermocouple needed to be pressed against the surface using a weighted pole.

Following the work undertaken in part 2 of this chapter, and thermography U-value measurements by Madding (2008), it was decided to use a 15 minute temporal resolution for data collection. As mentioned earlier, Biddulph *et al.* (2014) suggested that heat flux data should be collected over at least three days. Work by Baker (2008) utilised a 27 day period and recommended at least one week for measurement. This recommendation was supported by Asdrubali *et al.* (2014), who advocated three days if the indoor temperature was steady, and one week if not. Since the dwellings where the experiments were to be undertaken were in constant occupation, the internal temperature was likely to vary over a three-day period, therefore each experiment was conducted for one week.

As with the case studies reported in part 2 of this chapter, internal and external conditions were monitored prior to and during the experimental period using a WH1080 wireless weather station. As part of this, internal and external temperatures were recorded for later analysis.

All sensors connected to a calibrated Campbell Scientific CR1000 data logger (Campbell Scientific, 2014), which was used to collect data for the experimental period. Figure 78 shows a photo of the CR1000 data logger used. The LoggerNet software (version 4.2.1.1) (Campbell Scientific, 2013) was used to program and collect data from the four sensors. At the end of the weeklong experiment, the data was downloaded from LoggerNet and inserted into Microsoft Excel for analysis.

To begin with the measured voltages from the heat flux sensors needed to be converted into the heat flux (Q). To do this, the measured voltage V_{sen} was divided by the sensitivity of the heat flux sensor E_{sen}, as illustrated in equation EQ. 3 (Hukseflux, 2006). Each heat flux sensor came with a designated sensitivity constant.

$$Q = \frac{V_{sen}}{E_{sen}}$$

EQ. 3. Equation for determining heat flux from Hukseflux heat flux sensor (Hukseflux, 2006).

Combining the calculated in-situ heat flux measurements with internal and external air temperatures, it is possible to use equation EQ. 4 to determine fabric U-values.

$$U = \frac{Q}{Ti - Te} \ W/m^2K$$

EQ. 4. Equation for determining in-situ U-values from heat flux. (Baker, 2008).

Where:

U = U-value (W/m^2K)

Q = Heat flux (W/m^2)

Ti = Internal air temperature (K)

Te = External air temperature (K)

Accounting for multiple measurements over time, Baker (2008) presents a modified version of EQ. 4, through EQ. 5. This equation makes use of the data through applying a moving average of readings over time. Baker proposed using such an averaging method of equation to allow for transient changes in climate and material properties. Without using an averaging method of mathematical analysis, results would be presented as extreme peaks and troughs in U-value results, dependant on the conditions at the exact point the measurements were taken. By using an averaging method, all of the data throughout the entire experimental period can be combined, to indicate an overall U-value for the construction.

With regards to equation EQ. 4, Baker (2011) cautions against relying upon air temperature data for in situ U-value measurement since such data might not be representative of the air temperature directly adjacent to the sample. Baker also cites the increased risk of solar exposure as a limitation to using this equation.

$$U_t = \frac{\sum_{0}^{i=t} Q_i}{\sum_{0}^{i=t} Ti_i - \sum_{0}^{i=t} Te_i} \; W/m^2K$$

EQ. 5 Equation EQ. 4 re-presented as a moving average equation

(Baker, 2008).

Where:

U_t = Average U-value over *t* hours (W/m^2K)

Q_i = Heat flux at interval of *i* hours (W/m^2)

Ti_i = Internal air temperature at interval of *i* hours (K)

Te_i = External air temperature at interval of *i* hours (K)

Thermography measurement methodology

The overall basis for the thermography measurement methodology used in these experiments replicates many aspects from the methodology developed and used within part 2 of this chapter. This included:

- Using a calibrated FLIR T620bx thermal camera (see appendix B for technical specifications).
- Setting the thermal camera on a tripod to observe the target area.
- Avoiding occupant interference
- Avoiding unwanted foreground objects

Once the thermal camera had been set on a tripod, it was positioned to view the same area as covered by the heat flux and thermocouple sensors. Because the objective of this study was to measure the in-situ U-values of wall case studies, it was not important to capture entire elevations within the FOV as in part 2 of this chapter. Therefore, the distance that the camera was from the surface was kept to a minimum (approximately one to two meters). This ensured an optimal measurement based on the cameras MIFOV performance.

A mains power connection was established for the camera and left to acclimatise for 30 minutes (Vollmer & Möllmann, 2010). While acclimatising, a periodic image capture program was set within the camera to record images every 15 minutes (in line with the heat flux sensor and thermocouple measurements).

Along side the sensors attached to the wall, a piece of crumpled aluminium foil (which had been flattened) was placed within the camera FOV. This would enable the measurement of the RAT (Fokaides & Kalogirou, 2011).

The thermal camera collected thermal images every 15 minutes for a weeklong period, which directly corresponded with the data collection procedure with the sensors/data logger.

After the data had been collected for each experiment, the thermal images were uploaded and tuned using ThermaCam Researcher Professional 2.8 SR-1 (FLIR, 2004a; FLIR, 2004b) so that each image could have the correct atmospheric and reflected apparent temperature settings for each time period. The data was then collected into an excel spread sheet, where an adaption to Madding's thermography U-value equation (EQ. 2) (Madding, 2008) was used to calculate a U-value for each time stage. Madding's equation was adapted to measure average U-values over the total duration of the survey period (EQ. 6), in the same manner that Baker's (2008; 2011) equations functioned.

$$U_t = 1/R_t = \frac{\sum_{0}^{i=t} \Delta Tio_i}{\sum_{0}^{i=t} (4\varepsilon\sigma Tm^3 \Delta Tr)_i + \sum_{0}^{i=t} (h_c \Delta Ta)_i} \, W/m^2K$$

EQ. 6. Madding's (2008) equation (EQ.2) re-presented as a moving average equation.

Where:

U_t = Average U-value over t hours (W/m^2K)

R_t = Average R-value over t hours (m^2K/W)

ΔTio_i = Temperature difference between inside air and outside air (K)

Sum of:

ΔTr = Temperature difference between surface and reflected apparent temperature (K)

Tm = Mean temperature (K)

ε = Emissivity of the surface

σ = Stefan-Boltzmann constant - 5.67×10^{-8} ($W(m^2K^4)^{-1}$)

At interval of *i* hours.

Sum of:

h_c = Convective heat transfer coefficient (W/m^{2}K)

ΔTa = Temperature difference between the surface and inside air (K)

At interval of *i* hours.

One of the most important aspects to input into this equation was the convective heat transfer coefficient. There appears to be much ambiguity over this value, and can be subject to a number of elements such as airflow across the surface. Being a large topic in itself, this thesis does not focus on the detail of convective heat transfer coefficient. For the internal experiments in this section, an equation provided by Madding (2008) (EQ. 7) has been used to measure the convective heat transfer coefficient for laminar air flow over a surface. This equation was originally sourced from Holman (1997).

$$h_c = 0.25\left(\frac{\Delta T_a}{L}\right)^{\frac{1}{4}}$$

EQ. 7. Equation for determining the convective heat transfer coefficient for laminar air flow over a surface (Holman, 1997).

Where:

h_c = Convective heat transfer coefficient (BTU/hour·ft^2·F)

0.25 = Constant drawn from Holman (1997)

ΔT_a = Temperature difference between air temperature and surface temperature (degrees F)

L = Length of surface (Ft)

As this equation makes use of imperial units, Madding provides a conversion factor of 5.673 to obtain the convective heat transfer coefficient in metric units.

Uncertainty analysis methodology

Whilst measured in situ U-values can be assessed to gauge how accurate a construction might be compared with each other and different benchmarks (Literature and design), it must be remembered that all measurements contain a degree of inaccuracy (Bell, 2001). One identical measurement taken several times over, is unlikely to be the same (Carlson, 2002). Bell (2001) explains that there is a difference between 'error' and 'uncertainty', which need clarification. While **error** is '*the difference between the measured value and the true value',* **uncertainty** is *'a quantification of the doubt about the measurement result'.* Bell adds by suggesting that while errors are corrected when possible using equipment data corrections, those that cannot be accurately corrected presents a source of uncertainty. While errors are inevitable and are never eliminated, the aim is to minimise these or to have an understanding of their scale (Taylor, 1997).

The reason for uncertainty analysis of the in situ U-value measurements obtained during the experiments in this section of chapter 6 aids in the better understanding of the doubt surrounding the results and in particular, how much variance this doubt/result discrepancy has over final measurements.

The key element to uncertainty analysis is identifying and quantifying errors. Bell (2001) presents a list of potential error sources, which may be taken into consideration. Error sources include:

- The measurement apparatus
- The measurement procedure
- Operator skill
- Quality of sample
- Environmental changes

The sensitivity of each part of each equation (EQ. 5 and EQ. 6) was determined before conducting a 'root mean square' (RMS) uncertainty analysis equation. The resultant product indicated the uncertainty (±) of the measured U-value.

To begin with, measurement errors were determined for each part of the applied equations and for the apparatus used. The following section details the errors selected for the uncertainty analysis procedure.

- **Heat flux U-value errors**
    - **Heat flux sensors.** Each heat flux sensor is supplied with a certificate of calibration. Within this certificate it details the sensitivity of the sensor, a figure that is factored into the Campbell LoggerNet software/CR1000 data logger (Campbell Scientific, 2013; Campbell Scientific, 2014) as readings are taken. In addition to this sensitivity is a known overall uncertainty of measurements, which according to Hukseflux (2006), (who manufacture the sensors) is ±5% for the sensor.

  - **Thermocouples.** Due to a lack of manufacturer data for the thermocouples used, errors margins were obtained from Baker (2011) as being ±0.5K.. Further checks using a high accuracy mercury thermometer confirmed that ±0.5K proved appropriate. It is also important to recognise that each thermocouple gave very subtle differences in temperature measurement. However the subtleties were not considered to be worse that the ±0.5K error used.

  - **Hobo data logger.** For the insulated concrete block case study, it was not possible to obtain external surface wall temperature data using thermocouples as previously obtained on the cob and stone case studies. To overcome this a Hobo U12-012 data logger (Onset, 2010) was used to obtain this data. This had a measurement error of ±0.35^{o}C.

- **Thermal camera U-value errors**
  - **Thermal camera.** The thermal camera used for all three of these experiments was a FLIR T620bx. This had an measurement error of ±2^{o}C or ±2% of reading (FLIR, 2012). It was difficult to determine which of these two errors to use, however following simple calibration checks with hot water containers and thermocouples (Not withstanding the thermocouple errors), an error of ±2% was proven as being most appropriate for these experiments. To harmonise the errors from the thermal camera, the same camera was used for all three experiments.

  - **Weather station.** As with the thermocouples, there was no manufacturer data on temperature error margins. To overcome this, a mercury thermometer was used to measure air temperatures alongside the weather station (internal and external) sensors. At least 5 readings were taken inside and outside over a 24-hour period and the average errors were determined. The internal air temperature sensor was measured as having a ±0.5K error, while the external air temperature had a ±1.0K error.

- **Convective heat transfer coefficient.** Although reliant on apparatus measurements, which themselves hold sources of error, the equation used for the convective heat transfer coefficient in this work has an error of ±15% of any reading generated by the equation (Holman, 2012).

- **Emissivity.** Like convective heat transfer coefficient, the measurement of emissivity is reliant upon thermal camera measurements. There were no known error margins on emissivity found, therefore a series of emissivity measurement checks (ITC, 2006) were performed on similar painted plaster finish surfaces. From these checks, an error of ±0.05 was determined for the emissivity value in these experiments. It is also known that emissivity varies with temperature (Vollmer & Möllmann, 2010) and wavelength (Avdelidis & Moropoulou, 2003; Ravindra et al., 1994). With this in mind, it is possible that the emissivity value might have changed from one reading to the next. This was not factored into the uncertainty analysis, as this was deemed accounted for through the ±0.05 error.

In summary the following errors were used for the uncertainty analysis:

- Heat flux sensors = ±5%
- Thermocouples = ±0.5K
- Thermal camera = ±2%
- Weather station internal air temperature = ±0.5K
- Weather station external air temperature = ±1.0K
- Convective heat transfer coefficient = ±15%
- Emissivity = ±0.05
- Hobo U12-012 = ±0.35°C

With the errors identified for each piece of apparatus and the equations used, the next step was to re-calculate the U-value equations, though this time each error needed to be factored into the equation one at a time. Equation EQ. 8 presents an example where the heat flux U-value equation (EQ. 5) is perturbed by one error, which in the case of this example is the positive perturbation of heat flux (Q). Had this example been a negative perturbation of Q, then the equation would have read Q_i - EQ_i.

$$U_t err\_Q+ \;=\; \frac{1}{\dfrac{\sum_{0}^{i=t} \Delta Ts_i}{\sum_{0}^{i=t} [Q_i \;+\; EQ_i]} + r_{int} + r_{ext}} \; W/m^2K$$

EQ. 8. Example of Baker’s (2011) (EQ. 5) U-value equation perturbed by one error (positive heat flux ‘Q’ error in this case).

Where:

$U_t err\_Q+$ = Average U-value over *t* hours where the equation has been perturbed by a positive heat flux error (W/m^{2}K)

Q_i = Heat flux at interval of *i* hours (W/m^2)

EQ_i = Heat flux error (W/m^2)

ΔTs_i = Surface temperature difference between internal and external surfaces at intervals of *i hours* (K)

r_{int} = Internal surface resistance (m^{2}K/W)

r_{ext} = External surface resistance (m^{2}K/W)

Equation EQ. 8 shows one example where the main equation factors in measurement errors. Subsequent equations were then performed, which allowed for all of the other errors in turn. Given the number of equations needed to allow for all of the errors, these are not included within this text. The spread-sheets (with all of the data) used throughout these experiments can be found on the CD accompanying this thesis.

Once all of the errors had been processed through the U-value equations, the next step was to conduct the RMS equation, which would derive the overall uncertainty of the U-value. Equation EQ. 9 shows an example of the RMS equation for the heat flux experiments, while equation EQ. 10 shows an example of the RMS equation for the thermography experiments. Within the RMS equation, all of the errors are factored in.

$$OA\_U_t = \sqrt{[(U_t - U_t err\_TS_{int}\pm)^2 + (U_t - U_t err\_TS_{ext}\pm)^2 + (U_t - U_t err\_Q\pm)^2]}$$

EQ. 9. Heat flux U-value RMS equation. Based on equation by Baker (2011).

Where:

OA_U_t = Overall uncertainty U-value (±)(W/m^{2}K)

U_t = Measured average U-value over *t* hours (W/m^{2}K)

$U_t$err_ = Average U-value of *t* hours perturbed by the following errors (all in (W/m^{2}K)):

$TS_{int}\pm$ = Internal surface temperature error (±)

$TS_{ext}\pm$ = External surface temperature error (±)

$Q\pm$ = Heat flux error (±)

$$OA\_U_t = \sqrt{\begin{aligned}[&(U_t - U_t err\_\Delta TioT_{in}\pm)^2 + (U_t - U_t err\_\Delta TioT_{out}\pm)^2 + \\ &(U_t - U_t err\_\varepsilon\pm)^2 + (U_t - U_t err\_Tm^3T_{surf}\pm)^2 + \\ &(U_t - U_t err\_Tm^3T_{ref}\pm)^2 + (U_t - U_t err\_\Delta TrT_{surf}\pm)^2 + \\ &(U_t - U_t err\_\Delta TrT_{ref}\pm)^2 + (U_t - U_t err\_\Delta TaT_{surf}\pm)^2 + \\ &(U_t - U_t err\_\Delta TaT_{in}\pm)^2 + (U_t - U_t err\_h_c\pm)^2]\end{aligned}}$$

EQ. 10. Thermography U-value RMS equation. Based on equation by Baker (2011).

Where:

OA_U_t = Overall uncertainty U-value (±)(W/m^{2}K)

U_t = Measured average U-value over *t* hours (W/m^{2}K)

$U_t$err_ = Average U-value of *t* hours perturbed by the following errors (all in (W/m^{2}K)):

_$\Delta TioT_{in}\pm$ = Temperature difference between inside air and outside air perturbed by (±) internal air temperature error

_$\Delta TioT_{out}\pm$ = Temperature difference between inside air and outside air perturbed by (±) external air temperature error

_$\varepsilon\pm$ = Emissivity error (±)

$Tm^3T_{surf}\pm$ = Mean temperature perturbed by (±) internal surface temperature error

$Tm^3T_{ref}\pm$ = Mean temperature perturbed by (±) reflected apparent temperature error

$\Delta TrT_{surf}\pm$ = Temperature difference between surface and reflected apparent temperature perturbed by (±) internal surface temperature error

$\Delta TrT_{ref}\pm$ = Temperature difference between surface and reflected apparent temperature perturbed by (±) reflected apparent temperature error

$\Delta TaT_{surf}\pm$ = Temperature difference between the surface and inside air perturbed by (±) internal surface temperature error

$\Delta TaT_{in}\pm$ = Temperature difference between the surface and inside air perturbed by (±) internal air temperature error

$h_c\pm$ = Convective heat transfer coefficient error (±)

Equations EQ.9 and EQ.10 are presented in a diagrammatic format, which helps to show the relationship of the errors to the sensor equipment, equations and uncertainty results. These flow diagrams have been influenced by Coleman &

Steele (1999), who detail similar uncertainty flow diagrams. Figure 79 represents the heat flux U-value experiments and figure 80 represents the thermography U-value experiments.

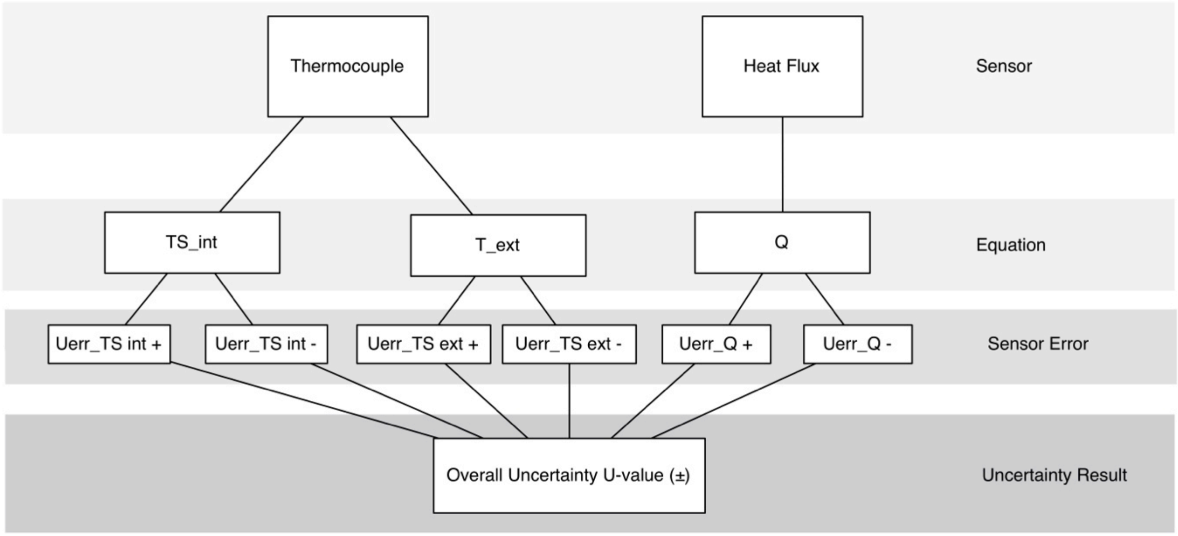


Figure 79. Uncertainty flow diagram for the heat flux U-value experiments. Based on EQ. 9.

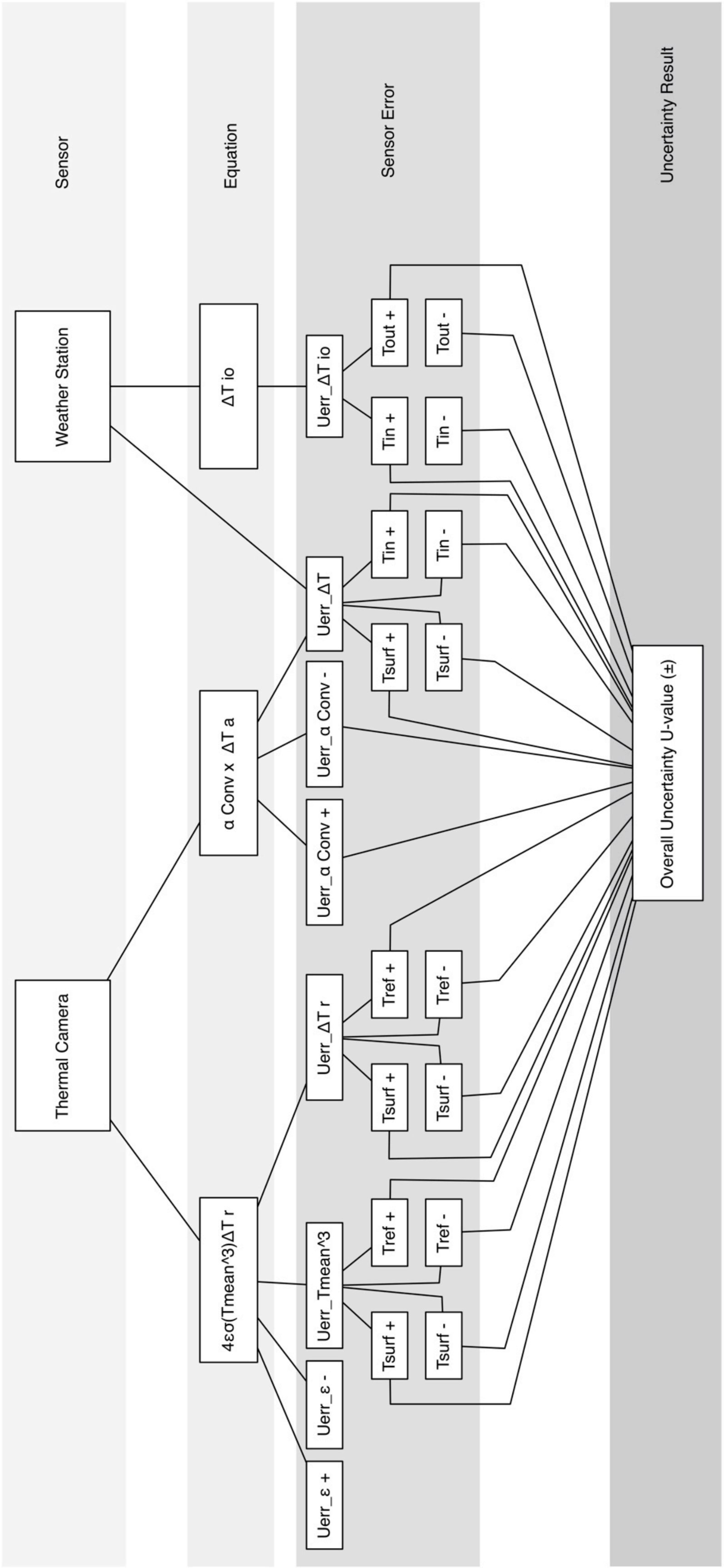


Figure 80. Uncertainty flow diagram for the thermography U-value experiments.

Based on EQ.10.

6.4.3 Results

Having established the methodology and U-value equations to be used for the case studies in this part of chapter 6, the following section details the quantitative results from each (thermography and heat flux) experiment.

Case study 1. Cob wall construction

Undertaken over a weeklong period from 15:15 on the 5th January 2015 to 15:00 on the 12th January 2015, heat flux and thermographic data was gathered for the cob wall example described in the above methodology. Table 15 in appendix G presents the parameters for case study 1.

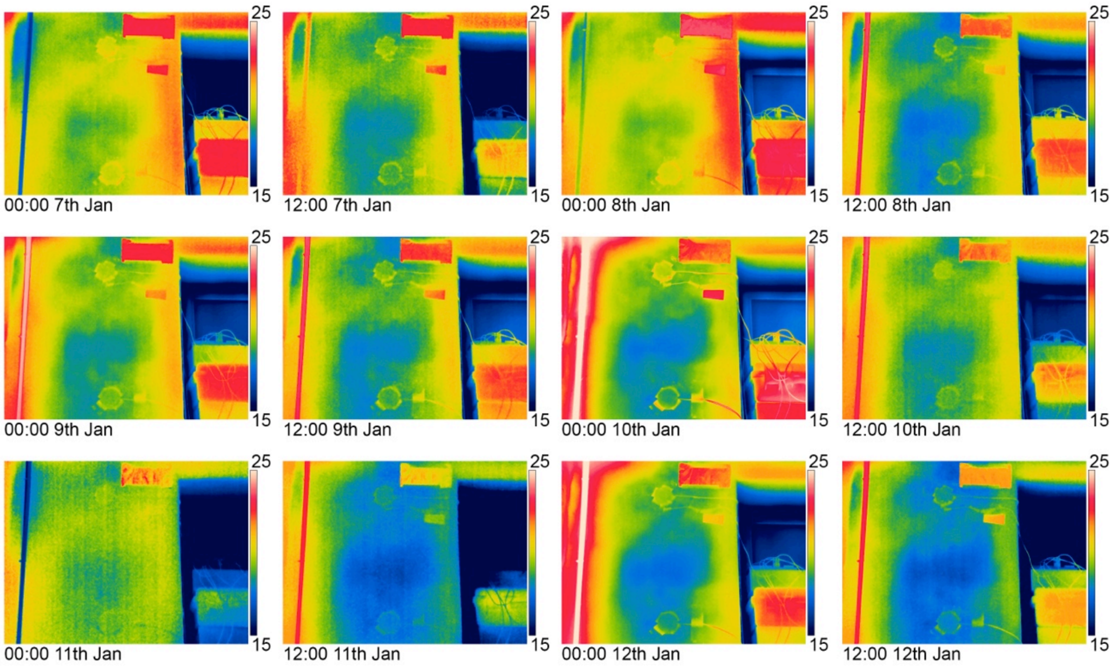


Figure 81. 12-hourly spaced thermal images recorded from 00:00 on the 7th January to 12:00 on 12th January.

Given the large number of thermal images (672) obtained as part of the thermal imaging experiment, figure 81 above presents a 12 hourly sampled selection of thermal image results from the Cob experiment. Using qualitative analysis as an initial method of assessment, the results show subtle variations in colour patterns/surface temperatures from one day to the next at the same time period. For example, the image recoded at 12:00 on the 11th January appears cooler than the thermal image recorded at 12:00 on the 7th January.

Whilst every effort was taken to avoid cold bridging from windows and floors, and to avoid potential sources of interference, the location of the heat flux sensors/thermal camera was constrained by the cable lengths and need to obtain external surface temperatures. The thermal images in figure 81 show that to the left of the heat flux sensors was a hot water pipe, also to the right of the sensors was a window jamb. Both of these might have impacted upon the results, though a central location between the two was chosen for measurement to minimise their impact.

Another limitation to the results was the unknown composition of cob material. Given the age (1720) of the dwelling, the cob material might have comprised of a range of components (Rye & Scott, 2012). Based on several documents, which describe the material constituents of cob (Bedford et al., 2002; Devon Historic Buildings Trust, 1992; East Dorset District Council, 2008; Keefe, 1993), components can include straw, mud, stone, clay, chalk and hair, much of which depends on the materials available at the location. Also the proportional quantities of each component will vary along a wall. This meant that while one U-value might be measured for the location sampled, a slightly different composition of cob in another location might yield a higher or lower U-value. Although inspecting a construction with an unknown composition adds to the uncertainty of U-value analysis, given the common local vernacular of this material, it would be remiss to ignore this material on this basis. The argument for inspecting such a material is also strengthened by the need for in-situ analysis if cob U-values are to be understood at all.

With the objective of this experiment to compare U-value measurements, quantitative analysis was the primary focus of investigation Measured U-values were inputted into a graph (Figure 82), which presented moving average values from the heat flux and thermography experiments. In addition to a direct comparison between the two data sets, benchmark data was obtained from literature and a design based U-value, which was derived from material thicknesses and literature thermal conductivity values.

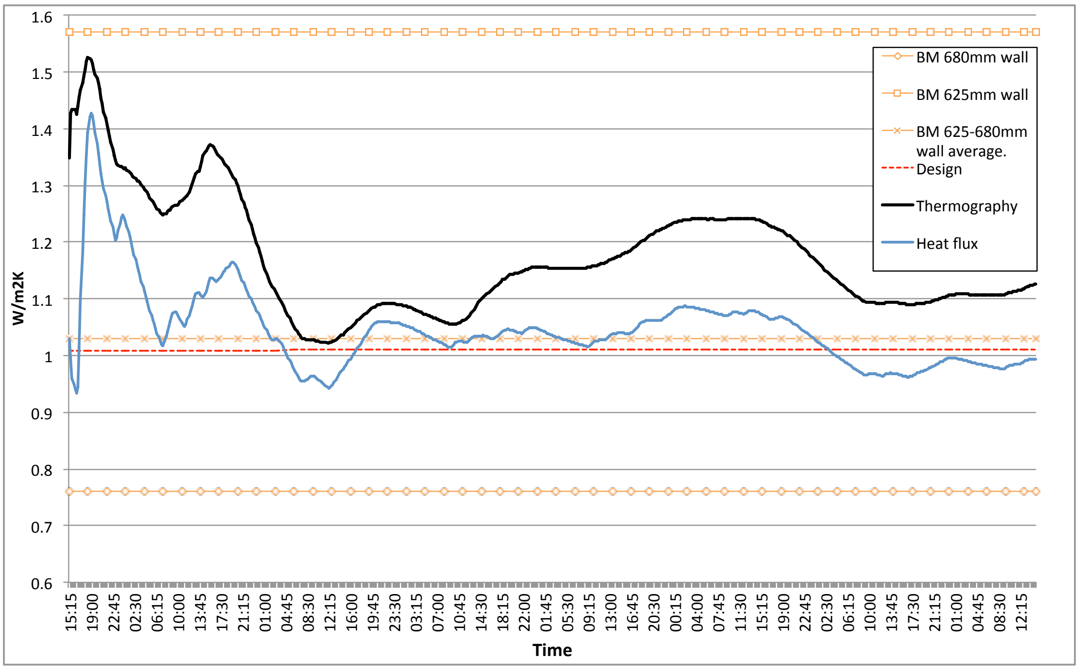


Figure 82. U-value results from thermography and heat flux measurements for cob wall case study over seven days.

Literature benchmarks were sourced from Rye and Scott (2012). In their work, they measured in-situ U-values over a large number of cob-constructed dwellings using a heat flux sensor methodology. From their research, wall thicknesses varied from about 625mm to 680mm. Measured U-values varied with thickness. Both 625mm and 680mm thick cob wall U-values were benchmarked. In addition, an average U-value from 625mm to 680mm cob wall data was derived and used as a benchmark. Table 5 lists the design based U-value data used for this benchmark, which was sourced from Anderson (2006) and BS EN 12524:2000 (2000) and equated using the Build Desk software (Build Desk, 2010).

Material	**Thickness (m)**	**Thermal conductivity (W/mK)**	**Thermal resistance (m2K/W)**	**Data source**
External boundary layer	-	-	0.040	Anderson (2006)
Cement/sand render	0.03	1	0.030	BS EN 12524 (2000)
Cob	0.54	0.73	0.740	BS EN 12524 (2000)
Gypsum Plaster	0.03	0.57	0.053	BS EN 12524 (2000)
Internal boundary layer	-	-	0.130	Anderson (2006)
Rtotal			0.992	
U-value (W/m2K)			**1.008**	

Table 5. Design based calculation data for the cob wall case study (Anderson, 2006; BSi, 2000).

Case study 2. Stone wall construction

This experiment was conducted for a week starting at 16:15 on the 15th January 2015 and ended at 16:00 on the 22nd January 2015. The experiments in this case study immediately followed the experiments from case study 1. Table 17 in appendix G presents the parameters for case study 2.

12 hourly spaced thermal images from the solid stonewall case study are presented in figure 83. Before quantifying the thermal images for in situ U-values alongside the heat flux measurements, qualitative analysis was performed on the thermal images. As with the cob wall case study, there appeared to be subtle surface temperature changes from one day to the next at the same time periods. However the night-time thermal images (00:00) appeared warmer than the day-time thermal images (12:00). This was assumed to be heat storage within the wall, resulting from the household central heating system.

In most of the thermal images during this experiment, more clearly defined shapes could be detected compared with the cob case study. Although these could not be ascertained for certain, one theory was that these shapes corresponded to stones within the wall. Another observation was a temperature differential between the left (warmer) and right (cooler) parts of the thermal image. It had been reported by the occupants, that in the past, condensation and mould growth had been present below the windowsill. However there were no current signs of this. From the thermal images, overall observations suggested an area of increased thermal conductivity in this area.

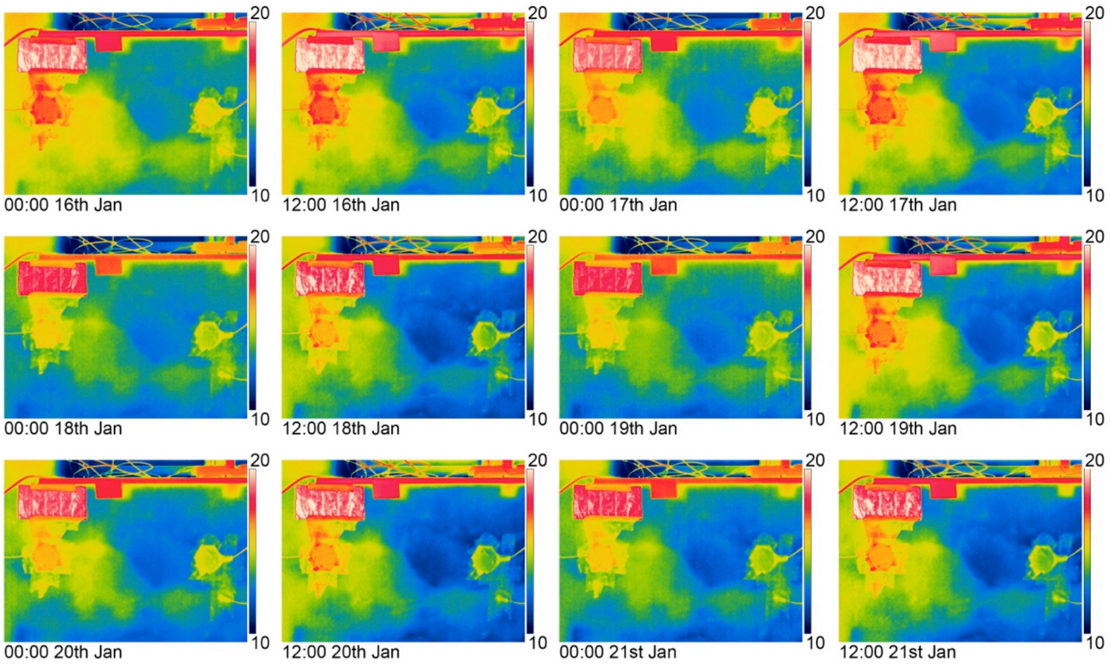


Figure 83. 12-hourly spaced thermal images recorded from 00:00 on the 16th January to 12:00 on 21st January.

While it was known that the wall comprised of solid stone work with a render and plaster finish on either side, key aspects of the wall build-up were unknown:

- The quality of the stone
- The composition of mortar used between the stone
- The ratio of mortar to stone
- The type of stone material (Granite was assumed, given its common occurrence within other local dwellings)

Marshall et al. (2014) describe the random rubble stone wall, which this case study will most likely resemble. They explain that the wall will comprise of two halves of stones that are as flush as possible and face the inside and outside of the building. Within the two halves will be smaller stones set into mortar. While the thickness of the facing stones is often unknown, it is the fill material that can pose a great unknown. Baker (2011) discusses this, adding the inclusion of voids in stone walls as another factor that can impact on thermal conductivity. For U-value equations, Baker allows for mortar within a stonewall by designating a ratio of 40% mortar to 60% stone in the wall. This was determined through field experiments on other stonewall examples. Yet, this ratio is unlikely to be universally applicable for all stonewalls, or indeed difference locations along the same stone wall. This factor could help explain the qualitative observation of cooler and warmer appearing surfaces in the thermal images.

As with the experiments in case study 1, every effort was made to avoid thermal bridging from window jambs/lintels/sills etc. or other known sources. Figure 84 show photos of the equipment set-up for the experiments in this case study. (A) Thermal camera. (B) Aluminium foil reflector for RAT. (C) Data logger. (D) Heat flux sensor. (E) Internal surface temperature sensor. (F) External surface temperature sensor.

Figure 84. Internal experiment set-up (left). External experiment se-up (right).

Following initial qualitative analysis, in situ U-values were measured using the thermography and heat flux methodologies detailed earlier in this chapter. Figure 85 presents the moving average results from these measurements over the weeklong period.

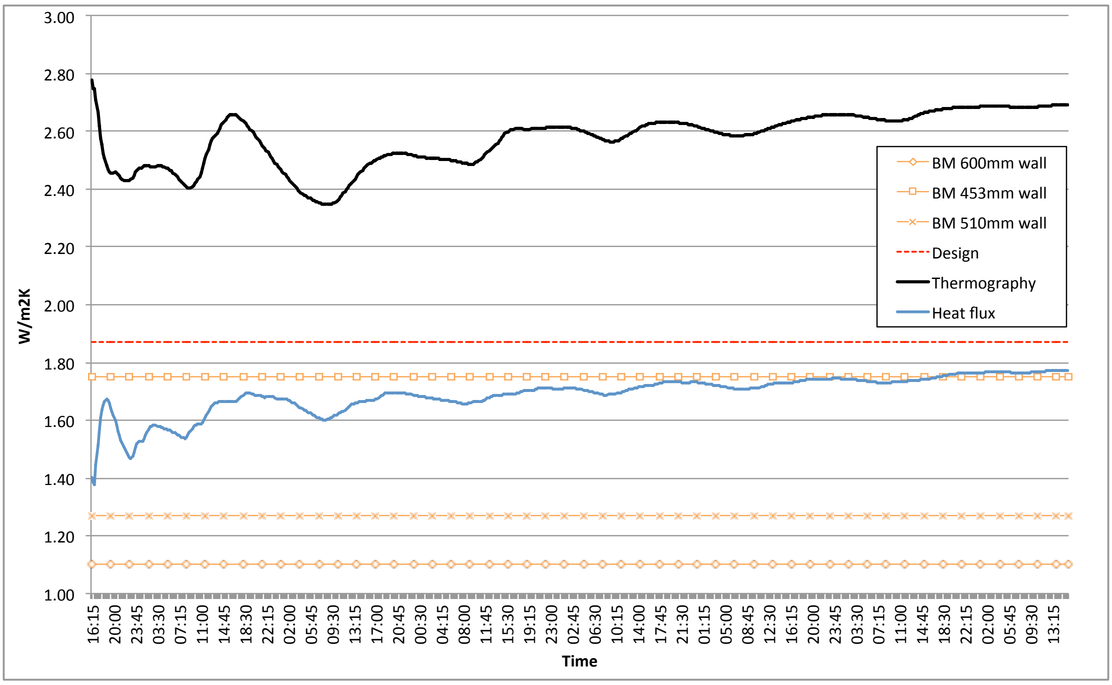


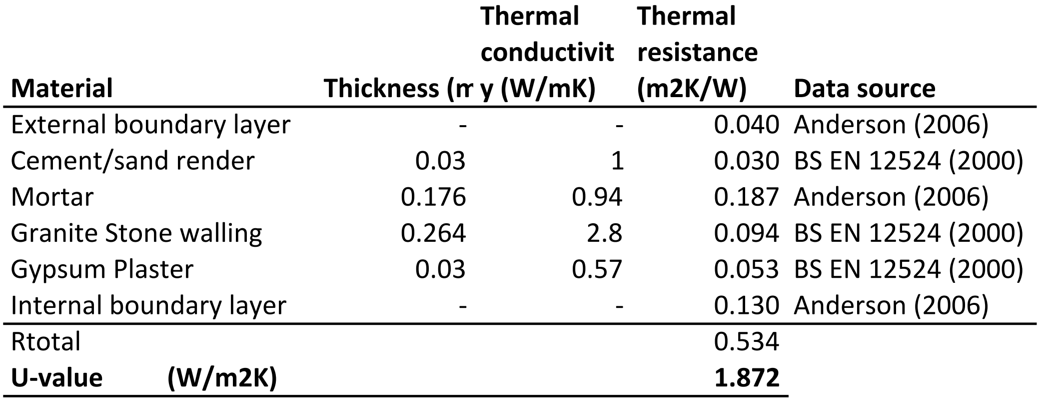
Figure 85. U-value results from thermography and heat flux measurements for stonewall case study over seven days.

In order to compare the results from the measured in situ U-values, benchmark data was obtained from literature examples of similar stonewall U-values and estimated U-values for this wall construction using design based calculation methods.

The literature benchmarks sourced for this case study were found in documents by Baker (2011) and Rye and Scott (2012). In both sources, in situ U-values had been obtained for similar thickness/construction stonewall build-ups as that in this case study using a heat flux method of measurement. The following benchmarks were used to compare against this case studies measurements:

- 600mm thick stone wall = 1.1W/m^{2}K (Baker, 2011)
- 510mm thick stone wall = 1.27W/m^{2}K (Rye & Scott, 2012)
- 453 mm thick stone wall = 1.75W/m^{2}K (Rye & Scott, 2012)

The design based equation method was performed using the Build Desk computer software (Build Desk, 2010). Based on a 500mm thick solid stone wall with a cement render and gypsum plaster finish on either side, this calculation made use of thermal conductivity data from Anderson (2006) and BS EN 12524:2000 (2000) (Table 6). Like Baker, this calculation used a ratio of 40:60 for the mortar and stone constituents in the wall.



Material	Thickness (m	Thermal conductivity (W/mK)	Thermal resistance (m2K/W)	Data source
External boundary layer	-	-	0.040	Anderson (2006)
Cement/sand render	0.03	1	0.030	BS EN 12524 (2000)
Mortar	0.176	0.94	0.187	Anderson (2006)
Granite Stone walling	0.264	2.8	0.094	BS EN 12524 (2000)
Gypsum Plaster	0.03	0.57	0.053	BS EN 12524 (2000)
Internal boundary layer	-	-	0.130	Anderson (2006)
Rtotal			0.534	
U-value (W/m2K)			**1.872**	

Table 6. Design based calculation data for the stone wall case study (Anderson, 2006; BSi, 2000).

Case study 3. Concrete block, insulated cavity wall construction

While the first two case studies investigated traditional materials, which would have pre-dated building regulations with regards to U-value standards, the third case study was chosen to investigate the two U-value measurement methodologies on a more modern (circa 2014) wall construction. The in situ U-value experiments for this case study were conducted for five days, starting at 21:30 on 28th February 2015 and ended at 20:30 on 5th March 2015. Table 17 in appendix G presents the parameters for case study 3. Because of equipment failure during this experiment, it was only possible to obtain 5 days worth of complete data, unlike the first two experiments. Following this period, external air temperatures rose to unacceptable levels, which precluded a secondary experiment on this wall.

Figure 86 presents thermal images at 12 hourly spacings, taken at 00:00 and 12:00 time periods. From these images, initial qualitative analysis was conducted. Unlike the first two case studies, there were fewer qualitative features of interest. Wall surface temperatures appeared to rise in the evening period. Also an unknown cooler patch of wall became more apparent throughout the experimentation period.

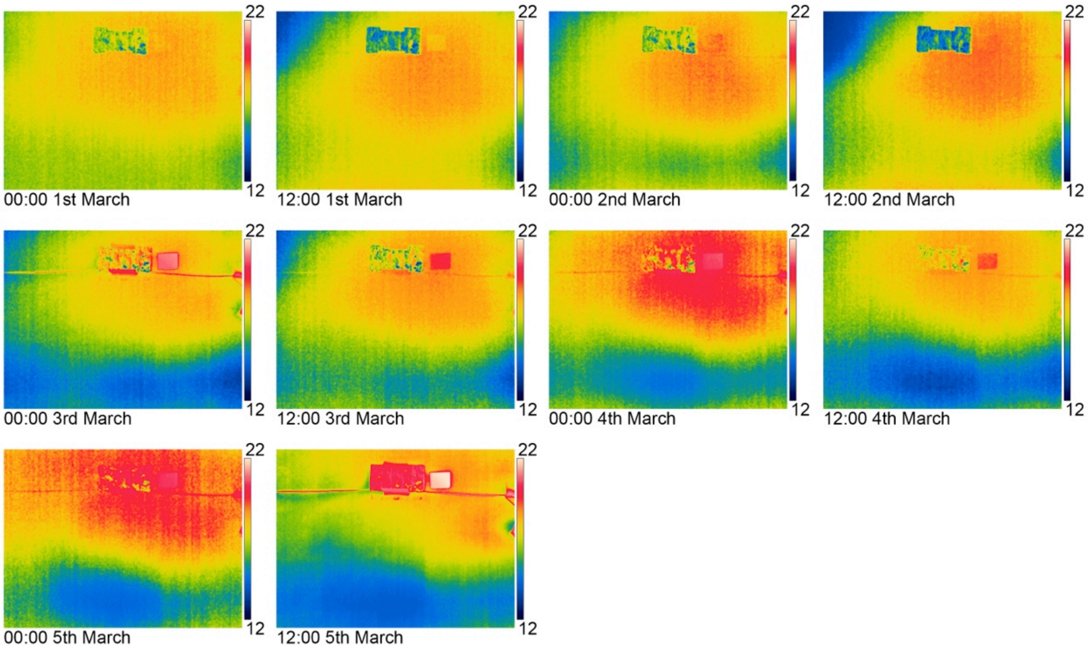


Figure 86. 12-hourly spaced thermal images recorded from 00:00 on the 1st March to 12:00 on 5th March 2015.

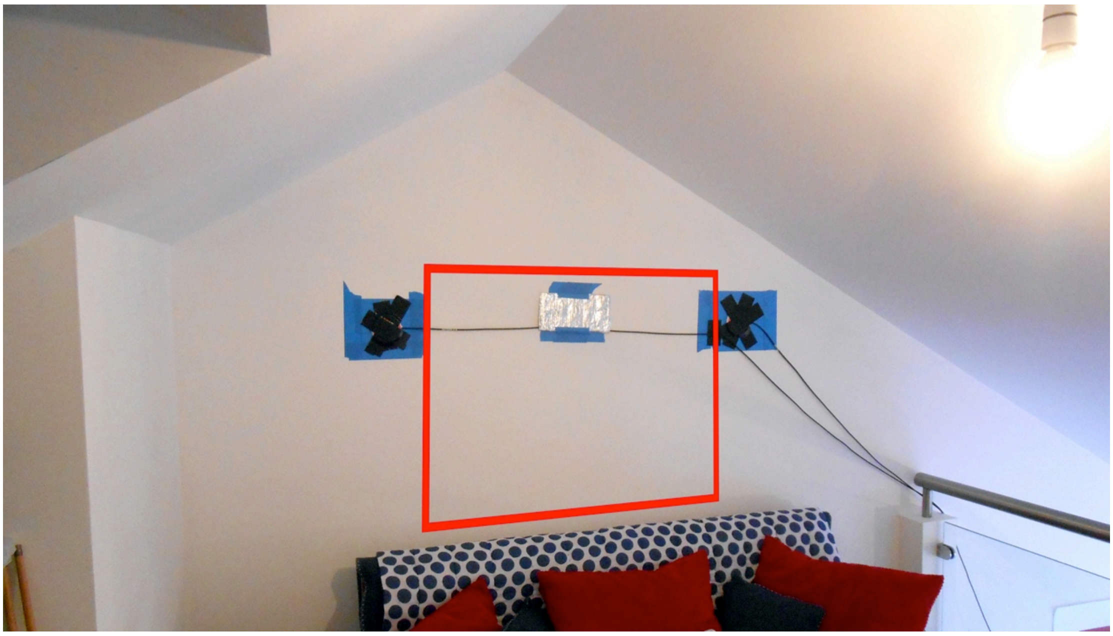


Figure 87. Internal equipment setup for case study 3.

Figure 87 shows the internal experimental equipment set up. The thermal camera viewed an area marked by the box in this photo. As with the other two case studies, this location was chosen in order to minimise the risk to readings from potential thermal bridging sources. With this internal location selected, it proved too great a distance to stretch a K-type thermal couple to measure the external surface temperature. Therefore, for this case study, a Hobo U12-012 temperature/relative humidity/light/external data logger (Onset, 2010) was used to measure the external wall surface temperature at 15-minute intervals, in line with the other equipment.

Analysing the data using quantitative analysis, figure 88 below presents the moving average in situ U-values results from the heat flux and thermography experiments.

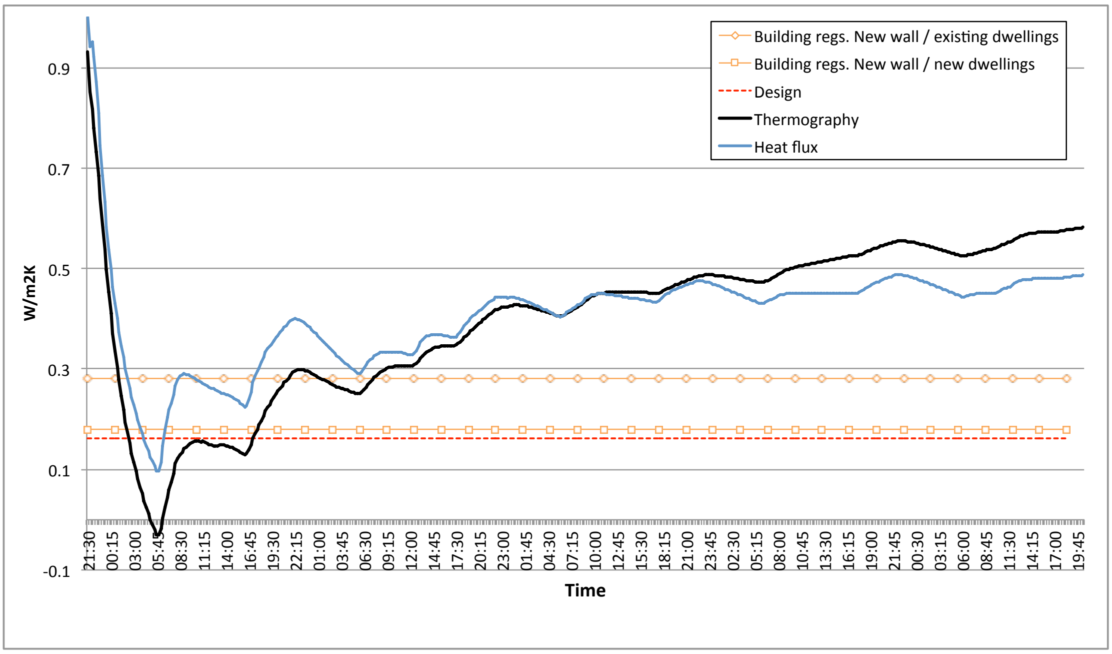


Figure 88. U-value results from thermography and heat flux measurements for concrete block, insulated cavity wall case study over seven days.

While literature U-value benchmarks could be sourced for case studies one (cob) and two (stone), modern day constructions are less standardised due to the increased options in building materials and construction methods. It was therefore not possible to obtain literature benchmark U-values for the concrete block, cavity insulated wall construction in case study three. Nevertheless modern building work now needs to comply with building regulations, which stipulate minimum U-values for different building components. The building regulations that applied to this extension (completed in 2014) on an existing dwelling set minimum U-values of 0.28W/m^{2}K for new walls, as specified under the Building Regulations for England and Wales, Part L1B (2010 edition) (DCLG, 2010b). Had this wall construction been part of a completely new dwelling, it would have needed to comply with Part L1A (2013 edition) (DCLG, 2014b), which stipulates minimum standards of 0.18W/m^{2}K for new walls. As such, both of these minimum standards were used as the benchmark data for the measured results from these experiments.

A design-based benchmark was also calculated for this wall. As the wall build-up was known given its recent completion, it was easier to equate a design-based U-value from accurate component thicknesses and manufactures thermal conductivity values. As with the first two case studies, Build Desk computer software (Build Desk, 2010) was used to formulate the design-based U-value (see Table 7). To allow for thermal bridging through cement mortar between the concrete blocks, two resistance routes were equated. The mortar route (R2) accounted for 5% of the design based U-value, while the concrete block route (R1) made up 95% of the U-value. The design based U-value was calculated to be 0.162W/m^{2}K, which was lower than the minimum building regulation standards set for new walls in new dwellings.

Route	Material	Thickness (m)	Thermal conductivity (W/mK)	Thermal resistance (m2K/W)	Data source
	External boundary layer	-	-	0.040	Anderson (2006)
	Plaster skim	0.003	0.57	0.005	BS EN 12524 (2000)
	Cement/sand layer	0.02	1	0.020	BS EN 12524 (2000)
R1	7 Newton dense Thermalite concrete block	0.1	0.19	0.526	Hanson (2015)
R2	Mortar joints	0.1	0.88	0.114	CIBSE (1999)
	CavityTherm. Full fill cavity insulation.	0.1	0.021	4.762	Xtratherm (2013)
	Un-ventilated cavity	0.005	-	0.180	Anderson (2006)
R1	7 Newton dense Thermalite concrete block	0.1	0.19	0.526	Hanson (2015)
R2	Mortar joints	0.1	0.94	0.106	CIBSE (1999)
	Silicone TC 15 Render	0.01	0.83	0.012	K-Rend (2014)
	K dash external surface finish	0.01	0.47	0.021	K-Rend (2014)
	Internal boundary layer	-	-	0.130	Anderson (2006)
R1 Resistance	95% of construction			6.223	
R1 U-value				**0.161**	**(W/m2K)**
R2 Resistance	5% of construction			5.391	
R2 U-value				**0.186**	**(W/m2K)**
Rtotal	(95% R1 & 5% R2)			6.181	
Total U-value				**0.162**	**(W/m2K)**

Table 7. Design based calculation data for the concrete block, insulated cavity wall case study (Anderson, 2006; BSi, 2000; CIBSE, 1999; Hanson, 2015; Kilwaughter, 2014b; Kilwaughter, 2014a; Xtratherm, 2013).

6.4.4 Analysis

Three case studies were examined using both thermography and heat flux in situ U-value measurement methodologies. Reviewing the final U-value results from the moving average data over the experimental periods, the overall finding was that in each case study, the heat flux U-value was lower than the thermography measured U-value. Whilst not indicative a feature on its own, this initial overall observation formed the basis for in depth analysis. This analysis is discussed below.

Comparison with design-based estimates

One of the first methods of analysis was to compare measured results with design-based estimates. Percentage differences between the final (last running average calculated U-value) measured and design-based estimated U-values are presented below:

- Stone final U-value heat flux – 5.62%
- Stone final U-value thermography – 30.47%
- Cob final U-value heat flux – 1.47%
- Cob final U-value thermography – 10.53%
- Insulated concrete block final U-value heat flux – 66.73%
- Insulated concrete block final U-value thermography – 72.17%

This data is illustrated graphically in Figure 89 below.

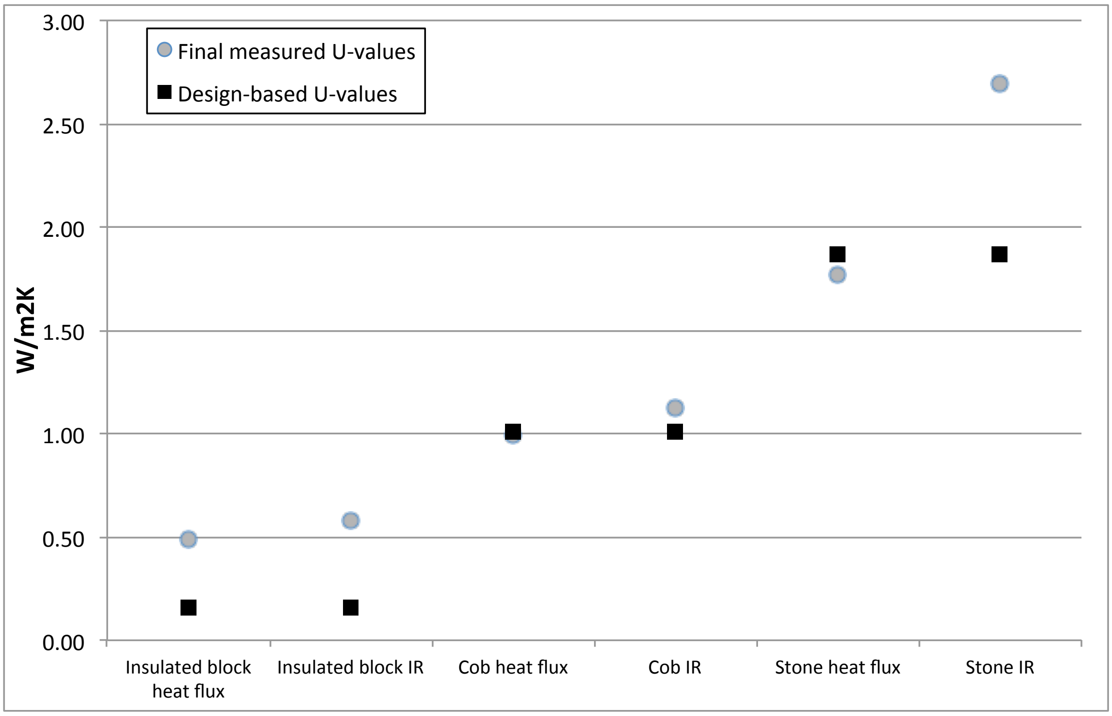


Figure 89. Difference between measured and design based estimate U-values.

Both of the older, un-insulated wall constructions showed a much lower heat flux measured U-value difference to design based estimates compared with the more modern insulated concrete block wall. With regards to this discrepancy, it could be that the insulation and small (5mm) air cavity were impacting upon measured results, and might suggest a limitation of these methodologies for in situ U-value measurement on similar constructions. Pearson (2011) hints at poorer result accuracy when seeking to measure in situ U-values of well-insulated/low U-value constructions. Therefore, further experiments (outwith the scope of this thesis) using other more modern insulated constructions would help to explore this issue in greater detail.

Specifically comparing the final thermography and heat flux U-value results presented additional interest. In each case study, the final heat flux U-value was closer to the design-based estimate than the thermography results. In particular the stone and cob heat flux U-values were within 6% of the design estimate, as indicated in Figure 89. These were more surprising given the lack of clear information on stone and cob wall construction build-ups.

Comparisons between the insulated concrete block and cob case studies show how the heat flux and thermography U-values in each case are similar to each other (0.10W/m$_2$K difference for insulated concrete block, 0.13W/m$_2$K difference for cob). A larger discrepancy (0.92W/m$_2$K difference) could be seen between the two different measurement methods for the stone case study.

It is important to remember that design-based estimates are as the name indicates, ‘estimates’. They are calculated based on steady state conditions, and rely on manufacturers data for conductivity values. So, while presenting an indication of potential construction thermal transmittance, the actual ‘as-built’ thermal transmittance might be very different. Nevertheless, design-based estimates offer a useful benchmark and suggest that the heat flux methodology can provide more accurate U-value results compared with time-lapse thermography.

Analysis of result fluctuations

From reviewing the graphs for each case study in this section of chapter 6, it became clear that the moving average results for the thermography U-values comprised of greater fluctuations over the survey duration compared with the heat flux moving average results, which appeared to be smoother/steadier. This can be seen in Figure 82 (cob) and Figure 85 (stone). In Figure 88 (insulated block wall), it can be seen how the thermography U-value takes a steeper rise over time compared with the heat flux results, which is more consistently steady.

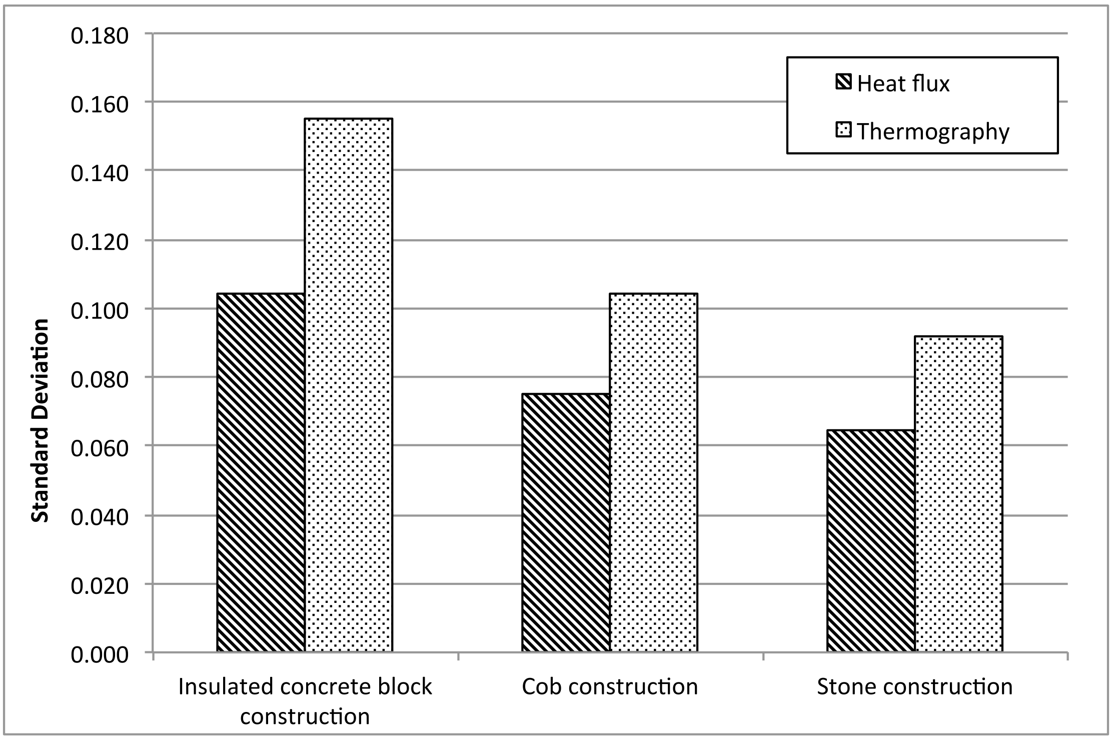


Figure 90. Comparison of the standard deviation between case study and methodology moving average results.

Further analysing the variation of moving average results from the mean, comparisons were made between the standard deviations for each case study and methodology. The results from this comparison are illustrated in figure 90. These results show that the heat flux U-value results are consistently less variable compared with the thermography U-value results.

These findings suggest that there is more variability in the thermography data compared with the heat flux data. To review this further, the U-value results were assessed on a non-moving average basis, where each U-value measurement was representative of a specific moment in time rather than an accumulative value. Figure 91 illustrates the difference in result variability by showing the non-moving average results from the stonewall case study. It is clear to see how the thermography U-value results fluctuated much more than the heat flux results.

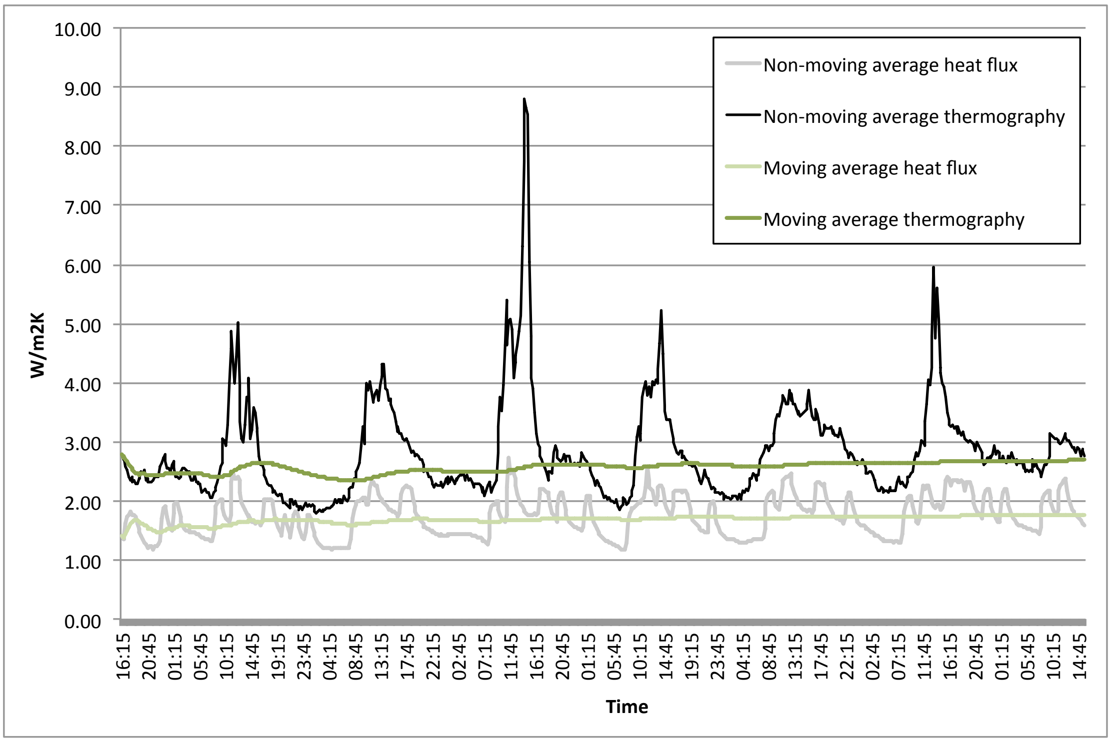


Figure 91. Non-moving average and moving average U-value results for the stonewall case study.

In the stonewall example, heat flux U-value results fluctuated from 2.73W/m^{2}K to 1.17W/m^{2}K. This gave a difference of 1.56W/m^{2}K between highest and lowest U-values. Thermography U-value results however fluctuated by 7.00W/m^{2}K (From 8.79W/m^{2}K – 1.79W/m^{2}K). Similar findings were observed between the results from the cob and insulated concrete block wall case studies. The sharp/high fluctuations in results appeared to correlate with diurnal patterns since peaks came during the daytime periods. These fluctuations will have impacted upon the moving average because of the extreme difference compared with evening/night results. As observed in figure 91, there were more extreme peaks present in the thermography results compared with the heat flux results and consequently casts doubt over the accuracy of the thermography U-value compare with the heat flux U-value.

Another observation made from the moving average U-value results for all experiments was that these did not stop fluctuating towards the end of the survey periods. This was because there were times when the internal and external conditions were closer to thermal equilibrium than other times. For example, it was observed that smaller fluctuations (about 0.5W/m^{2}K difference between measurements over this time period) were experienced in thermography U-value results between the hours of about 20:00 and 07:00 the following day for the stone wall case study. This can be seen in figure 91, which also illustrates the higher fluctuation in thermography results outside of this time period (up to 6.3W/m^{2}K difference between measurements outside of this time period). Similar patterns were experienced from the heat flux measurements and other constructions. Although the experiments in this part of chapter 6 observed and took into consideration (within calculations) both night-time (20:00 – 07:00) and daytime (07:00 – 20:00) periods, the best results were obtained during the night-time periods. This would be expected due to the added/known influences more prevalent during the day, such as solar gain, domestic heating, required ventilation etc. This suggests that another way of analysing the data is to disregard the more fluctuating day-time data, in favour of focusing on the more steady night-time data for moving average in-situ U-value estimations.

Had the experiments lasted longer than one week, the final U-value figures might have been different. This would be due to the effects of further climatic influences. For example, had an experiment lasted for two weeks, and the second week experienced increased solar exposure, the final U-value results might have been adversely affected compared with had the results only lasted one week. This therefore raises the issue that although these experiments can be reproduced (i.e. the methodology can be repeated in an identical manner), the results are unlikely to be reproduced due to differences in conditions. This is an important factor to remember, since the inability to reproduce U-value results questions the accuracy of measurements, since U-values might change from one day/week/month to the next. Theoretically asking, which U-value measurement is correct, and which is incorrect? The answer might be to take an average between results, such as the moving average methodology used in these experiments, though it seems that for more accurate results, periods of very low fluctuations should be targeted, to minimise the impact that high fluctuations can have on final results (which could possibly skew results to be better or worse than they actually are).

Limited assessment of building thermal performance

Although time-lapse thermography enables an average measured U-value to be determined from the collected data for a given location and the construction build-up at this location, the ability to determine a building's total heat loss using this methodology would be very difficult. This is because the camera is set to view one location on the entire building, and is usually limited by the boundary of the box measurement tool used within the camera to collect quantitative data. Figure 92 shows the FOV used for the stonewall case study. Putting this into context, Figure 93 shows the remainder of that wall. A black dotted box denotes extent of survey

FOV illustrated in Figure 92. It is clear to see that other parts of the wall and window were not included within the U-value measurement. Within figure 92, a box tool was placed over the wall as denoted by a black dotted box in this image. This further constrained the measurement area of this wall. The box tool did not take into consideration other aspects of the wall, which might have held an influence on thermal performance, such as the upper parts of the wall, either side of the window. Even if multiple boxes or other measurement tools are applied within the thermograms, there will be elements that are missed. This means that if there was a defect or change in construction (from the standard construction for that wall) within the region that was inspected, the final U-value result might not be representative for that wall.

Whilst there would be issues regarding the trade-off between spatial resolution and obtaining entire views within the camera FOV (that would permit U-value analysis of all components), as discussed in part 2 of this chapter, by only capturing a small section of the wall construction, the measured U-value can only ever offer a representation of the thermal performance for that specific boxed area. Likewise, if U-value analysis could be undertaken for an entire elevation, this would still only represent an indication for that specific room, rather than for the whole building U-value. Consequently, it seems that such quantitative analysis using time-lapse thermography should only prove indicative rather than conclusive in nature, where only parts of a building are assessed and assumptions made for other parts, which could be different unless those constructions are known to be homogenous across the entire wall.

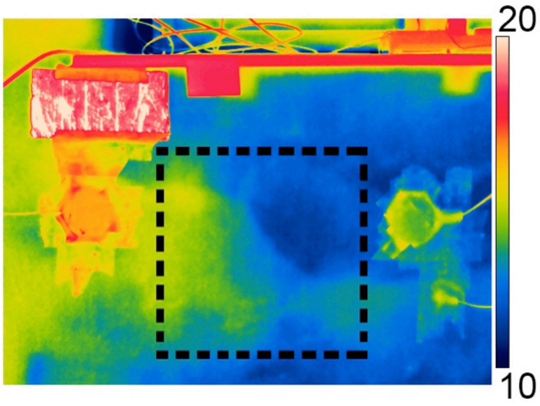


Figure 92. FOV used for time-lapse thermography U-value measurement.

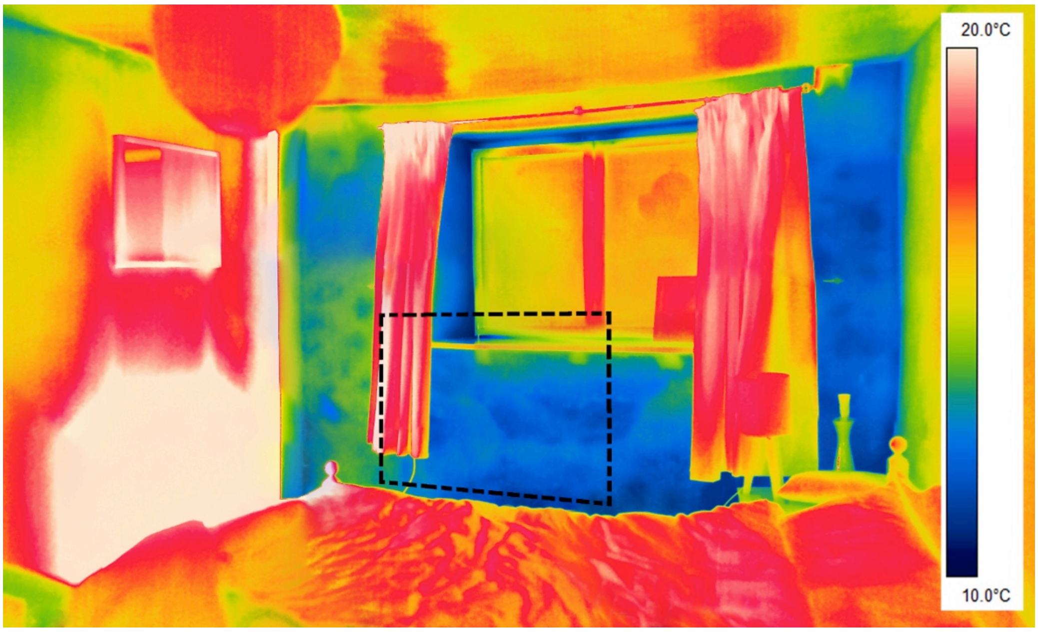


Figure 93. Larger angle FOV of same room as used for the stone wall case study.

6.4.5 Uncertainty Analysis

Having conducted an uncertainty analysis on the final running average U-values measured in each of the three case studies, further observations could be made. Table 8 documents the numerical uncertainty values as U-value percentage differences. Figure 94 illustrates these results in a graphical format.

Construction	Measurement methodology	measured U-value (W/m2K)	U-value uncertainty ± (W/m2K)	Percentage uncertainty ± (%)
Insulated concrete block construction	Heat flux	0.49	**0.11**	**23.22%**
	Thermography	0.58	**0.41**	**70.60%**
Cob construction	Heat flux	0.99	**0.11**	**11.12%**
	Thermography	1.13	**0.49**	**43.20%**
Stone construction	Heat flux	1.77	**0.16**	**8.77%**
	Thermography	2.69	**0.51**	**18.92%**

Table 8. Final uncertainty values (±) for the final U-value results.

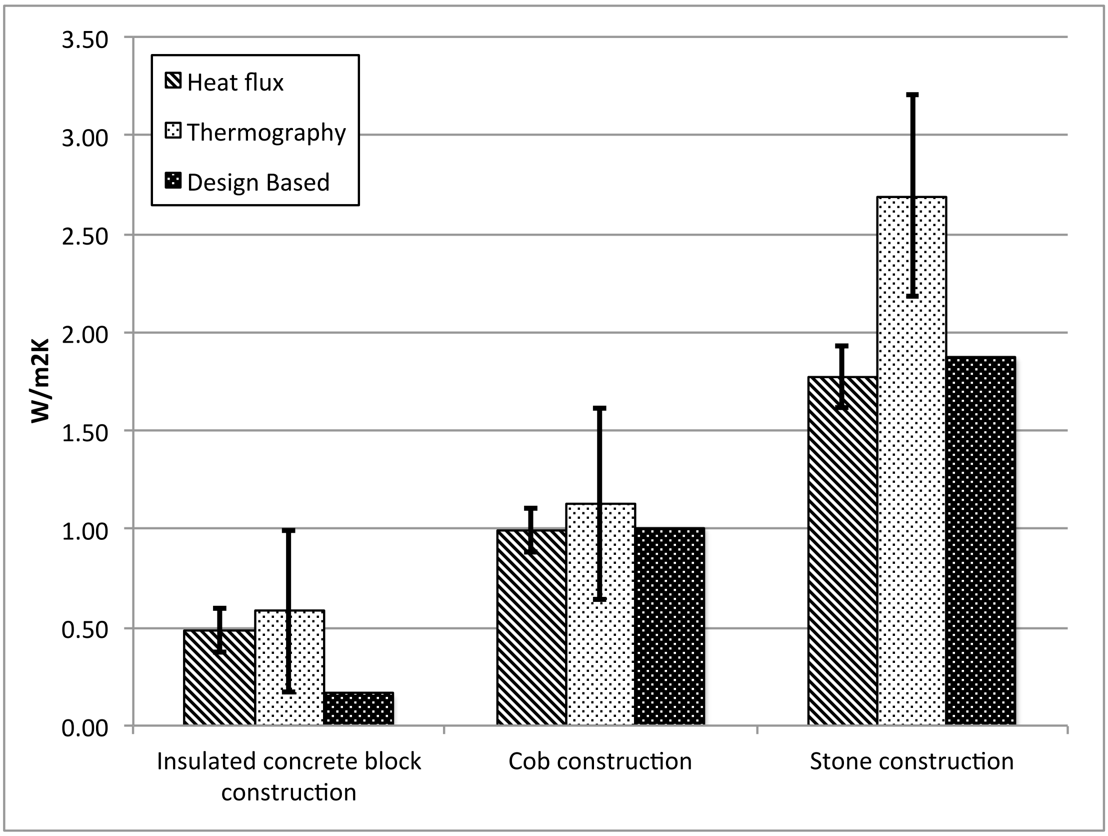


Figure 94. Comparison between the final running average (measured) U-value results, uncertainty analysis (± W/m_2K) and design based calculations for each of the values.

Having reviewed the uncertainty data for each of the case studies, it is clear that a greater degree of uncertainty in final U-value results was experienced with the time-lapse thermography methodology for all constructions than experienced through the heat flux methodology. This could be said to correspond with the greater complexity in mathematical equation and measurement procedure that exists with the thermography methodology compared with the heat flux methodology. Connected to this is the fact that there is no direct connection to the sample during the thermography measurements. Therefore, while the heat flux sensors will be primarily measuring conduction heat transfer, the thermal camera will be detecting heat transfer via convection, radiation and conduction, all of which are factored into the more complex equation proposed by Madding (2008).

Comparing the difference in U-value uncertainty between the experiments showed consistencies between each of the three case studies. Heat flux uncertainty resulted in ±0.11W/m^{2}K to ±0.16W/m^{2}K, and was lower than the uncertainty for the thermography results, which comprised of between ±0.41W/m^{2}K to ±0.51W/m^{2}K. Further analysis of the U-value uncertainties using percentage values compared with the final U-value (Table 8) show that whilst uncertainties in results present less impact to highly conductive constructions such as the solid stonewall, as the construction becomes less conductive, the final U-value becomes less reliable. These results suggest that in situ U-value measurement is much harder to achieve on more modern highly insulative constructions, and further experimentation would be needed to explore this theory further.

Since current building regulations call for minimum U-values of between 0.28W/m^{2}K (DCLG, 2010b) (alterations to existing dwellings) and 0.18W/m^{2}K (DCLG, 2014b) (new dwellings), fluctuations in the final (Last accumulated running average U-value result) thermography U-value results for the insulated concrete block construction seem very significant. With a ±70.6% (±0.41W/m^{2}K) uncertainty value, the measured U-value could have ranged between 0.17W/m^{2}K and 0.99W/m^{2}K, and renders the final result too uncertain to be meaningfully reliable.

In comparison with literature benchmarks, the stone (±11.12%) and cob (±8.77%) construction heat flux results were close to Baker's (2008) ±10% uncertainty margin for stonewall constructions. Madding (2008) found that thermography uncertainties varied from about ±4% to ±14% depending on the NETD of the thermal camera, and expected uncertainties of about 12%. The results from these three case studies did not correlate with Madding's uncertainties, though could have varied due to the in situ nature of these experiments compared with Madding's more laboratory approach. Pearson (2011) argues that thermography U-values will be at best ±25% from measured results.

6.4.6 U-value analysis of a known building defect

Whilst no 'known' defect was detected during the case studies conducted for this part of chapter 6, it is likely that in-situ U-value measurements might be used to assess the severity of a known building defect in comparison with a construction in non-defective state. It was therefore deemed important to examine the quantitative thermography and heat flux in-situ U-value methodologies on a sample that had a known building defect. To explore this, a supplementary experiment was conducted. This experiment replicated the methodology used in this part of the chapter to investigate the impact that building defects can have on U-value performance. A weeklong experiment was devised to test an insulated (wood fibre insulation) wall build-up under two conditions. One free from defects and the other comprising of a known defect, which in this case as moisture ingress.

Because of the difficulties in finding a known damp sample, a laboratory experiment was devised, which made use of a hot and cold box climate chamber to test a multi-layer build-up. The methodology, results and analysis from this experiment can be found in appendix A.3.

Findings from this research showed that a greater difference between wet and dry samples was found towards the beginning of the experiment. As the wet sample dried out, the difference with the dry sample reduced.

However analysing the scale of differences between the two methodologies showed a much greater U-value difference in the thermography methodology compared with the heat flux methodology. This increased difference in thermography results lessened after approximately one day, when the sample had appeared to dry most significantly, though continued at a steady rate throughout the experiment, as the sample continued to dry. It was always greater than the heat flux U-value.

An uncertainty analysis was conducted for the two samples and two methodologies. It was observed that the heat flux results had an uncertainty of about ±7% on measured U-values. This was much lower than the thermography U-value results, which contained a greater degree of error in measurement, at ±24.0% to ±31.0% on measured U-values. Such high uncertainties in results devalues the thermography U-values.

Undulations were noticed in the thermography U-value moving average results, which were not present in the heat flux results. Coupling this with the uncertainty analysis for this methodology added weight to the theory that U-value measurement by thermography did not give a very accurate a result. In contrast, the heat flux methodology appeared to offer a U-value that was closer to the estimated design U-value and with less uncertainty.

In summary, whilst qualitatively detecting/illustrating the difference in thermal patterns between a defective and non defective sample over time, this experiment supports the key findings from the other case studies in part 3 of this chapter by showing that heat flux U-values are closer to estimated design U-values and carry less uncertainty than thermography measured U-values. These findings add weight to those from the real building case studies in further question the application of time-lapse thermography for quantitative U-value measurement in favour of more traditional heat flux measurements.

6.4.7 Part 3 Conclusion

Part 3 of this chapter has explored the validity of time-lapse thermography for U-value analysis in comparison with the more commonly used heat flux measurement methodology.

Overall findings from three different case study constructions (and the supplementary experiment in appendix A.3) show that when compared with design-based estimate U-values, the heat flux methodology is more accurate than time-lapse thermography for in situ U-value measurement. Where heat flux U-value were within 6% of design estimates and thermography U-values varied from between 10% - 72% compared with design estimates. Assessing the uncertainty of measured data provided further insights into the success of either methodology. Again, heat flux U-value results contained less uncertainty (between ±0.11W/m^{2}K to ±0.16W/m^{2}K) compared with the uncertainty in thermography results (±0.41W/m^{2}K to ±0.51W/m^{2}K).

Examining the moving average U-value data lines for all three case studies showed how there were greater fluctuations in the thermography U-value results compared with the heat flux U-value results.

These results show that U-value analysis by passive time-lapse thermography can only offer estimations of potential U-value performance at best. Because of the high uncertainties, result fluctuations, disparity with design-based estimates and limited FOV, U-value analysis by thermography cannot be used to base meaningful judgements on overall building thermal performance. Nor should professionals be too quick to base thermal improvements on such results. Instead, the existing heat flux methodology should be utilised ahead of thermography for in-situ U-value measurements.

The key benefit that thermography offers compared with heat flux measurement is the ability for non-contact analysis. Whilst shown as a limitation to this methodology for accurate quantitative analysis, there might be times when U-value estimates are required from inaccessible areas, and could prove to be a useful application.

Given the identified difficulties with in situ U-value measurement from time-lapse thermography, this work has raised further doubts over the potential application of single moment in time passive thermography for meaningful/successful U-value measurement.

Although this part of chapter 6 did not intentionally look at building defects, which has been the primary focus of this thesis, it had been identified that U-value measurement by thermography is one of the most demanded quantitative performance aspects requested by building professionals. While every effort had been made to avoid potential thermally significant building defects, it was not known for certain whether such defects existed in any of the case study wall samples. However, in the stonewall construction case study, it was suggested by the occupants that condensation and mould growth had been present in the past. Therefore potential defects or thermal weaknesses in existing buildings might impact upon U-value results. As discussed earlier, a supplementary experiment in appendix A.3 was conducted to help gain a deeper understanding of the impact that building defects might have on in-situ U-value measurements.

6.5 Chapter 6 summary

Within chapter 5, it was found that some defects could not be sufficiently characterised from single moment in time (snap-shot) images. This therefore questioned the success of qualitative and quantitative defect detection/assessment using traditional thermography methodologies (walk-through). One of the main factors that limited defect characterisation using traditional thermography was found to be transient climatic changes and material properties. To address this issue, time-lapse thermography was proposed.

Time-lapse thermography is an existing methodology that has been reported as being used by other thermographers in chapter 3. However compared to some of the more commonly used thermography methodologies such as traditional and aerial thermography, time-lapse appeared to be a niche application. The specific focus of literature to date has been on time-lapse thermography for quantitative analysis, in particular in-situ U-value measurement. Chapter 6 explored the use of time-lapse thermography for qualitative and quantitative analysis on both laboratory and real world case studies (Objective 4).

Through undertaking three separate investigations, the application of time-lapse thermography as an alternative to traditional walk-through thermography has been demonstrated. The findings from time-lapse thermography have been organised into a diagram (Figure 95), which highlights the benefits and limitation discovered from outcomes from each section and case study.

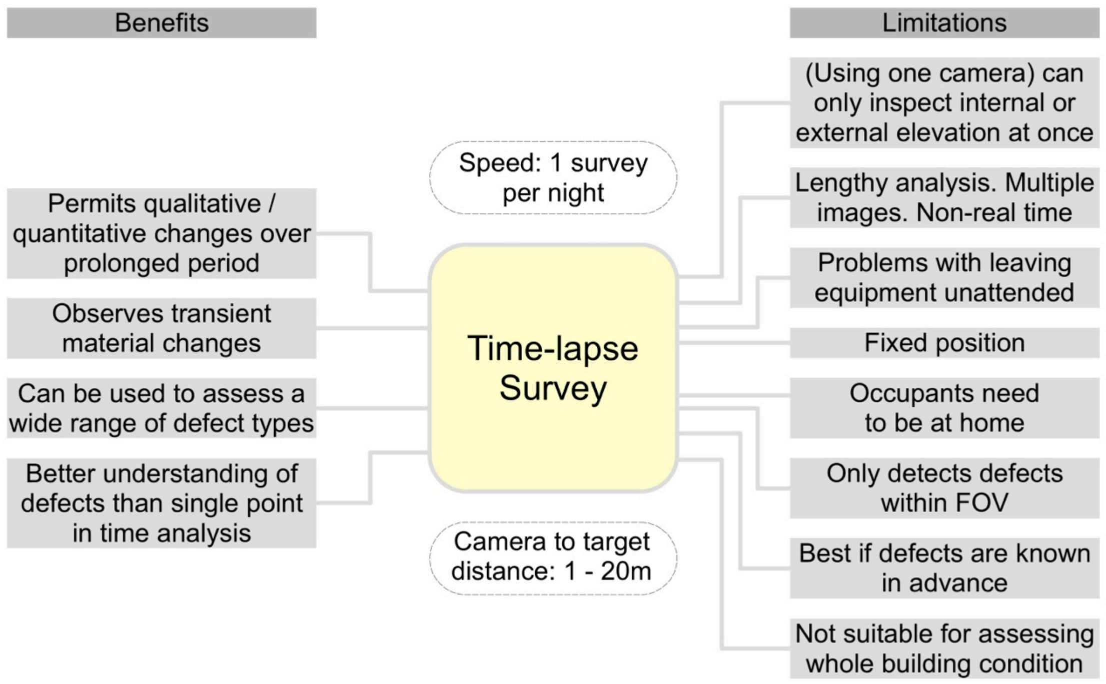


Figure 95. The benefits and limitations to time-lapse thermography.

In part 1, single layer samples were inspected using time-lapse thermography to explore the basic principles of this methodology on dry and wet materials. This relatively simple experiment successfully showed how time-lapse thermography could be more informative on construction behaviour than traditional single point in time analysis. In particular, results showed how material properties changed over time under the influence of heat and moisture. This would have been difficult to perceive using traditional methods of thermographic analysis.

While part 1 comprised of laboratory work, part 2 began to consider time-lapse thermography as a practical methodology for real world building inspections. Time-lapse thermography was seen to offer an evolution of sequential images, thereby capturing material and construction properties at different states (dependant on the conditions that were subject to them). Time-lapse thermography helped to better understand/observe some of the known transient limitations such as solar gain and moisture. These are known to impact on qualitative thermal patterns. So by factoring these into time-lapse sequences, traditionally hard to characterise defects became easier to understand/assess.

Within part 2, an investigation on time-lapse temporal resolutions was made. While temporal resolutions of 20-30 minutes plus appeared suitable for qualitative analysis, shorter temporal resolutions over several days were recommended for quantitative analysis. One such quantitative analysis application was in situ U-value measurement. This became the focus of parts 3 and 4.

For part 3, weeklong time-lapse inspections were conducted over three different types of building construction. Time-lapse thermography was used to measure in situ U-values of these constructions and was compared with heat flux measured U-values obtained at the same time intervals. Results from both experimental methods were benchmarked against design-based estimates.

Overall findings from the three case studies found that the thermography U-values were less close (10%-72%) to the design based U-values than the heat flux measurements (less than 6%). Thermography results were also found to contain greater uncertainty (±0.41W/m^{2}K to ±0.51W/m^{2}K) compared with heat flux results (between ±0.11W/m^{2}K to ±0.16W/m^{2}K) and appeared to have greater fluctuation in moving average U-values throughout the experimental period compared with the heat flux U-value.

Whilst experiments in part 3 showed that U-values could be measured using time-lapse thermography, the uncertainty/inaccuracy of results compared with the heat flux methodology led to the conclusion that in situ U-value measurement by thermography is subject to too many external influences (such as climatic conditions) to be meaningful or useful. Results seemed to be at best estimates, which should not be relied upon when making decisions for building improvements. Having encountered difficulties with in situ U-value measurement by time-lapse thermography, this further questioned those practitioners, who are using single point in time image inspections for such quantitative analysis.

In summary, the work in this chapter has shown how time-lapse thermography can present a more informed view/understanding (from sequential image evolution) of building defects and changing material properties. For situations where defects or constructions are hard to characterise/understand this is a methodology that should be considered by professionals for better understanding. Whilst time-lapse thermography affords the opportunity to obtain better (than single images) quantitative data, this work has proven that there are other methodologies available, which at present are more successful/suitable for the task.

Reflecting on the potential application for time-lapse thermography in practice, a key question might ask whether the benefits of time-lapse thermography outweigh the constraints of this methodology?

Whilst this question is difficult to categorically answer, the work in this chapter has shown that for those defects, which are hard or impossible to characterise using single moment in time image recording methods, transient investigation (time-lapse) is the only thermographic method available. Other methods of NDT may aid in longitudinal investigations, such as heat flux sensors or thermal probes, such methods only offer single point/location analysis. Thermography on the other hand, offers multi-point analysis through a thermal picture. Therefore time-lapse thermography has the added benefit of assessing entire regions of construction at the same time rather than small specific locations. The key to assessment using time-lapse thermography appears to be through combining this methodology with other NDT methods at the same time, as experienced through part 3 of this chapter. Dual data analysis helps to validate/corroborate the accuracy of data collection.

One of the key barriers to the routine uptake of this methodology however is speed. Speed equates to time (to set-up, conduct and analyse), which equates to money (cost of survey, resources, etc.). As discussed in part 2 of this chapter, time-lapse is a complex methodology to set up and analyse, which could discourage commercial application. Yet the aforementioned benefits and known limitations to other thermography methodologies make time-lapse thermography a realistic commercial tool. Especially if there is a problematic building defect, which cannot be characterised using other methods of inspection other than destructive testing (which may not be possible).

The current commercial development of passive building thermography however appears to be driven by the need to reduce costs and increase survey speed (the opposite to time-lapse thermography). To better understand how successful a cheap and fast methodology is at defect detection and characterisation (compared with walk-through and time-lapse thermography) the next chapter investigates a walk-past methodology, which is a form of pass-by thermography.

7.0 Walk-Past Thermography

In chapter 6, time-lapse thermography was explored as an alternative to traditional walk-through thermography (chapter 5) for improved defect characterisation. Whilst time-lapse thermography was found to enable a more informed understanding of building defects using image evolution analysis techniques, one of the key criticisms centred on the lengthy timescales involved. Equipment took a long time to set-up, surveying periods lasted for several days in which rooms were unable to be used and analysis was lengthier than traditional thermography analysis. These time dependant practical issues cast doubt over the commercial application of time-lapse thermography for routine inspections, because time equals money.

As described in chapter 3, over the past six years (Figure 29) some thermographers have started using very fast thermographic analysis methods whereby cars drive past or people walk-past buildings capturing single elevations of multiple buildings during one survey session (BBC, 2015; Currie, 2012; Essess, 2015; IRT surveys, 2012a; Phan, 2012). The aim of these methodologies has been to speed up thermographic assessments so that costs can be reduced. As a methodology currently being used by other commercial thermographers, and at the other end of the spectrum to time-lapse thermography, it was deemed important to explore the benefits, limitations and applications for a pass-by thermography methodology. This chapter uses walk-past thermography to inspect four separate case studies located in the South West of England (**Objective 5**). The locations of these case studies are provided in figure 96.

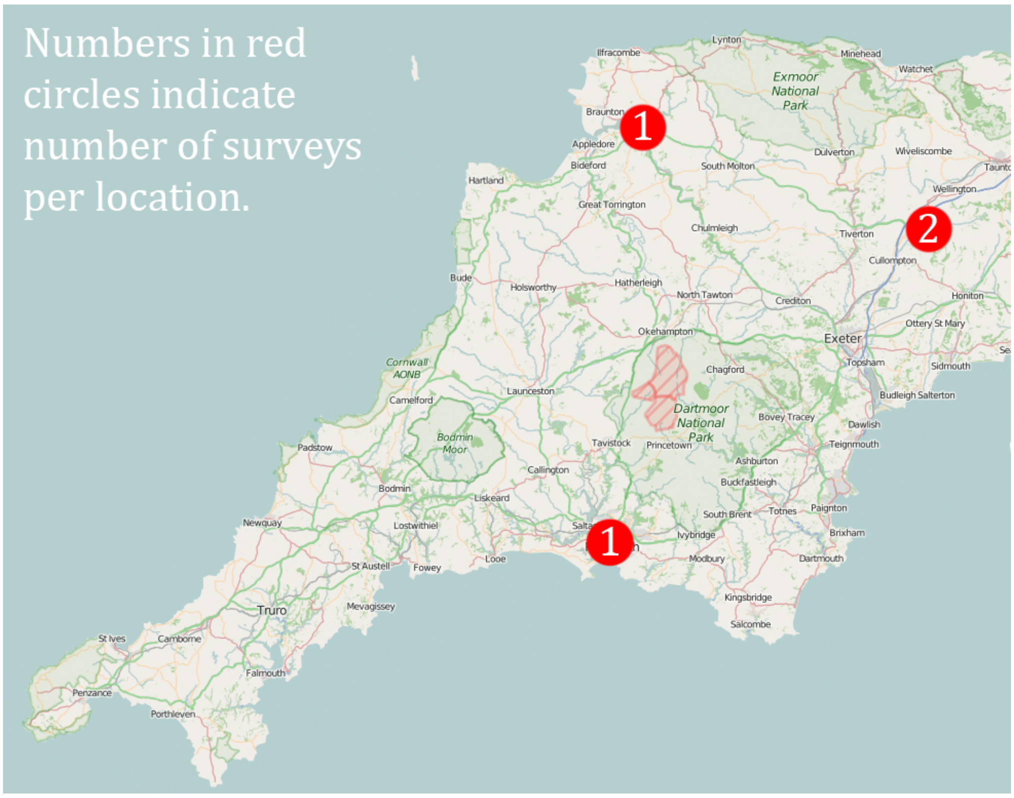


Figure 96. Case study location map.

Each case study comprises of one residential street, where only the front elevations of dwellings were thermally imaged.

Although some thermographers use pass-by thermography for quantitative analysis (Currie, 2012; IRT surveys, 2012b), doubts over the validity of this application discussed in chapter 3 suggest that only qualitative analysis should be used under this methodology and shall be the sole focus in this chapter.

7.1 Detailed Methodology

Since this project did not have access to vehicle-mounted thermal camera equipment, as used by MIT and Essess in their drive-by thermography work (BBC, 2015; Essess, 2015; Phan, 2011; Phan, 2012), it was not possible to automatically capture thermal images of dwellings from a moving car. Additionally, it was deemed unsafe to attempt a drive-by thermographic survey given the need for frequent pausing (to capture an image) and driving at slow speeds along public highways. Phan (2012) found that speeds of less than 10mph were needed to avoid image blur from their two camera system (using FLIR Photon 320 thermal cameras). Because of these limitations, a walk-past survey as selected for the work in this chapter.

In chapter 3, a methodology for walk-past thermography proposed by Phan (2012) was presented. This chapter makes use of, adapts and overcomes the shortfalls found in Phan's walk-past methodology to present a more detailed methodology for the inspection of multiple dwellings from the street.

7.1.1 Case study selection

It was first important to find suitable residential streets that comprised of at least seven dwellings consenting to a thermal survey. This number was derived from the fact that a maximum of six dwellings could be inspected using a walk-through methodology. Therefore any more than six, would need to be imaged on another evening. One advantage of the walk-past methodology was the ability to survey more than six dwellings in one evening. Four streets in Devon were selected as case studies for thermographic investigation. The criteria for choosing these streets was as follows:

a) Each street comprised of one predominant period of housing construction. Several housing periods were sought for this research and included dwellings that were constructed prior to the 1900s, in the 1950s, 1970s and the 1990s.

b) Different building constructions were also sought for inspection. Constructions that represented those typically found in the South West of England were sought and included solid wall masonry, insulated cavity wall and un-insulated cavity wall.

c) One of the business partners for this research project was a Cornish housing association. With access to thousands of dwellings, they provided one case study, which offered the analysis of rented accommodation. This contrasted with the remaining three case studies, which comprised of predominantly privately owned dwellings.

d) Case study selection was also based on convenience sampling, where streets were chosen in close proximity to the thermographer performing the inspection.

Once the case study streets had been identified, it was important to gain permission from each individual household (homeowner/tenant/landlord) to image their dwelling. To do this, an information sheet was prepared (see appendix I), which explained the project, a brief overview of thermography, when the survey would be conducted and what the survey would entail. The information sheet also clarified that thermal imaging would only be undertaken if the householders consent had been received prior to the survey. Householders were also reassured of their right to withdraw at any point before or after (up to 6 months) the survey. The methodology for seeking approval from householders was verified by

Plymouth University's Research Ethics Committee (see appendix H) prior to the research commencing.

Because not all dwellings had given permission by the time of the survey, there were times where consecutive dwellings could not be imaged. This sometimes made comparisons between neighbouring dwellings more challenging and was acknowledged as a limitation to this research.

7.1.2 Data collection and analysis

To begin with, a plan was drawn up to determine the order in which dwellings would be surveyed. The thermographer made use of a FLIR T620bx thermal camera and monitored the weather conditions as described in chapter 4.

Figure 97. Illustration of walk-past thermography survey.

The thermographer walked the survey street, passing each designated dwelling one-by-one, where the thermographer would pause to capture thermal images as illustrated in figure 97. Due to the camera lens having a FOV of 25° x 19° the thermographer stood no more than 20m (see Figure 98) from a typical two storey dwelling to capture as much of the buildings elevation within one image. This often meant standing on the furthest opposite side of the street to the observed dwelling. However, such distances were not always possible, nor were all dwellings two storeys in height. Consequently, there were some occasions in which the thermographer stood closer to the building and needed to either record images at an angle to the dwelling, or capture multiple images, which were combined into a single larger view of the entire elevation as conducted by Phan (2012).

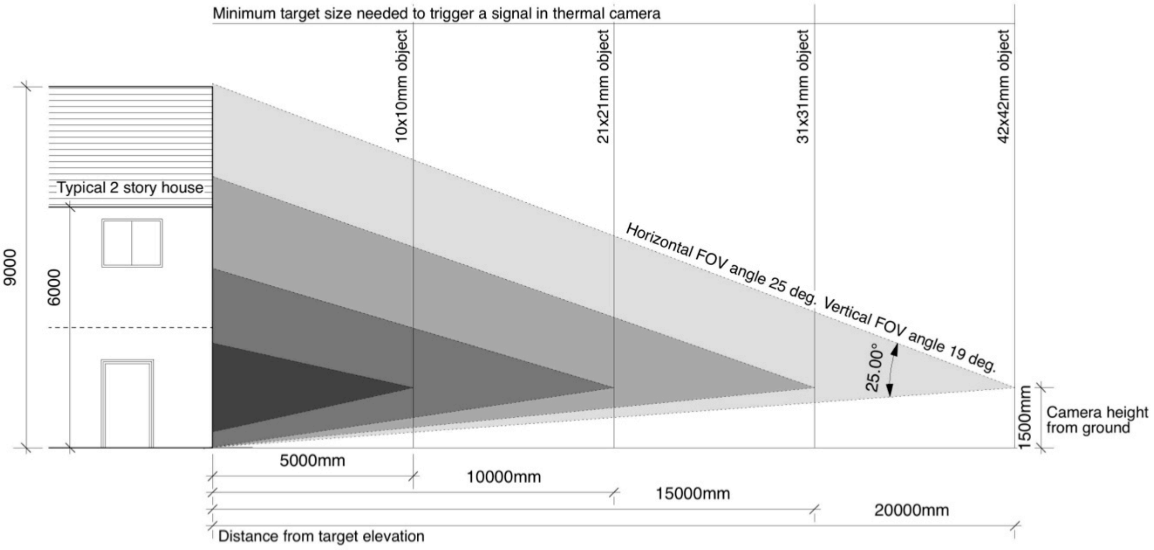


Figure 98. Minimum target size (related to distance from target surface) needed to trigger signal in thermal camera (based on the technical specifications of a FLIR T620bx thermal camera).

As discussed in chapter 6, which reported on time-lapse thermography investigations undertaken on real buildings, distances of 20m to the target surface pose limitations to the spatial resolution. Using the same thermal camera for the walk-past surveys, defects with a thermal signature smaller than 42x42mm in any direction might not be adequately detected due to falling out with the MIFOV measurement ability.

After completing the survey, all thermal images were uploaded to a computer and assessed using the FLIR tools+ software (FLIR, 2014a). This included adjusting the level of each dwelling's image, to ensure that all thermal images from the same case study contained the same temperature span. Furthermore, all dwelling images were positioned on a single sheet next to each other, making it easier for qualitative cross comparison. The methods of qualitative analysis employed for this research included (Walker, 2004):

- Target signature – Determining the presence and type of potential defect within an elevation based on past experience from similar buildings.
- Target symmetry – Assessing different parts of a single elevation to determine / check the presence of potential anomalies.
- Target comparison – Comparing one elevation with other elevations of similar properties to determine the presence and type of defect.

7.2 Results

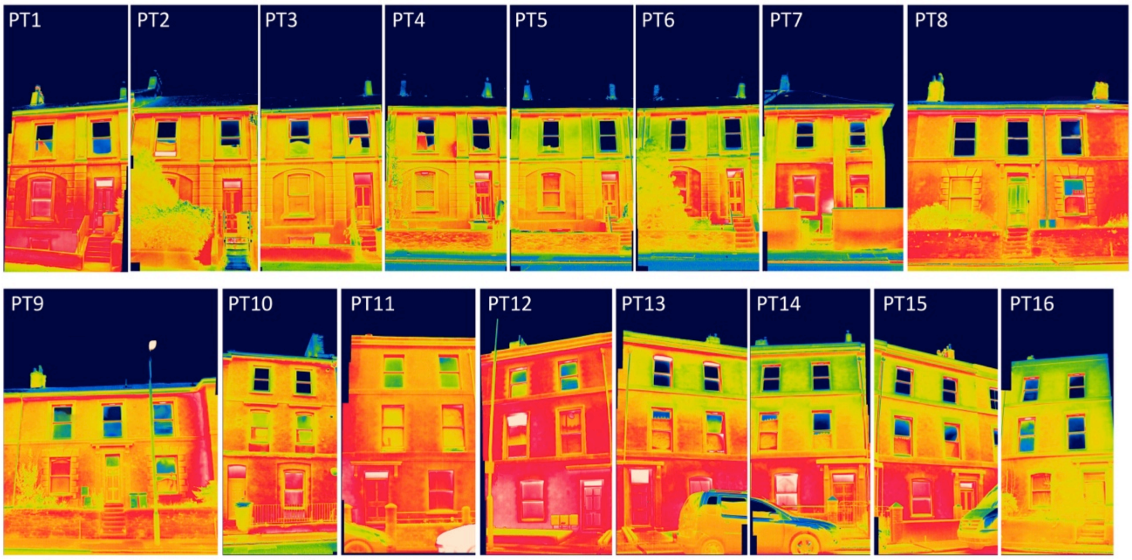
The following section presents qualitative results obtained from each of the four walk-past thermography case studies conducted during March 2014.

7.2.1 Case study A

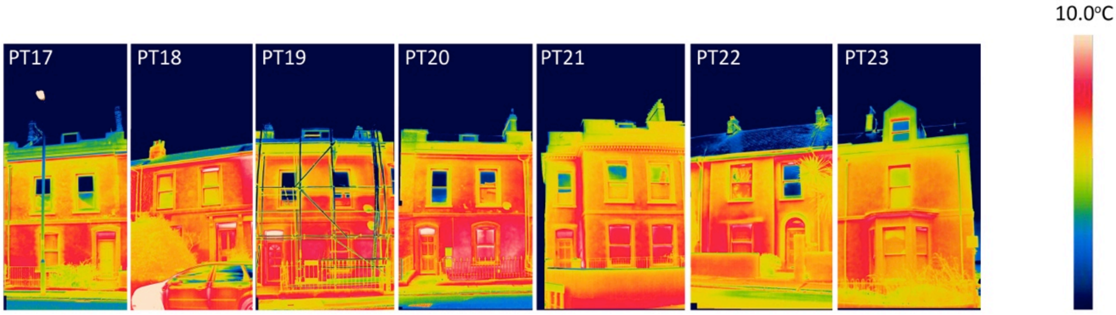
Case study A. observed a residential street in the city of Plymouth, which comprised of predominantly terraced, tenanted dwellings that were managed by the housing association project business partner.

The dwellings surveyed comprised of two and three storey height buildings, most of which have been sub-divided into single floor, self-contained flats. The buildings date from the late 1800s and have solid stonewall construction. The majority have single glazed sliding sash windows. Figure 99 shows a photograph of the street, while table 18 in appendix G presents the parameters for this case study.

Figure 99. Photograph of case study A street.



North Street Elevation (PT1 - PT16)



South Street Elevation (PT17 - PT23)

3.0°C

Figure 100. Thermal image results from case study A.

Figure 100 shows each of the thermal images recorded during the walk-through survey of case study A. Through a review of the thermal patterns in these images; a number of observations could be made:

- Because most of these dwellings were formed of a similar construction and design, it was easy to conduct target comparison analysis between dwellings. This helped with the detection of certain defects, such as the detection of potential cold bridging around structural wall components (dwellings PT4 and PT7) and ventilation losses from windows (dwellings PT3, 11,13,14,15 & 18).

- Some of the dwellings appeared warmer than others, where for example the first and second floors of PT12 presented a warmer apparent temperature compared with the same floors on PT11 and PT13 to PT16, which were of the same construction. Another observation was that the ground floors in many of the dwellings appeared warmer than upper floors.

- Roofs were difficult to observe due to dwelling heights, camera angle to the roof and the presence of raised parapets in some situations. When a roof could be observed they often appeared much cooler than other parts of the structure, and similar to the temperature of upper windows, suggesting the effects of cold reflections.

7.2.2 Case study B

The location for case study B was a Mid Devon village, which was surveyed between the late evening of 7th March through to the early morning of 8th March 2014. Although most of the dwellings were constructed prior to the 1900s, there were a couple which had been built more recently (1990s and 2000s). Furthermore, there were a variety of constructions present along this street. Because of these differences in period and construction, case study B proved more challenging for target comparison analysis than case study A. Figure 101 shows a view along the street surveyed for case study B. Table 19 in appendix G presents the parameters of the case study including the weather conditions.

Figure 101. Photograph of case study B street.

The dwellings in this case study were all two storey in height and privately owned and ranged from older solid stonewall and cob constructions to more modern insulated cavity wall constructions. More specific details on the dwellings inspected during this case study include (dwelling codes relate to Figure 102):

- UA1 – UA19, UA22 & UA23: All of these dated from before 1900. Some dated as far back as the 1700s (such as UA22 & UA23). These dwellings were either terraced or semi-detached and comprised of solid stone and or cob wall construction.
- UA21: This dwelling was constructed in the 1990s and was a semi-detached property that had recently received cavity wall insulation.
- UA20 & UA24 - UA26: These dwellings were built in the 2000s and were comprised of insulated cavity wall construction.

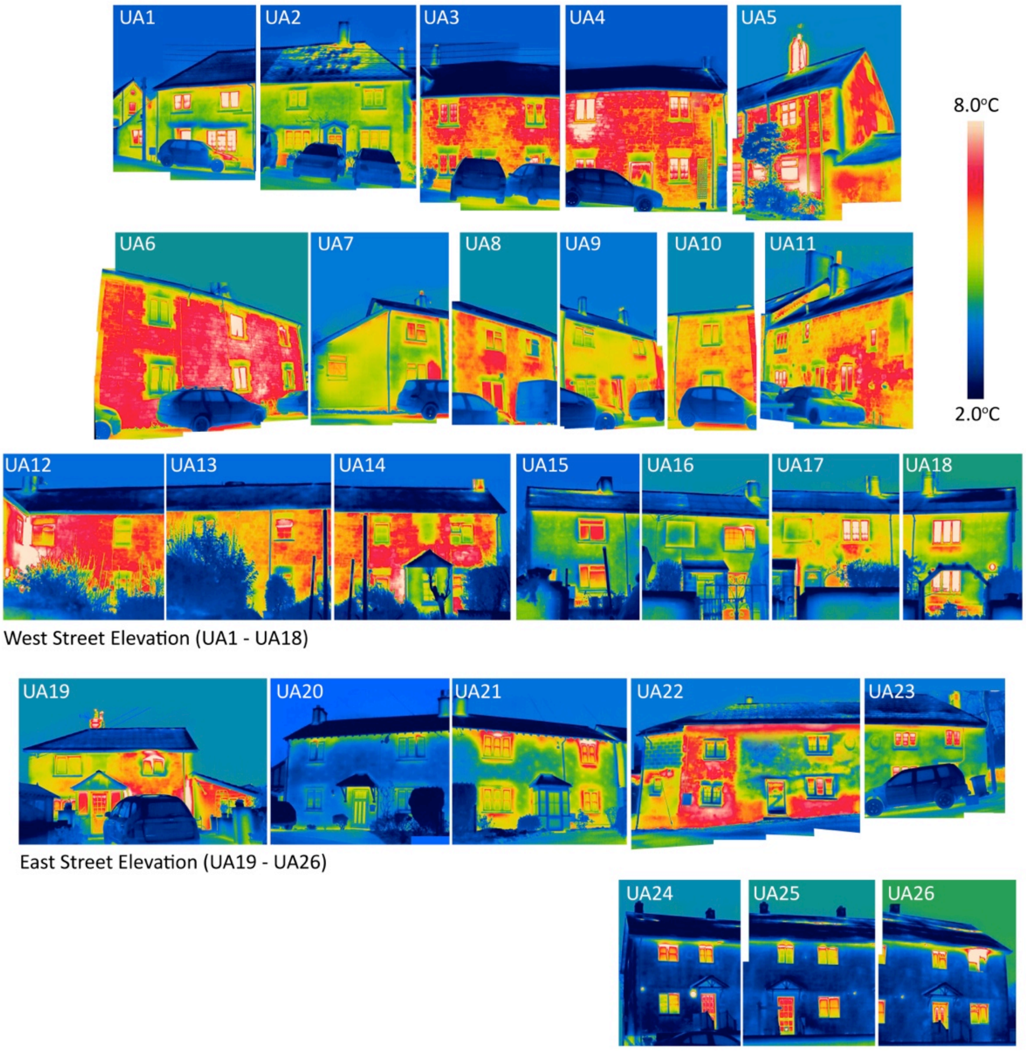


Figure 102. Thermal image results from case study B.

Results from the thermal images obtained during case study B are shown in Figure 102. From these images the following observations were made:

- A number of unexpected warmer patches were viewed on some of the dwelling elevations, which might have indicated the presence of building defects. The two potential defect types detected were cold bridging and ventilation heat loss.

- Possible ventilation heat losses were observed from around window frames in dwellings UA16, UA19, UA21 and UA26. However, it was difficult to ascertain for certain whether the windows were open or defective.

- Observations were made over the heat transfer through different wall constructions. A prime example of this was seen in dwelling UA22. Here the thermal image showed a section of solid stonewalling (centre) as being much warmer than the adjacent cob walling (right) and concrete block walling (left) on the same dwelling. All surfaces had been rendered so these constructions could not be easily detected without thermography.

- Some dwellings showed thermal patterns that suggested cavity wall insulation had been retrofitted. However, within some (such as UA21) there were warmer patches at the top of the wall and under windows, which suggested potential areas where the insulation had not been successful.

7.2.3 Case study C

Case study C also observed a residential street in a Mid Devon village. This was conducted very early in the morning on the 10th March 2014. These dwellings were all built in the 1950s and were originally council housing. However, now some of these dwellings are privately owned. Set within a cul-de-sac layout, most of the dwellings are either terraced or semi-detached with only two being completely detached. The construction is entirely cavity wall, though some of these dwellings have received cavity fill in more recent years. Figure 103 shows a photographic view of the street viewed in case study C. Table 20 in appendix G presents the parameters of the survey.

Figure 103. Photograph of case study C street.

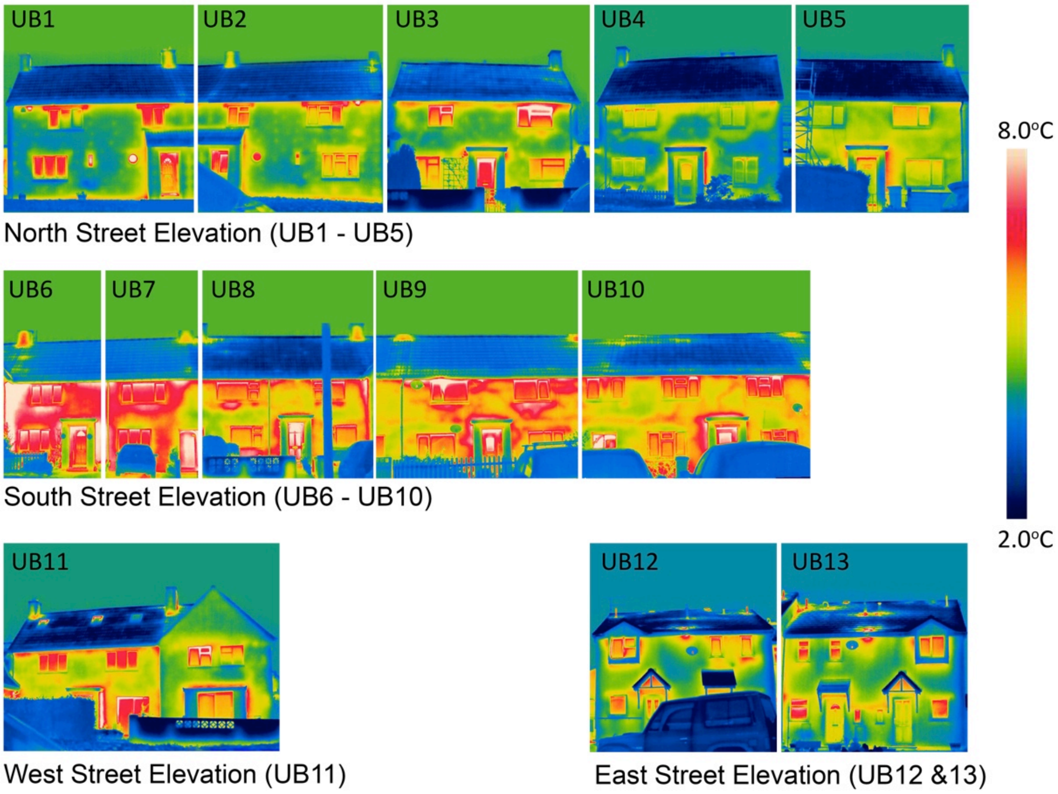


Figure 104. Thermal image results from case study C.

The thermal image results for this case study can be observed in Figure 104. From these images a number of observations were made:

- Unexpected warm patches were identified on the elevations of several dwellings. These indicated the presence of potential building defects, which were assumed to be cold bridging and ventilation heat losses. Dwellings that showed signs of ventilation losses include UB1 & UB5 (from doors) and UB9, UB11 & UB12 (from windows).

- Prior to the survey many of the householders had revealed information on retrofitted cavity wall insulation within their dwellings. Observations made from the thermal images supported this work. Dwellings UB1, UB2 and UB3 showed signs of cavity insulation drill points. Dwellings, UB4, UB8, UB9, UB10 and UB11 all presented irregular thermal patterns that suggested less successful (or degraded) pockets of cavity wall insulation than present in UB1, UB2 and UB3. This correlates with findings by Gupta, Barnfield & Hipwood (2014), who used thermal imaging to observe the success of cavity fill insulation in dwellings, and explained how retrofitted cavity wall insulation was very difficult to install.

- Within the roofs of dwellings UB12 and UB13, there were pockets of higher temperatures compared with other parts of the roof. These appeared to be around service penetrations and could have been potential defects, although it was not possible to ascertain for certain using this methodology.

7.2.4 Case study D

Case study D inspected a residential street in the North Devon town of Barnstaple. Constructed in the 1970s, the street comprised entirely of detached, owner-occupied chalet bungalows, which were either one or two storeys in height. The original construction of these dwellings was un-insulated brick/block cavity wall, though some had recently retrofitted cavity wall insulation. A photograph of the street surveyed in case study D can be seen in Figure 105, and table 21 in appendix G presents the parameters of the survey.

Figure 105. Photograph of case study D street.

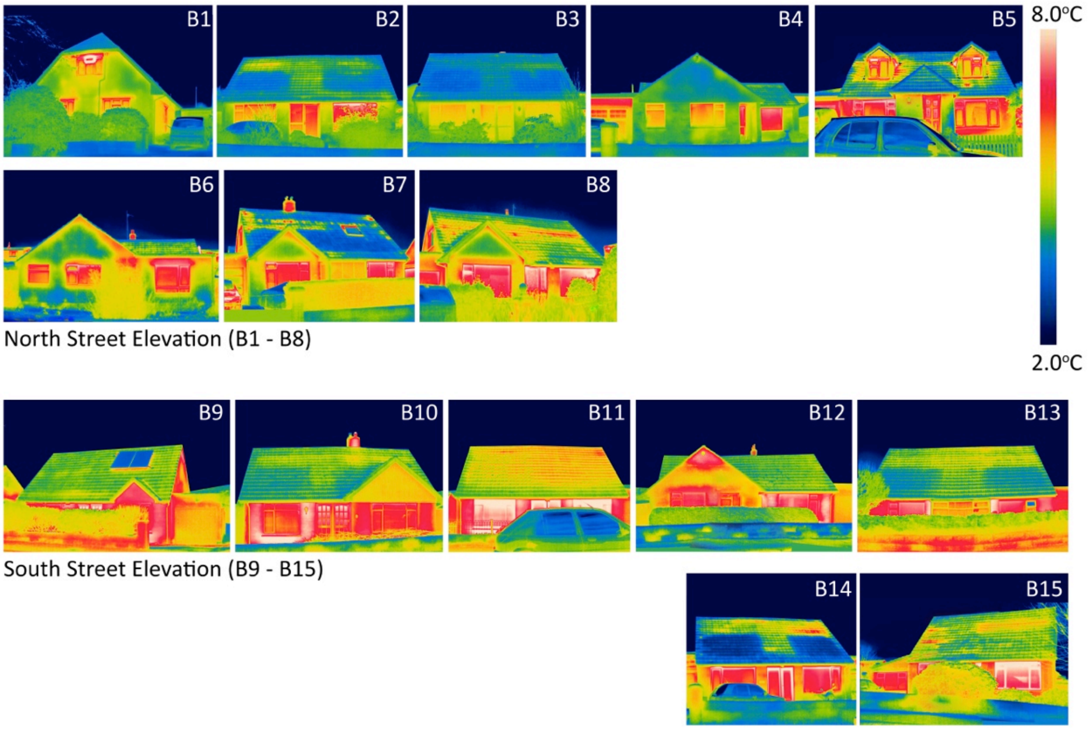


Figure 106. Thermal image results from case study D.

The results from case study D can be reviewed in Figure 106. The following observations were made from the thermal images:

- Like the other three cases studies, some of the dwellings in case study D showed signs of potential building defects, which were presented by warmer areas on elevations. From the shape and distribution of the warm patterns, the potential defects were assumed to be cold bridging. Incidences of this defect type were found in many of the dwellings and were located either in the roof/loft space or from window lintels.
    - Heat loss through the roof could be observed through dwellings B2, B3, B7, B8, B10, B13, B14 and B15, where clearly defined warmer patterns were visible at varying degrees of apparent temperature. A

warmer patch was also identified from the top of the gable wall in dwelling B12.

- Some of the dwellings with gable end features presented a clearer view of window lintels than those with an eaves line concealing the top of windows. In some circumstances (B1, B6, B8 and B12), some of these lintel areas were viewed as being warmer than other parts of the wall.

7.3 Analysis

The most apparent finding from undertaking walk-past thermography was the surprisingly low detection rate of building defects/thermal anomalies. There are two aspects to this finding. Firstly, there were only two defect groups potentially detected during the four case studies: cold bridging and ventilation heat loss. This meant that other defect groups, such as moisture ingress and condensation, might have been missed had they been present within the observed dwellings.

Secondly, there were very few clear occurrences of either cold bridging or ventilation heat loss defects. This factor became more apparent when working on case study A as the housing association estate manager, prior to the survey starting, had indicated the known existence of thermally significant building defects within many of the dwellings. In light of this personal communication, it was anticipated that numerous defects might be detected during the walk-past survey; however, few defects were detected. In particular, cold bridging was only clearly detected in two dwellings, where heat was coming from the edge of a protruding column detail (PT4 and PT7), and ventilation heat losses from sliding sash windows were detected in six dwellings. Therefore, out of 23 dwellings, only 8 individual potential building defects were detected. In addition to only detecting a small number of defects, those that were detected proved very difficult to explain conclusively. For example, it was sometimes difficult to ascertain whether windows were open, such as in PT2. The ability to distinguish and assess defects was limited by the distance the camera was from the elevation, the speed of inspection and the lack of internal information. This methodology was therefore unable to corroborate the pre-survey communication, which advised the likely presence of thermally significant defects.

Since the objective of these surveys was to find defects in buildings, the findings from these four case studies indicate that either the dwellings observed did not have many defects, or that a walk-past methodology misses defects and is therefore deficient as it doesn't achieve its basic aim.

There were a number of additional findings from these case studies, which have been split into two groups, benefits and limitations.

7.3.1 Benefits

Dwellings can be unoccupied

Unlike other building thermography methodologies such as a walk-through survey, walk-past thermography does not require occupants to be at home. Because the thermographer only focuses on one external elevation, captured from street level, they do not need access to the property.

Speed of survey

Walk-past thermography is a relatively fast methodology when compared with walk-through thermography. On average each dwelling took just over 7 minutes to complete. Based on this timing, and providing all dwellings are in close proximity to each other, this survey methodology would permit eight dwellings to be surveyed in one hour. Phan's (2012) preliminary walk-past methodology took 10-15 minutes per dwelling elevation. This longer time-scale seemed to correspond with the larger American dwelling sizes viewed as part of this work compared with those images in this chapter's research.

Where a single walk-through survey might comprise of a 60 – 150 minute inspection duration (Smale, 2014) (depending on the size of the dwelling), if a survey session lasts from between 8pm and 1am (6 hours duration), then a maximum of 6 dwellings could be imaged. In contrast, approximately 36 - 51 dwellings could be inspected in the same time using walk-past thermography (based on 7 – 10 minute dwelling inspections).

Comparisons made between dwellings

This methodology proved very useful for comparing dwellings observed within the same case study. By comparing similar dwellings, it became easier to make assumptions based on common patterns of heat loss, such as whether one dwelling had loft insulation compared with another. Comparisons from the four case studies included:

- Target comparison showed that a particular cold bridging defect was found in identical locations within two similar design dwellings (PT4 and PT7)

(Figure 107). Although not detected on the night, this defect may have been present in other similar dwellings with the same design.

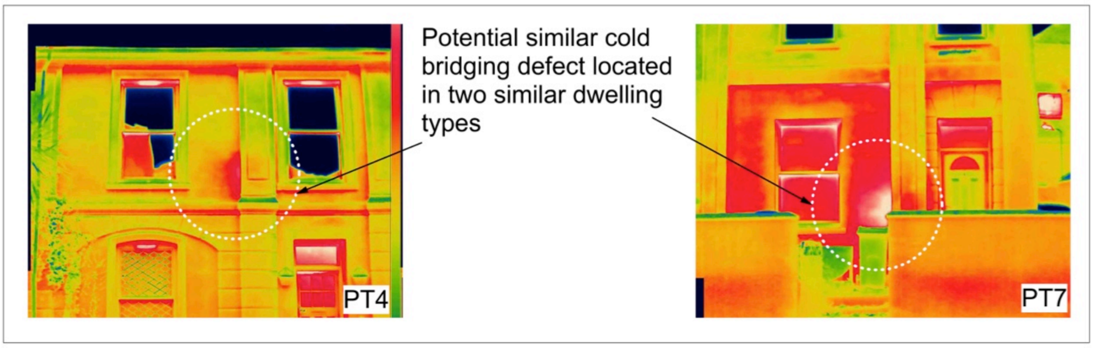


Figure 107. Common cold bridging heat loss between similar dwelling designs.

- Despite few similarities between dwelling ages in case study B, target signature methods of qualitative analysis helped to discern similar cold bridging heat patches in solid stonewall constructions. Examples include dwellings UA4, 8,14,17,18 and 22 (Figure 108). The extent of these as defects or simply the expected conductivity of the stonewalling was not known.

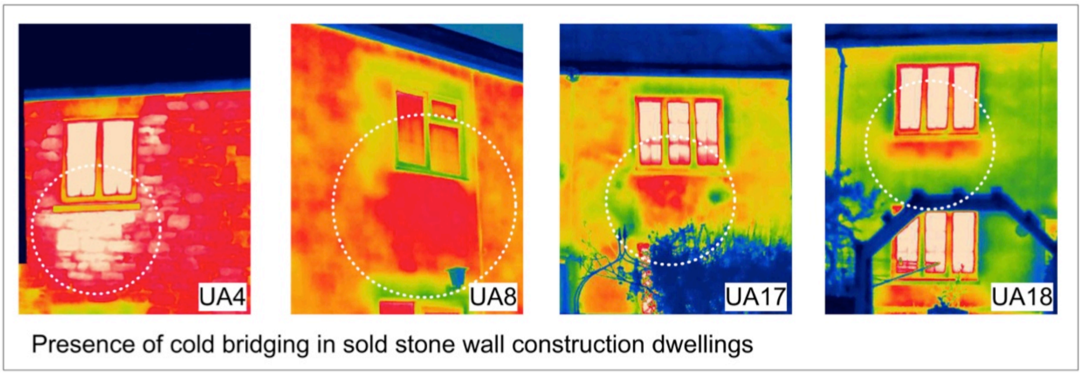


Figure 108. Common cold bridging heat loss between stone construction dwellings.

- Cross period comparisons were made in case study B, between the more modern (2000s) insulated cavity wall constructions of UA20, 24 – UA26 and the older pre 1900s solid wall constructions of UA1 – UA19, UA22 & UA23. As expected, the more modern constructions appeared to show less heat loss than older constructions (Figure 109). Yet comparisons between solid stone and cob walling (see UA22) on pre 1900s dwellings, highlighted the lower thermal conductivity of cob.

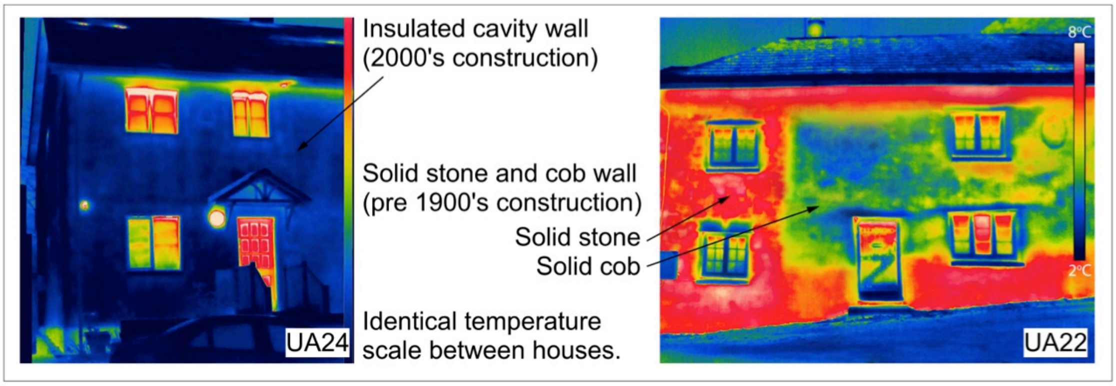


Figure 109. Comparison between different period constructions.

- Comparisons between the similar dwellings of UA1 and UA2 in case study B showed that when compared with each other, UA1 had warmer looking windows and UA2 had a warmer looking roof (Figure 110). Moving around these dwellings ruled out reflections (from windows), which led to the theory that UA1 had improved loft insulation and UA2 had improved glazing (likely double glazing).

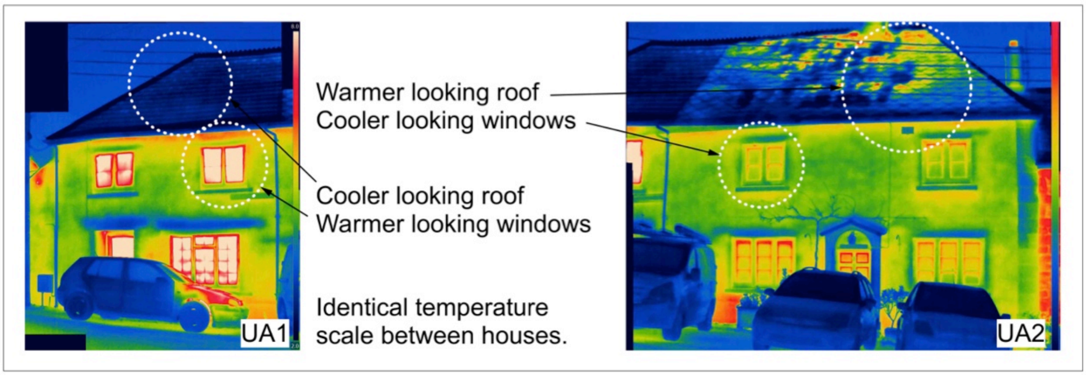


Figure 110. Comparison between similar dwellings with different heat loss patterns.

- Dwellings UB1 to UB11 in case study C, presented identical heat loss patterns around matching extruded components such as bay windows and porticos (Figure 111). Although difficult to ascertain for certain from external thermography, these were deemed to have been either cold bridging or ventilation defects.

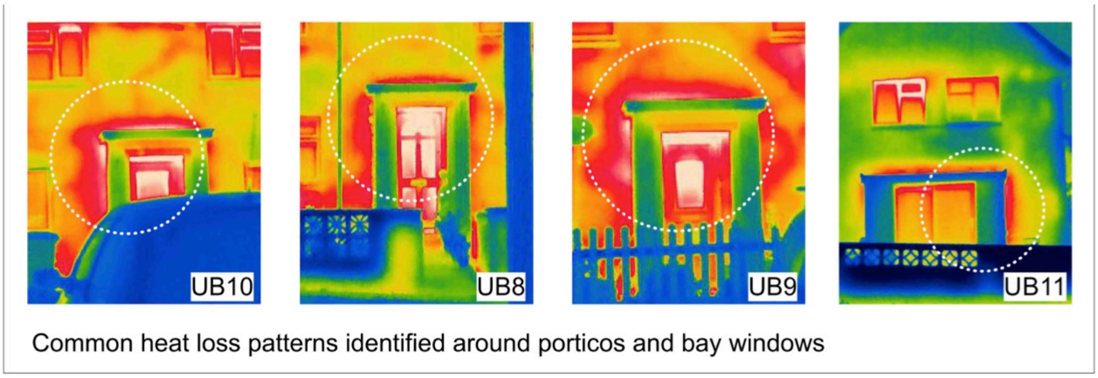


Figure 111. Similar heat loss patterns around identical building components.

- Comparisons were made between dwelling UB8 in case study C, which contained cavity wall insulation and adjacent dwellings UB6 and UB7, which did not have cavity wall insulation. The walls of UB6 and UB7 appeared warmer that of UB8 (Figure 112).

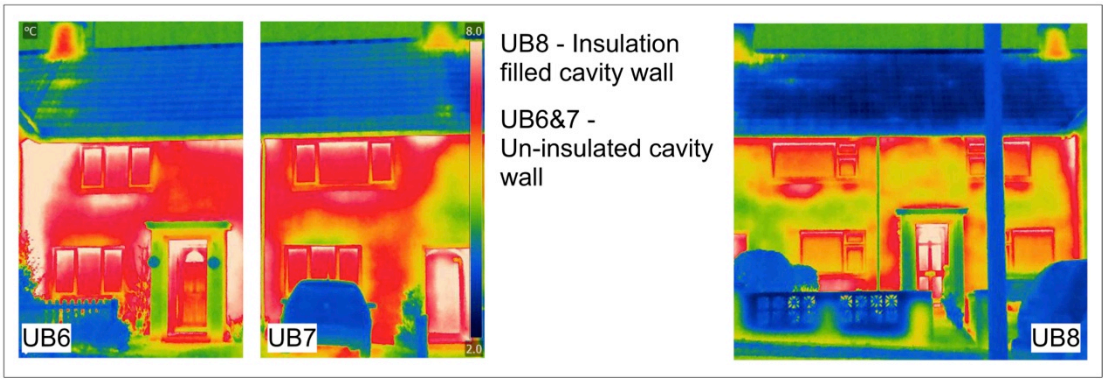


Figure 112. Difference between filled (with insulation) and un-filled cavity wall.

- Eight of the chalet bungalows inspected during case study D presented signs of similar warm patches within their roofs. These patches appeared to delineate a long warm area near to the ridge of the roof, with a central block falling towards the lower part of the roof, and suggested an absence of insulation in these regions of the roof (Figure 113).

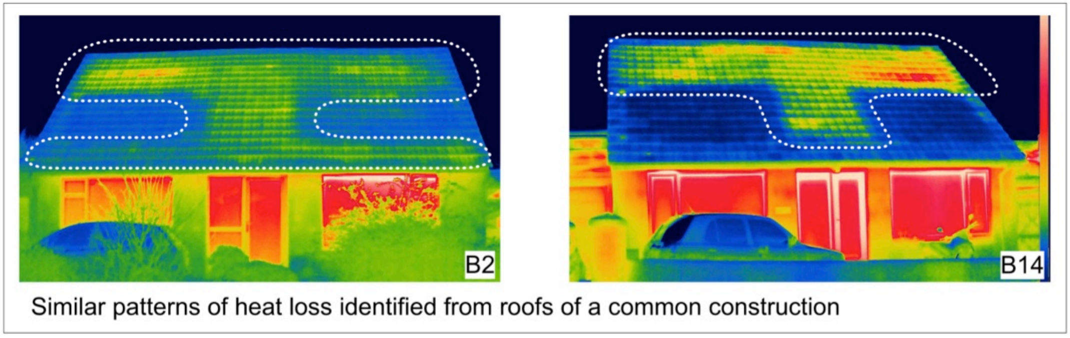


Figure 113. Common trend in heat loss patterns from identical roof constructions.

- Comparisons between window lintels in case study D highlighted a potential cold bridging defect (such as B7). However, this defect was not always present in identical properties (such as B8), which might suggest either fabric improvements or a lower internal temperature to B8, which might have made it more difficult for the thermal camera to discern the defect (Figure 114).

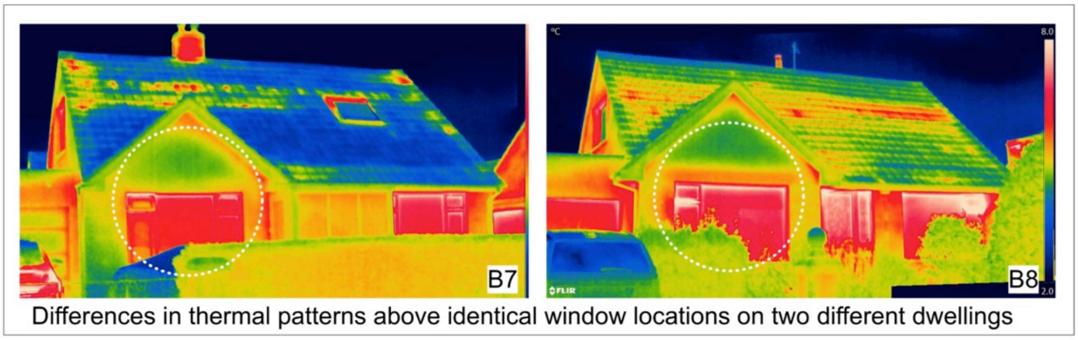


Figure 114. Difference in thermal patterns between similar dwellings.

7.3.2 Limitations

Spatial resolution versus whole elevation image capture

By seeking to capture as much of a two/three storey dwelling within the thermal camera's FOV, the thermographer needed to stand at distances of between 15 and 20 metres from the dwelling. As previously discussed, with increased distance comes a drop in spatial resolution (see Figure 98), since 42x42mm size radiation signals are missed at 20m. Therefore, some small defects that may have been present within the dwellings of case studies A, C and D might have been missed. Had the thermal camera been closer to the surface, these defects may have been identified or more clearly discerned.

Case study B provided an exception to this. Because the street was narrow (6m wide in places), the thermographer had to be closer to the dwellings. As a result it was important to capture lots of images, which were merged together into one larger mosaic image. While this took longer to undertake, it provided greater spatial resolution images, where the entire image might be made up of

1920x1440pixels (3x3 images of 640x480 pixels) for example. Yet this factor also posed new problems with image capturing:

- Being very close to the target surface meant that the lens perspective changed as the camera panned over an elevation. This made it difficult to photo-merge one thermal image with another, as building features did not always line up.

- Whilst the distance to building surface at eye level might be 6m, angling the thermal camera upwards to a second storey or roof, increased this distance. Figure 115 illustrates this limitation. Although this effect will also occur at distances of 20m, the effect is likely to be less noticeable given the increased angle needed to view high-level surfaces at 6m distances. Schwoegler (2011b) discusses the issue of angling the camera to view high level building elements, suggesting that it would be a limitation to pass-by thermography.

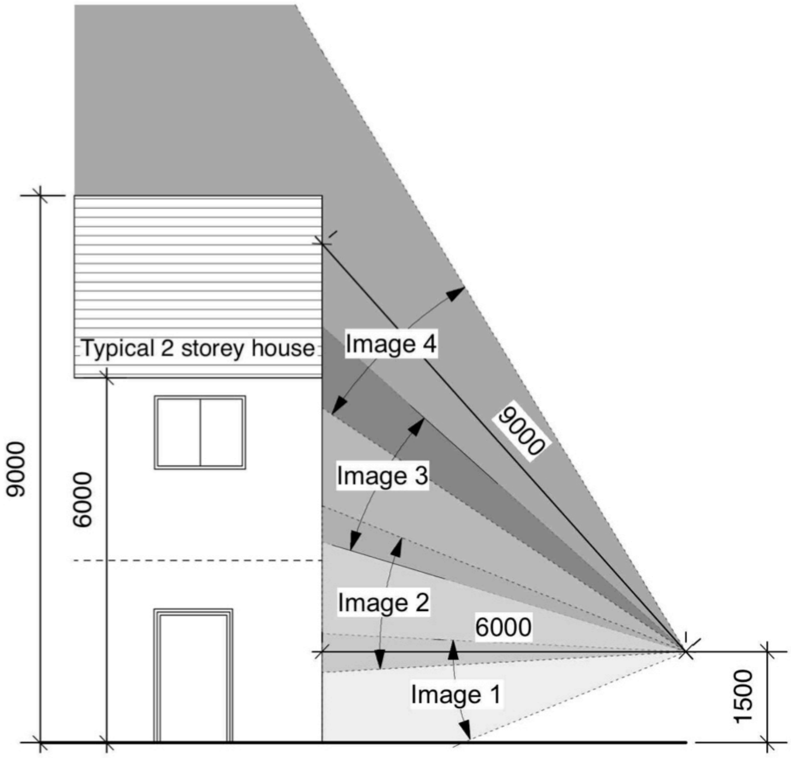


Figure 115. Camera to surface distance when standing 6m from a building.

Because of these limitations, some of the thermal images captured during case study B were taken at an angle to the dwelling. This was no greater than 65°, which is the maximum angle that can be used before emissivity discrepancies occur (Hart, 1991). This enabled distances of up to 10m to be used for some dwellings.

With limitations of being too close or too far from a target surface, it is clear that a balance between spatial resolution and ease of elevation image capture needs to be made. The optimal distance from the building that a thermal camera of the specification used in this research should be held at was deemed to be between 10 (21x21mm minimum defect size) and 15 metres (31x31mm min defect size). However, Phan (2012) argued that even at 10 metre some defects such as ventilation heat loss could be smaller than 22mm in size, which would be very difficult to detect above a 10m distance. This, therefore, questions the ability of walk-past thermography to successfully detect building defects.

Viewing angle

Holding the thermal camera at eye level means that the camera needs to pan up at an angle to view the upper parts of a building, as illustrated in Figure 115. All of the dwellings viewed had pitched roofs. When the angle of these pitched roofs is combined with the angle that the camera is from the surface, an angle of more than 65^{o} was not uncommon. At acute angles, the roofing materials (typically slate) emissivity and surface finish combine to reflect other sources of radiation such as clouds and a clear sky. This made it very difficult to discern real surface temperatures in case studies A, B and C. Any defects that might have been present would have been missed.

Case study D proved to be the exception. The large low-level roofs of the chalet bungalows were constructed of a rough concrete tile, which made it easier to view the surface temperature of these building elements and the possible defects beneath.

Weather conditions changing throughout survey period

While weather conditions may change from one survey to the next (day to day), making it difficult to compare dwellings from different case studies, some of the weather conditions also changed during the survey period. Air temperatures did not vary more than half a degree during each of the four case studies. This comfortably complies with guidance recommending that temperature changes are no greater than 5 degrees over the duration of a survey (BSi, 1999).

However, changes in cloud cover, which were particularly noticeable in case study A, might have presented problems during the survey. For example, as clouds move across the sky, the first dwelling may have reflected a cloudy sky, while by the time the second dwelling was surveyed, the clouds might have moved past. The difference between the two conditions could significantly affect image comparisons given the extremely low temperatures (about -50^{o}C (Pearson, 2011)) that a clear sky can emit compared with a cloudy sky (measured at approximately -6.1^{o}C).

Although not experienced during these case studies, other significant weather changes during the period of the survey could greatly impact the ability to compare dwellings. For example, the first dwelling in a survey might be subject to dry conditions, while subsequent dwellings surveyed following a period of rainfall may present different thermal patterns/readings.

Another weather related limitation, was the inability to determine the extent of solar exposure during the day leading up to the surveys. The potential effects of thermal mass were observed in case studies C and D. Schwoegler (2011b) highlights solar loadings in combination with the thermal capacity of different building materials as a potential limitation to pass-by thermography.

Unknown occupancy behaviour

The behaviour of occupants was very difficult to ascertain/predict using a walk-past thermography methodology. Despite all residents knowing the night of the survey, they were not told the exact time that their home would be viewed. Furthermore, the information sheet explained to residents that they did not need to be at home. Therefore, when inspecting a dwelling, it became difficult to ascertain:

- Whether dwellings were currently occupied, and how many people were inside;
- What the internal heating program was. Had it been on all day, only an hour or two before the survey or had it just been turned on?

By conducting surveys at night, one technique was to note whether any lights were on in the house. The thermal image sometimes verified these observations, though could not be used to determine the internal temperature or heating program. Without this information it proved difficult to ascertain whether one building was better insulated than another. For example, when comparing dwellings UA15 and UA17 in case study C, both appeared occupied (lights were on); however, UA17 appeared to show more heat loss through the walling compared with UA15. It was difficult to know whether this was due to a higher internal temperature in UA17 due to potential defects or greater thermal conductivity compared with UA15.

Foreground obstructions

As encountered during the walk-through and time-lapse thermography investigations, a common limitation found during each of these case studies was the presence of foreground obstructions. While such obstructions might be easily avoided during a walk-through survey, where the thermographer moves around the building, in a single elevation street survey there are a number of features that could mask potential building surfaces. Garden foliage and vehicles were the most common obstructions, which masked areas of building elevation. Examples of such obstructions can be seen in dwellings PT2, PT6 and PT18 of case study A. These might have masked potential defects, which would not have been detected during the walk-past survey.

Building orientation

Hart (1991) explained that different façade orientations perform differently to each other, depending on wind, solar loading and rain exposure. Despite planning for survey conditions that followed a cloud-covered day, in some of the case studies, images of south facing elevations presented walls, which appeared slightly warmer when compared with north facing elevations. One explanation for this was that leading up to the survey there might have been periods of direct solar exposure, which would have warmed the south facing walls. Examples of potential south facing solar exposure, where the effects of stored thermal mass might have been displayed, were seen in case study D, dwellings B9 – B15 and case study C, dwellings UB6 to UB10. Although internal occupancy and heating parameters were unknown, if these dwellings were displaying signs of thermal storage, then the image results might have been adversely affected, and some defects could have been masked.

Single elevation analysis

One of the key characteristics of walk-past thermography is single elevation observation (Schwoegler, 2011b). This elevation is usually the side of the dwelling facing the street. All other external elevations are not included. Because of this factor, only part of the dwelling is inspected. Therefore, if building defects were present elsewhere on the dwelling, these would have been missed. It is also not possible to make generalised statements (quantitative or qualitative) on the presence of defects or overall thermal conductivity based on the information from one elevation.

External analysis only

Another important characteristic of walk-past thermography is that only external surfaces are inspected. While there are some (Colantonio, 1999; Holst, 2000) who advocate the use of external thermography for (traditional walk-around) building inspections in preference to internal thermography, Vollmer & Möllmann (2010) argued that external thermography can only ever provide an overview of a building. On the basis that very few building defects were detected as part of these walk-past surveys, this research appears to verify Vollmer & Möllmann's caution against using external thermography alone. The thermal images collected only provide a basic overview of the front elevation, which may explain some of the building defects but is likely to have missed many more.

7.3.3 Potential Application

Given the recognised limitations of walk-past thermography and the technology currently available, quantitative analysis in particular seems to be ineffective using this methodology. Likewise, this work has shown that doubts could equally be raised over the use of walk-past thermography for successful qualitative analysis. Yet despite this, there may be application areas that could make use of the unique benefits that this methodology contains.

Comparisons between similar dwellings are made easier by the opportunity for analysis under the similar/identical conditions experienced in a single night. With the ability to quickly assess many dwellings in a single night, owners of large dwelling stocks such as housing associations may value the ability to compare dwellings of a similar form and construction. Having a better understanding of common trends in fabric heat loss, as discovered in case study D would make it easier to arrange a large-scale/neighbourhood programme of refurbishment, where every dwelling of that construction could be repaired/upgraded. This strategy could align with recommendations by Gupta *et al.* (2015), who advocate city-wide/community upgrades where replicable interventions could be more easily undertaken than the more demanding 'whole house' renovation. In such a case, walk-past thermography might be one method used by communities and developers to make tailored improvements on several similar dwellings, therefore applying the economies of scale.

A traditional walk-through survey costs in the region of £400, with a traditional walk-around survey costing £250 (Red Current, 2012a). Although the cost of a walk-past survey is currently unknown, based on the shorter time scales involved compared with traditional thermography, the survey costs are likely to be less. Alongside an ability to make fast and multiple dwelling comparisons, lower priced surveys are more likely to attract interest from organisations such as housing associations given the number of dwellings that might need inspecting, and the finances available. Furthermore, inspections can be undertaken without the need to engage with dwelling occupants, which speeds up the survey procedure.

Despite the limited success that walk-past thermography had in detecting defects in these case studies, Pearson (2011) stated that any defects detected from the outside will almost always present themselves more clearly on internal inspections. On this basis, it is likely that those defects detected externally will prove more significant than those only detectable from the inside. Therefore, landlords with large dwelling stocks, such as housing associations, might find that the data from walk-past thermography could help them to identify the more problematic dwellings under their control. For example, out of 100 dwellings, 10 might show signs of cold bridging. The housing association could then target remedial action over these dwellings as a priority. To help improve this methodology, building managers should ensure that all dwellings have their heating systems on and at a designated temperature for a prolonged period of time. This would mitigate the limitation of unknown occupancy and internal temperatures discovered through this research.

7.4 Summary

Within existing literature, there are conflicting comments on the application and success of a fast pass-by thermography methodology. On one hand, pioneers of this technology, MIT/Essess (Essess, 2015; Phan, 2012) and IRT surveys (2012a) advocate the ability to obtain useful quantitative data from these surveys. Yet on the other hand, others, such as Schwoegler (Schwoegler, 2011b) caution against the over reliance on data from these methodologies due to known limitations and variations. In light of these conflicts, and as the antithesis to time-lapse thermography, a walk-past pass-by thermography methodology was explored (Objective 5). The findings from walk-past thermography have been organised into a diagram (Figure 116), which highlights the benefits and limitations encountered during the case studies.

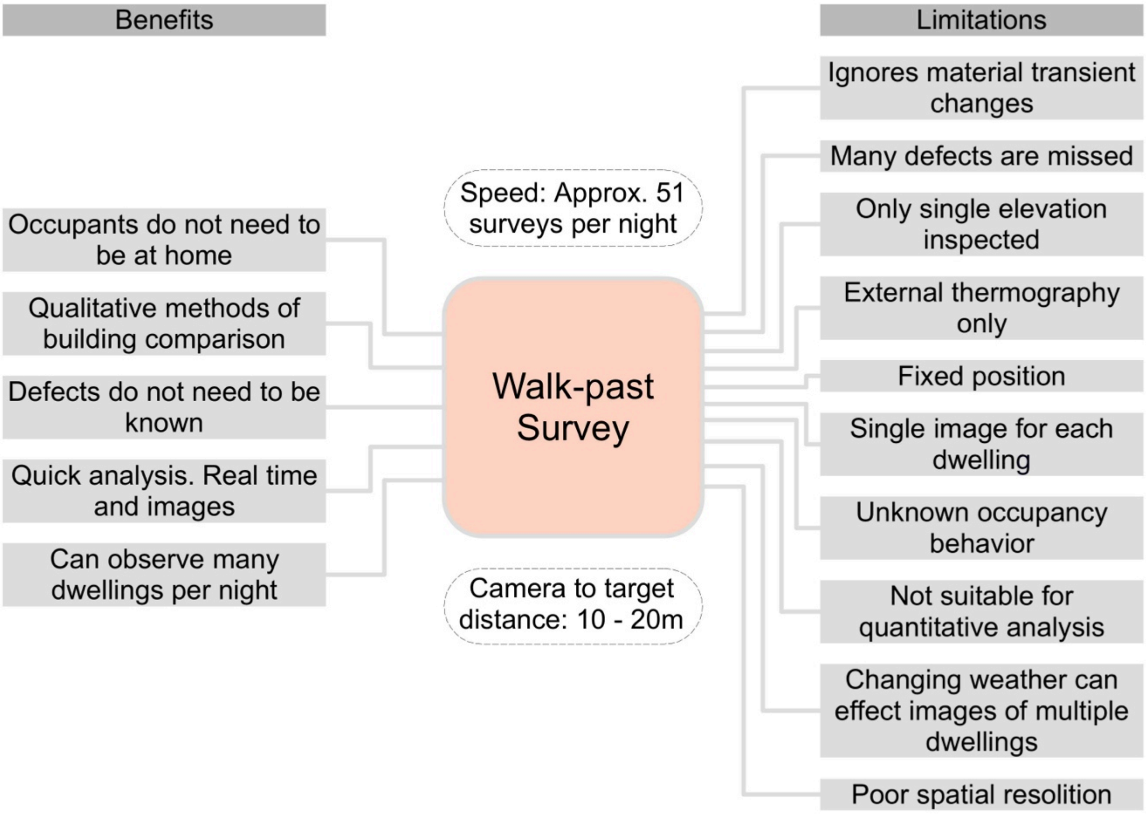


Figure 116. The benefits and limitations to walk-past thermography.

Only two types of defect were detected using walk-past thermography. Ventilation and conductivity heat losses. All other defect groups were missed. This correlates with the literature review matrix in chapter 3, which found that other pass-by thermography research/work had only detected these two defect groups. Therefore moisture defects were being completely missed during this methodology. Furthermore, defect characterisation was even less likely using this methodology.

Although not investigated during this chapter, it the shortfall in defect detection and characterisation compared with other methodologies places key doubts over the effective application of walk-past thermography for quantitative analysis. Key limitations to walk-past thermography have been identified as:

- Only able to inspect single external elevations
- Differences due to alternative building orientations
- Changeable weather conditions through the survey period
- Too fast to comprehend the effects from transient changes
- Viewing angle/emissivity limitations
- Unknown occupancy/internal air temperatures
- Camera too distant from the target surface for entire elevation images
- Unavoidable foreground obstructions

Despite these limitations, this research found that a walk-past methodology could successfully compare dwellings of similar forms and construction to determine the presence of common defects. By only capturing one elevation from the street and not requiring interaction with householders, this methodology was proven to be faster than more lengthy methodologies, such as traditional walk-through thermography. This enabled 45 more dwellings to be assessed in a single night (and under similar weather conditions) from walk-past thermography (max 51 dwellings) compared with walk-through thermography (max 6 dwellings). Because of these benefits, it is proposed that the walk-past thermography methodology could be useful for owners/managers of large dwelling stocks, such as housing associations. Although not providing a comprehensive assessment of each dwellings building defects, walk-past thermography could be used for large scale, quick and lower cost (than traditional thermography) inspections, where problem dwellings or building defect trends can be quickly identified for further investigation and improvement.

8.0 A roadmap for building thermography application

Chapters 5, 6 and 7 have presented detailed findings from multiple experiments and case studies, which have explored the use of three different passive building thermography methodologies. These were walk-through (Traditional), time-lapse and walk-past thermography. Each methodology encompassed a broad spectrum of approaches, from fast to slow, external only to internal and external, and from close-up to distant viewing ranges.

Based on the findings from this research, chapter 8 considers the practical application for these three thermography methodologies (**Objective 6**). In particular:

- How each methodology could be used in coordination with each other or alternative methods of thermography and NDT rather than acting as an independent procedure.
- How other thermographers and building managers might be able to make better decisions upon the selection of the correct thermography methodology for the task they are faced with.
- What the commercial and policy implications might be for alternative thermography methodologies.

8.1 Combining thermography methodologies

Until now, this thesis has considered the different thermography methodologies as separate entities, where one might be chosen in preference to another for a thermographic survey of a building. Given the known strengths, weaknesses, benefits and limitations to each methodology this section considers how they might be used in coordination to better understand building defects.

Just as there are few documents comparing the different passive building thermography methodologies, little has been written on combining methodologies as part of a phased approach. As reported in chapter 3, one paper by Brady (2010) began to explore this issue, by proposing a phased approach for large building inspections.

Correlations between Brady's work and the work in this thesis can be made, in particular with the work in chapter 5, which explored traditional walk-through thermography that made use of panoramic images in addition to close up detailed images. Undertaken with Brady's work in mind, this image scaling activity began to confirm the benefits of phased thermography, initially proposed by Brady.

However the work detailed by Brady also starts to suggest how different thermography methodologies could be used to complement each other or to make surveying multiple dwellings more efficient.

Making use of each thermography methodologies strengths/benefits as part of a drop-down, phased approach where more than one methodology is used could help to mitigate the known limitations/weaknesses. Comprising of two or more phases, the first approach would use methodologies, which provide a quick, low detail/resolution and high volume (of defects and properties) overview at the macro scale before moving on to the micro scale for more detailed inspections at a slower speed, increased resolution and case specific. This approach is illustrated in Figure 117, which shows the theoretical drop-down, phased approach.

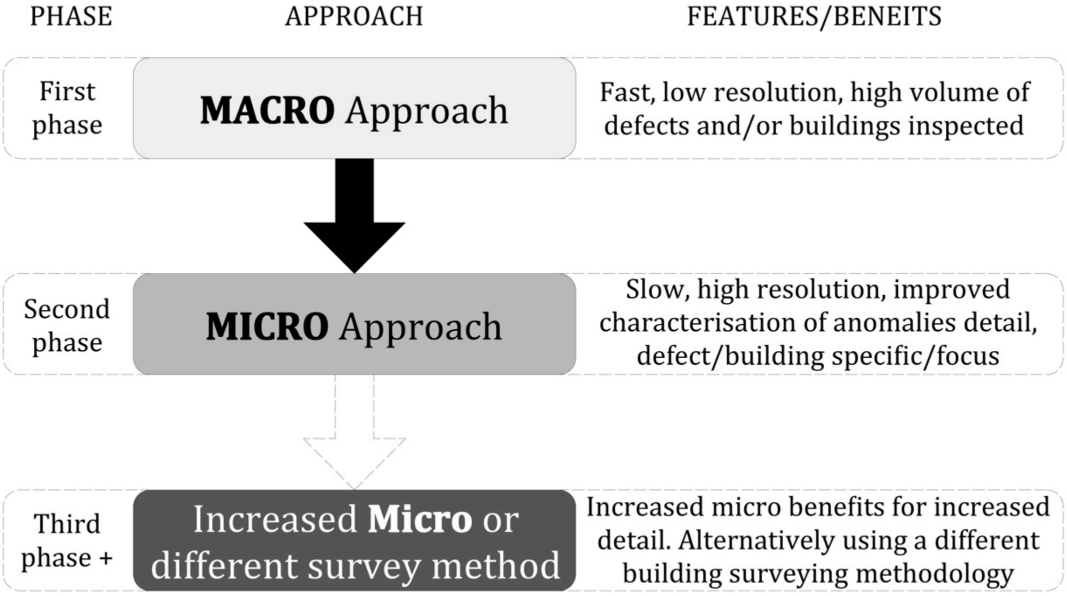


Figure 117. Theoretical drop-down, phased approach.

The following example scenarios describe how the theoretical drop-down, phased approach could work in practice. These have been based on the outcomes from the investigated three methodologies, and existing literature relating to alternative methods of NDT.

Scenario 1

A housing association wishes to make improvements to 50 identical neighbouring dwellings that they manage. They intend to use thermography as a method to qualitatively detect any potential defects that can be rectified as part of a whole scale improvement regime. They are looking for a low cost solution, which meets their needs.

To conduct only walk-through thermography on each dwelling might be viewed as prohibitively expensive (based on £400 cost estimate by Red Current (2013)), and might be constrained by transient changes in conditions over several days, if only 6 dwellings are inspected per evening. Conversely, to only conduct walk-past thermography for such scenario, whilst all dwellings could be surveyed in one evening, it is highly likely that not all common defects would be detected.

Consequently it might be more appropriate to propose walk-past thermography as a first stage in a phased approach. This would enable all of the dwellings to be imaged together very quickly and under very similar external climatic conditions. Using qualitative analysis techniques, it would be possible to make direct comparisons between each of the dwellings, so that any common defects could be identified (as found in chapter 7). This methodology could also help to indicate those properties that might be performing worse than others. A second stage to the phase, would involve walk-past thermography. This methodology could be used to either inspect those that appeared to have the worst/most potential defects (discovered during the walk-past thermography inspections), or 10% of the dwellings could be inspected to identify common problems compared with the walk-past thermography results.

By using this two staged thermography approach, the speed and lower cost (compared with a walk-through survey) of a walk-past methodology has been utilised to gain a quick overview of all the dwellings. This corresponds with Brady's (2010) overall images. Given the known poor quality in defect detection from walk-past thermography, this methodology cannot be relied upon to make strategic decisions on repairs. However, by using walk-through thermography on a selected number of dwellings, the quality issue can be partially addressed, and used in combination with walk-past thermography to inform a program of improvement works.

Scenario 2

A private resident has approached a thermographer asking for a thermographic survey of their home. They explain how one room seems colder than others; though do not fully understand the problem. They would like to know what the problem is, so that they can make improvements.

The common approach for this type of enquiry would be to use a traditional walk-through thermography methodology, which might indeed locate the problem area. However the defect might be very difficult to characterise, making diagnosis more difficult and any subsequent recommendations (for further inspections or remedial action) inaccurate.

Instead, a two-phased approach could be used. This would start by using a traditional walk-through methodology to identify all areas of potential anomaly. Where an anomaly cannot be clearly characterised, a second phase could make use of time-lapse thermography, which has been proven (chapter 6) to offer more detailed analysis of thermal anomalies.

By using this two-stage approach, the dynamic real time analysis offered from walk-through thermography is utilised to locate multiple defects, while time-lapse thermography assists with difficult defect characterisation due to transient analysis.

Scenario 3

A recently completed building is having an air-tightness test to validate its air-tightness rating for compliance Part L of the building regulations. The building fails this test and the construction team cannot understand where the fabric is failing. Whilst one method to locate failures is smoke testing, which can be time-consuming if using a smoke pencil, (Pickavance & Jones, 2006) an alternative is to use walk-through thermography.

Therefore, the first phase would be the air-tightness test; the second might be to use a smoke pencil or walk-through thermography where all elevations of the building are inspected for air permeability. Pickavance and Jones (2006) explain that thermographic inspections should be conducted during the airtightness test and that the building should be depressurised.

The added benefit of using thermography instead of smoke is that insulation continuity inspections can be undertaken at the same time, providing an added benefit to ventilation heat loss inspections. Work by Kalamees (2007) is one example where a thermographer has successfully located air leakage in dwellings using thermography in combination with air-tightness testing.

Scenario 4

A high thermal performance dwelling has just been completed and is being monitored using the coheating method of analysis. The objective is to compare the performance gap between predicted and actual heat loss (WARM, 2010). After a two-week period, measured results are found to be much poorer compared with predicted performance.

As a second phase, thermography could be used to better understand why/how the building is performing in the way it is. This second phase could take two approaches. Firstly, a walk-through methodology could be used to quickly identify potential problems in the fabric. An alternative approach might be to use time-lapse thermography during the coheating test. This could be used to observe a typical construction detail over the two-week period, and better understand/visualise the heat flow through the fabric. The ultimate aim of using thermography to complement coheating testing, would be to pinpoint areas of weakness for possible remediation and to help the building more closely achieve its predicted performance levels.

Scenario 5

A housing association has recently completed a street of 30 dwellings. They are keen to monitor the performance of these dwellings over a prolonged period of time to ensure that they maintain thermal performance levels, which meet with the Decent Home standard.

Addressing this brief could take the format of a two phased approach to thermographic analysis. Firstly, walk-past thermography could be conducted every year to check the condition of each dwelling. This methodology would feature repeat thermography, where images would be recorded of each dwelling irrespective of the presence of identified defects. Images of these dwellings could be compared with previous years to assess condition. The second phase of this approach could be to utilise repeat walk-through thermography on one dwelling.

Should any defects be detected in this dwelling, it might indicate the potential for common defects in the other identical dwellings. Differences in climatic conditions etc. would need to be factored into the analysis of repeat images, and would be a limitation. However this phased methodology might help to quickly identify emerging defects before they become too significant.

Further scenarios

These five scenarios perfectly illustrate the added benefits that thermography methodologies can bring when combined with each other or other NDT techniques instead of being used in isolation. Although these scenarios suggest the use of two methodologies, there might be opportunities to combine three or four methodologies, such as walk-past, walk-through and time-lapse thermography. Whilst these example scenarios show how methodologies could be combined, the selection and design of methodology regimes will largely dependant on the particular situation being faced. For example, how many dwellings? Are the dwellings the same? Are defects expected (what defects)? What are the cost limitations? Etc.

The scenarios discussed above are not exhaustive. There will be many other methods of combining thermography methodologies together and with other methods of NDT. For example, UAV and aerial thermography could be added as a phase in detailed building inspections, or repeat thermography might be used at set stages throughout the construction of a building to validate workmanship. The work in this thesis establishes the principle for methodology combination, which should be utilised/furthered by others in future work.

8.2 Method of selecting thermography methodologies

In addition to considering how different thermography methodologies might be used in combination with each other, the work in this thesis has also helped to inform the decision making process, for selecting the most appropriate thermography methodology for a given task. Figure 118 illustrates the decision-making process framework. This framework has been designed based on typical workflow scenarios that might be encountered by building managers commissioning a building survey and by professional building surveyors and thermographers who might need assistance with selecting the most appropriate surveying methodology for a particular survey. Although the focus of this framework is on the selection of passive building thermography methodologies, other methods of building surveying have been included as alternative methods, which might complement or be used in combination with passive building thermography. It is also useful to understand the alternative methods of approaching a similar scenario.

The development of Figure 118 has been greatly influenced by the findings from this thesis. In particular from the findings discovered during the practical experiments and case studies undertaken on the three investigated methodologies. For example, the figures for the ‘number of dwellings inspected per survey’ have been derived directly from the case study results for time-lapse, walk-through and walk-past thermography. This relates to the practical ability for one person to survey as many dwellings in one evening (from approximately 7pm to 12pm) as possible for each methodology. Accordingly, a maximum of 6 dwellings could be inspected using walk-through thermography during one evening.

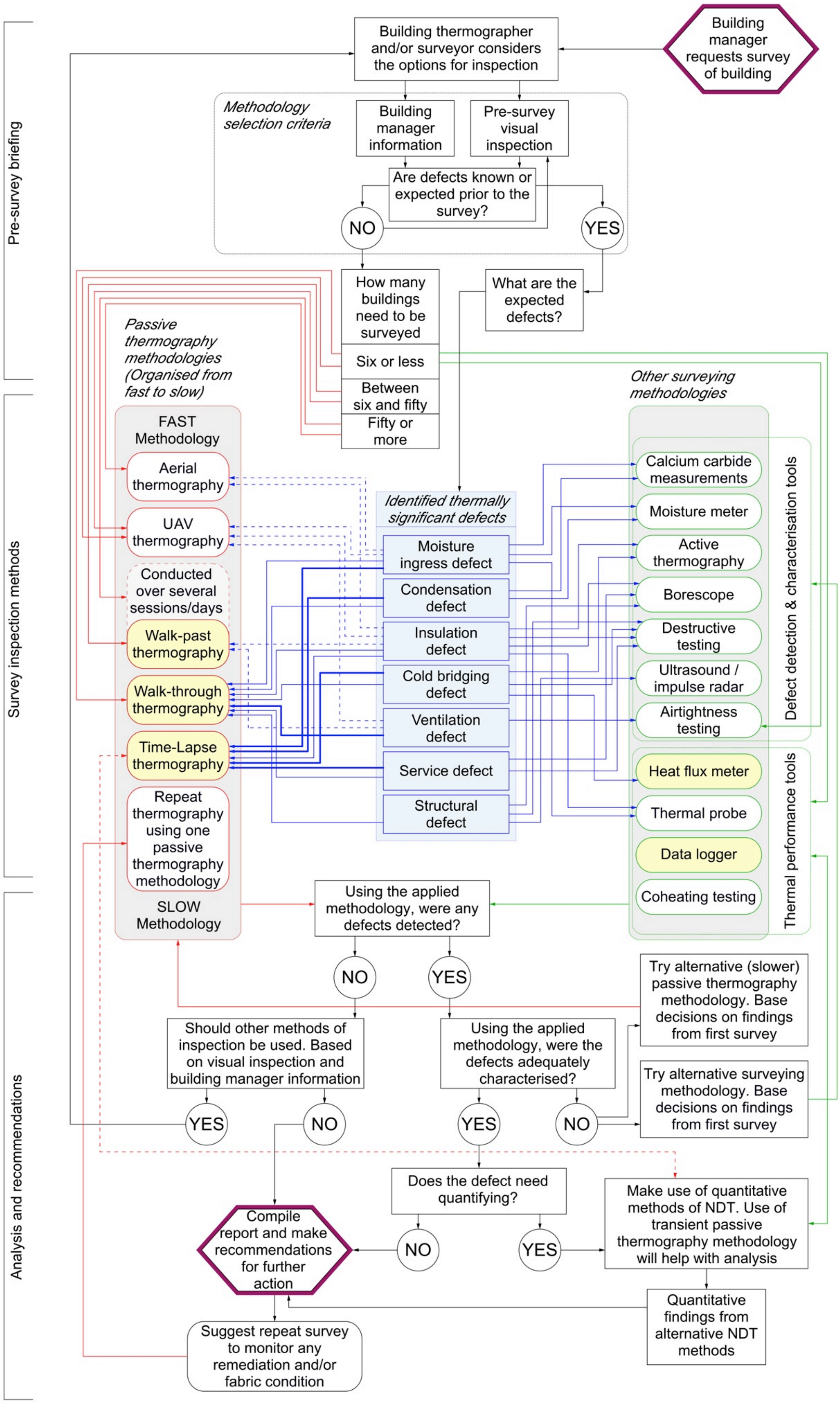


Figure 118. Thermography methodology decision-making framework.

It is important to note that assumptions made on the methodologies not directly inspected during this thesis have been based upon findings from past literature. With further experience/research using those methodologies not explored through this thesis, this information might be adjusted. For clarification, the methodologies practiced during the primary research chapters of this thesis have been highlighted in yellow in the framework diagram (Figure 118).

To help indicate which methodologies are more successful at discerning/characterising defects than others, lines linking methodologies to defect types have a coding system. These are been based on the observed success of each methodology during the primary research chapters.

- Dotted lines indicate low success in defect detection and characterisation (compared with solid lines).
- Lightweight solid lines indicate improved success (over dotted lines) in defect detection.
- Bold solid lines indicate improved success (over lightweight solid lines) in defect characterisation.

The first step on the decision making process is to consider the options available for conducting a building inspection. To help with this, information from the building manager or a per-survey visual inspection might help to understand whether defects are known prior to a survey or not. Some of the investigated case studies (such as case study A in chapter 6 for example) demonstrated that there were circumstances when defects were known prior to a survey. This will therefore influence the selection of thermography methodology, because some methodologies were viewed as being more successful than others at defect characterisation. For example, a surveyor might select time-lapse thermography over walk-through thermography to better understand moisture ingress.

When defects are not known or expected in advance of a survey, then it becomes important to understand the scale of the survey. Most private domestic clients will likely request a single dwelling survey, which is typically dealt with under a traditional walk-through methodology. If a building manager owns more than six neighbouring dwellings, such as a housing association, then walk-through thermography of each dwelling becomes impractical due to the time scales and costs involved. Therefore a walk-past survey might be seen as being more appropriate in this situation. However, from tracing the dotted lines back to the detectable defects, the diagram illustrates the limited success that walk-past thermography has.

Whichever methodology has been chosen, a series of questions should be asked of the findings/results afterwards. If defects were not anticipated prior to inspection, the first question should be whether defects were subsequently detected or not. If they were detected, the next question needs to ask whether the methodology used adequately characterised the defect. This was found to be important because as discovered during the research of this thesis, some methodologies such as walk-through thermography were successful at 'detecting' potential defects, yet they were not always successful at 'characterising' defects. In order to make informed decisions for future action on defects, this work has shown the significance of defect characterisation in addition to the initial detection.

Should the response to the detection of defects be negative, then either alternative methods of inspection should be considered or a report should be prepared.
If the response to defect characterisation is negative, then two further courses of action should be taken.

The first would be to utilise another passive thermography methodology that was slower and more detailed than the methodology used to begin with. This correlates with the recommendations for combining methodologies for improved defect detection and characterisation. For example, a walk-through methodology might detect a defect, though following up with a time-lapse methodology might better characterise the defect. Having exhausted all passive thermography methodologies, the second course of action would be to make use of alternative surveying methodologies. These might include active thermography, air-tightness testing, heat flux measurement, moisture meter analysis or even destructive testing etc.

Should a particular defect or building issue be successfully characterised, then the next question would be whether to undertake quantitative analysis or not. It this is the case, then quantitative methods of NDT should be used (Heat flux measurements, coheating test, etc.), which might be supported by transient thermographic analysis. The findings from both quantitative and qualitative results should be presented, outlining the findings with recommendations for further action if necessary

Whilst being classed as a specific methodology in its own right, repeat thermography could share any of the other passive thermography methodology procedures. For example, walk-past thermography could be undertaken at set periodic intervals (months, years etc.) so that new images could be compared with those taken at an earlier date. As discussed in chapter 3, repeat thermography offers the opportunity to monitor building components over more lengthy periods than time-lapse thermography, thereby enabling the evolution of defects to be detected over long periods of time (Lucier & Phillips, 2003), which can be appropriately dealt with.

8.3 Commercial and policy implications

Although reflecting upon the ways in which different thermography and other NDT methodologies can be best utilised for building inspection, defect detection and characterisation is fundamental to their application in real situations. Of equal importance to the application of new passive building thermography methodologies are the key commercial and policy implications, which need to be carefully considered. These include:

- How much it costs to commission/perform the survey.
- How future proof the technology and methodologies are for longevity.
- How different methodologies can shape national building regulations.

Cost of thermography methodology

It can be easy to disconnect the cost factor from the application of a particular methodology when conducting experiments and case studies through academic endeavours. Yet, if a new thermography methodology is to be utilised in the commercial world, then cost needs to be understood as this will likely be one of the main drivers.

In practice, survey cost is often a closely guarded aspect of commercial business. It is therefore not easy to benchmark the work in this thesis with cost estimates provided by those delivering similar methodologies on a commercial basis. Nevertheless, it is clear that certain factors will dictate the structure of survey costs. These will include equipment costs (thermal camera, camera maintenance, computers, printers etc.), general business costs (insurances, rent, rates, etc.) and staff costs (thermographers, transport, admin staff, etc.). While each of these will be factored into business overheads, the latter will also be time dependant. The scale of the survey (building size and type of survey) will dictate the staff resources required to fulfil the clients brief, and will impact upon survey cost. Once the overheads are considered, the next aspect that will dictate the survey cost is profit, and will be based upon business financial objectives, whist remaining commercially competitive.

As illustrated earlier, one company (Red Current, 2013) offers a walk-through survey of a single dwelling for £400. While this might not be reflective of other companies or building types and sizes, it does provide a benchmark, from which estimations can be made for the other two inspected methodologies. This is not an easy task given the large number of variables involved such as dwelling type, location, client brief, access issues and report format etc. One method of estimating methodology cost is to compare costs for each survey over one 24-hour period. This period is chosen, as a potential time-lapse period, which could be scaled up in terms of number of days that a survey is conducted for.
Six dwellings can be conducted in one 24-hour period using walk-through thermography. This equals a cost of £2400 (£400 x 6). One dwelling is surveyed during a 24-hour period using time-lapse thermography. Consequently the cost for

surveying one dwelling is £2400. 50 dwellings are surveyed during a 24-hour period using walk-past thermography. £2400 divided between 50 dwellings equals £48 per dwelling survey.

Although this method of estimating cost might not be completely accurate or commercially representative, it does start to illustrate the monetary implications of each methodology, a factor that a client will consider before commissioning a survey. They might question why they would pay £2400 for one survey, when another costs £48.

Although relating to the construction process specifically, Cunningham (2013) discusses cost in relation to client considerations, aspects, which easily translate to thermographic inspections. For instance, clients often strive for the cheapest solution, yet in doing so risk affecting the quality of service and might not achieve the best value for money. The Latham report (Latham, 1994) particularly focused on value for money within the construction industry as a whole. In this report clients and construction professionals were urged to consider the impact of cost based decisions on future performance, where for example, higher cost services might offer alternative solutions to a particular scenario, that could lead to reduced costs in the future.

This issue of value for money is critical for the commercial application of new methodologies. For instance walk-past thermography may be very cheap compared with a walk-through or time-lapse survey. However the work in this thesis has shown that results (at defect detection and characterisation) are significantly inferior to these two methodologies, and if defect detection is the primary aim, then a client will unlikely achieve value for money. It is therefore vital that the thermographer makes clear the distinction between cost and quality. This is illustrated in figure 119 below for each of the methodologies investigated through this thesis.

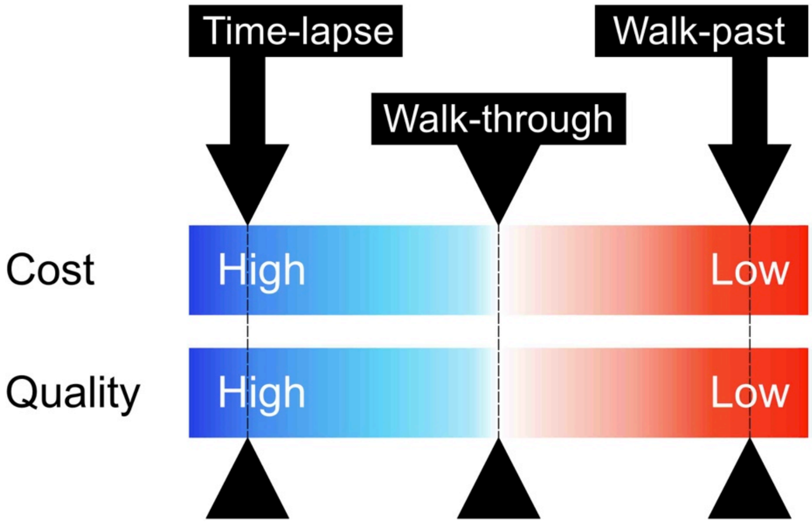


Figure 119. Relationship of cost and quality to thermography methodologies.

Future proof

Cost also connects with the future relevance of thermography as a technology and its methodologies. This is significant because cost is one of the driving factors behind the current direction that thermography is heading.

As discussed in chapter 3, one factor is the increased application of pass-by thermography (driving or walking). Like mentioned above, this is a relatively cheap methodology for clients and it is an area of thermographic inspection that appears to be growing (as reflected in table 1). If this trend continues, then based on the work in this thesis, it is likely that defect detection and characterisation will become more difficult to accomplish using thermography.

Another factor in the future development of thermography is the miniaturisation and cost reduction of equipment. In recent years, one of the leading manufacturers of thermal cameras have launched very low resolution (160 x 120 pixel sensor) relatively cheap (approximately £200) thermal camera, which fits to a smartphone (FLIR, 2014b). This product has been followed by similar relatively cheap thermal camera devices, which are helping to make this technology much more accessible to a wider audience. Whilst low cost cameras mean that people become more aware of thermography and heat loss in general, it also means that anyone with such a camera can provide and crucially interpret thermal images of heat loss from buildings. Great caution is therefore needed for two reasons. Firstly, the low resolution on these cameras makes image interpretation very difficult. Secondly, the users are unlikely to be trained to use and interpret the images being displayed. It is therefore even more important that potential clients appoint trained thermographers to inspect their buildings, as cheaper alternatives (unskilled personal using low quality cameras) could greatly add to the known limitations and significantly reduce the ability to detect or characterise defects.

As the technology and methodologies of thermography become faster, cheaper and easier to use, it can be suggested (based on the work in this thesis) that the quality of inspection will suffer. Clients may therefore start to doubt the usefulness of thermography as a technique for defect detection. Consequently it is important that thermographers strive to offer thermographer methodology options, which provide the best method of detection and characterisation for clients. Only through improved accuracy in analysis can thermography improve as a methodology for building inspections.

Shaping national policy

In order for new (residential and non-residential) buildings to meet Part L of the building regulations (DCLG, 2014b), blower door air-tightness tests are required for validation of air permeability (ATTMA, 2010). Whilst this deals with unwanted air-leakage, there is currently no required or approved method of assessing the continuity of insulation in buildings under Part L. This therefore highlights a key performance gap between designed and as-built performance, and is supported by Pearson (2015), who highlights this gap. Yet the work in this thesis has shown that thermography can be a realistic method of checking insulation continuity and workmanship on buildings. Taylor (2014) looked into the application of thermographic testing within the building regulations and through interviews with building control inspectors, identified cost as a key barrier to inclusion alongside air-tightness testing.

The cost for a typical air-tightness test is approximately £165 (ATT, 2015), which is comparatively cheaper than a walk-through thermographic inspection (£400). However the price difference between these methodologies would not be considered significant if undertaken in the context of a large building, and could therefore be included within Part L for non-domestic buildings. For domestic buildings, the cost difference becomes more apparent, and thermography costs would need to reduce.

The work in this thesis has shown how thermal performance changes in response to transient conditions in climate and materials. Yet the building regulations rely upon steady state conditions for measurement (Target Emission Rate and Dwelling Emission Rate for example). For improved accuracy and to help reduce the performance gap, it is therefore fundamental that methods of transient analysis are used. This would help to confirm compliance with the building regulations. One method of undertaking this could be to conduct lengthy heat flux measurements of building components in combination with walk-through thermography, which could be used to locate the most appropriate testing location.

Another method might make use of repeat thermography, where before and after refurbishment works can be more accurately assessed. If repeat inspections become a prerequisite for all major refurbishment projects (where the thermal fabric is being altered), thermographic examination prior to refurbishment would help to pinpoint key problems, enabling a more targeted refurbishment program. During post-refurbishment inspections, thermography would aid in showing what has been done and how successful the refurbishment has been. By using pre and post refurbishment inspections, a better understanding of the performance gap between refurbishment intentions and actual interventions can be observed and reduced.

The work in this thesis should also be used as the basis for updating the existing British Standard on qualitative passive building thermography, BS EN 13187:1999 (1999), which is 16 years old. This research project has shown how recent advances in camera and interrelated technologies have increased commercial interest and the number applications for building thermography. Yet, this project has also shown that with technological and application advancements, there are also new limitations, which need to be properly addressed. It is therefore time to update the British Standard, making it more applicable to modern day thermographic inspection on buildings.

8.4 Summary

In this chapter, a strategy of combining thermography methodologies with each other and alternative NDT techniques has been proposed. The aim is to make use of the benefits/strengths from more than one methodology, whilst also mitigating the limitations of others. A clear strategy for methodology coordination starts with quick techniques before moving onto slower and more detailed methods.

In addition to proposing a method for combining more than one thermography/NDT methodology, this chapter has also established a decision-making process for selecting the most appropriate thermography methodology for the particular task. The design of a decision-making diagram was based upon the culmination of findings from the primary research chapters of this thesis. A methodology decision-making diagram (Figure 118) was used to illustrate the stages that a thermographer or building manager might follow when selecting a methodology and indicated those methodologies that were better or worse (than others) at detecting and characterising particular defects.

Finally, this chapter has considered ways in which different thermography methodologies might be utilised within commercial application and governmental policy. This is particularly important to the realistic use of the work in this thesis.

9.0 Discussion

This chapter brings together the key findings from each of the investigated thermography methodologies. Assessing them as a whole this chapter will compare each methodology to better understand how each responds to particular defects or scenarios.

9.1 Comparative summary

Three very different thermography methodologies have been explored through this research project. Before comparing these methodologies, it is important to review the key outcomes, highlights, benefits and limitations to each. For this review, a comparative summary of the three investigated methodologies is presented in table 9.

To summarise table 9 in terms of building defect detection, walk-through thermography has been found to be much better than time-lapse and walk-past thermography for detecting multiple defects within one building (Objective 3). If this is the requirement set by a client then only walk-through thermography should be used. Walk-through thermography however occasionally struggles to characterise building defects. Ventilation heat losses were the only defect group that were indisputable based on single image analysis. While conduction heat losses were usually indisputable, it was sometimes not possible to ascertain whether these defects were resulting from other factors such as the presence of moisture. Moisture defects were very difficult to discern using single image analysis.

Methodology	**Walk-through**	**Time-lapse**	**Walk-past**
Number of dwellings surveyed per session	• 6	• 1	• 51
Time-scale for one dwelling survey	• 40-60 minutes	• >1 hour (days & weeks)	• 7-10 minutes
Approximate cost per single survey	• £400	• £3200	• £40
Methods of reporting	• Written reports • Large format panoramic images	• Time-lapse films • Surface temperature measurement	• Single images
Methods of analysis	• Internal and external • All building surfaces • Qualitative analysis	• Internal and external • One building surface • Qualitative analysis • Quantitative analysis	• External only • One building surface • Qualitative analysis
Distance to target	• 1-10 meters	• 1-20 meters	• 10-20 meters
Equipment Required	• Thermal camera • Weather station	• Thermal camera • Weather station • Tripod • Thermal couples • Data logger • Reflector (for t.reflect) • Power supply • Shelter • Security	• Thermal camera • Weather station
Defects that have the potential to be **characterised**	• Ventilation heat loss • Conductivity/thermal bridging heat loss	• Ventilation heat loss • Conductivity/thermal bridging heat loss • Moisture ingress • Condensation	• Ventilation heat loss
Defects that have the potential to be **detected**	• Ventilation heat loss • Conductivity/thermal bridging heat loss • Moisture ingress • Condensation • Defective services	• Ventilation heat loss • Conductivity/thermal bridging heat loss • Moisture ingress • Condensation • Defective services	• Ventilation heat loss • Conductivity/thermal bridging heat loss
Key benefits	• Dynamic inspection methods • All surfaces inspected • Quick/real time • Many defects detected	• Observe transient changes in materials • More accurate defect characterisation • Discern defect evolution	• Fast survey & analysis • No occupant interaction • Many dwellings surveyed per session • Dwelling comparison
Key limitations	• Single image • Difficult to characterise all defects • Ignores transient changes	• Single and fixed FOV • Defects need to be known in advance • Lengthy set-up/analysis • Safety & security issues	• Single image & elevation • Spatial resolution • External only • Few defects detected • Unknown occupancy

Table 9. Comparative summary of the three investigated thermography methodologies.

This is primarily due to the single-point-in-time image capturing technique used, which misses the transient nature of changing thermal patterns from constructions and defects. Specifically observing these transient changes through time-lapse thermography (Objective 4) (image/thermal pattern evolution) has been proven to enable improved defect characterisation compared with walk-past and walk-through methodologies.

Both time-lapse and walk-through thermography are however relatively slow methodologies and there is a small limit to the number of dwellings that can be inspected during one survey. As a result, walk-past thermography is being increasingly utilised by thermographers to inspect multiple dwellings. Research through this thesis (Objective 5) however has shown that this methodology is much less successful at both detecting and characterising building defects than time-lapse or walk-through thermography. If defect detection or characterisation is the primary motivation for (a client) requesting a thermographic survey in the first place, then walk-past thermography should not be selected. If cost factors constrain the ability to use walk-through or time-lapse thermography on multiple dwellings, then walk-past thermography might warrant inclusion (based on the benefit of dwelling comparison methods of analysis) as part of a phased approach with other thermography or NDT methods.

9.2 Comparative drivers

Each methodology has proven strengths and weaknesses, and each highlight a different set of drivers, which are guiding the use and development of passive building thermography. On review of the research in this thesis, three overarching themes have been consistently discussed within each secondary and primary research chapter. *Time, quantity and quality*.

- **Time** relates to the speed of the methodology, and how this serves to act as a benefit or limitation to defect detection/understanding.
- **Quantity** concerns the success of defect detection with regards to the number and type of defects detected during a single dwelling or survey. Quantity is also related in part with the theme of time as it also concerns the number of dwellings/surfaces inspected during a survey session.
- **Quality** has been discussed throughout this thesis as a potential barrier to defect characterisation. This theme deals with how well a methodology overcomes quality issues, such as spatial and temporal (connected with time) resolution for improved defect understanding.

Because of the interrelationship between these three themes and the thermography methodologies, an iron triangle diagram has been developed (Figure 120). This iron triangle diagram illustrates the key issues (time, quantity and quality) underpinning the three investigated thermography methodologies as circles. Where they overlap a new segment is created, which connects two of the issues. Each of these segments directly relate to one of the three investigated methodologies, where the two issues in the segment equal key features that motivate the methodology. The key issue not included within the segment equals a critical area of limitation that needs to be addressed by alternative methodologies.

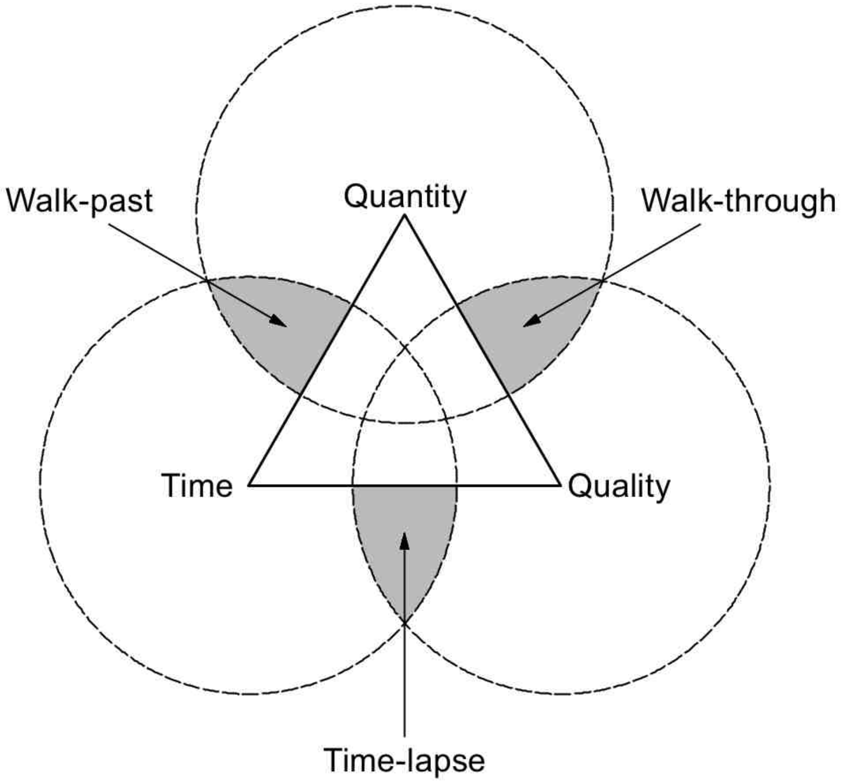


Figure 120. Relationship between methodologies and overarching themes.

Assessing the benefits to walk-through thermography clearly illustrated how quantity and quality were the key issues motivating this methodology. Quantity was important due to the broad range and high number of potential defects detected in a single dwelling. With regards to quality, walk-through thermography specifically addresses spatial resolution limitations through dynamic real time analysis. Thermographers can move around, closer or further away, inside or outside etc., which was found to help with defect detection and for certain defects, characterisation. It is therefore not surprising that this methodology remains the most common amongst thermographers and building managers. Despite the motivation of quality for walk-through thermography, qualitative image interpretation remains one of the greatest challenges to this methodology.

Image interpretation has been found to be largely dependent on transient factors, such as changing climatic conditions and material properties. Such transient conditions cannot be adequately understood based on single point in time image analysis, which severely limits the ability to interpret thermal images and successfully distinguish thermally significant building defects. Therefore, whilst relatively fast (compared with time-lapse) at inspecting dwellings during a survey or finding areas of thermal interest, the unfamiliarity with transient conditions meant that speed (time) was viewed as a key limitation to walk-through thermography.

Time-lapse thermography directly addresses the identified limitations to walk-through thermography. To do this it relies upon two key motivations, time and quality. Work in chapter 6 has shown that through observing a particular construction or defect over a prolonged period of time, transient climatic and material changes, (which are seen as a limitation to walk-through thermography) can be better understood. This leads to a clearer understanding of construction behaviour, so that discrepancies can be more accurately pinpointed and characterised, resulting in improved quality of defect detection and characterisation. Despite the benefits to quality from more lengthy investigation periods, time was also found to be a potential limitation when connected with cost, due to equipment set-up, survey and analysis periods, all of which might limit commercial application.

The main drawback to time-lapse thermography has been found to be the quantity of buildings, building regions (surfaces and elevations) and defects that can be observed/detected during one survey period. Having a single viewpoint for the duration of the survey meant that only defects within the FOV could be inspected. All other defects in that building would not be considered during the single survey period. Because of this, it is recommended that the presence of defects are known before committing to a lengthy survey to better characterise the defect.

Whilst time-lapse thermography uses time as a key motivator for the improved quality of building defect inspection by slowing the survey period down, walk-past thermography directly contrasts by using time as a motivator for increased quantity of building inspections per survey period. Although walk-through thermography might initially be deemed a relatively fast methodology, external inspections were found to take 25% less time to complete on average compared with internal surveys. This clearly supports the increased speed that walk-past thermography can hold over walk-through thermography, especially as only one elevation is being inspected. The speed and quantity of dwellings inspected are the key motivators to walk-past thermography and is also closely connected with cost, as lengthier surveys will prove to be more expensive than those that are quicker.

However it was identified from walk-past thermography that an increase in speed (time) and quantity leads to a significant reduction in quality of defect detection and characterisation. This was due to reduced spatial resolution, single viewpoint and lack of transient awareness.

Reflecting on the three passive building thermography methodologies investigated during this thesis, there does not appear to be a ‘one-size-fits-all’ option. Although walk-through thermography has been identified as the most commonly applied methodology and has been proven to be the most successful at locating ‘potential’ areas of thermal significance, the other two methodologies have illustrated enhancements on the traditional method. Although added enhancements (speed and quality) offer alternative solutions for tackling the fundamental problem (defect detection and characterisation), they also bring with them a host of new limitations and accentuate existing/known limitations.

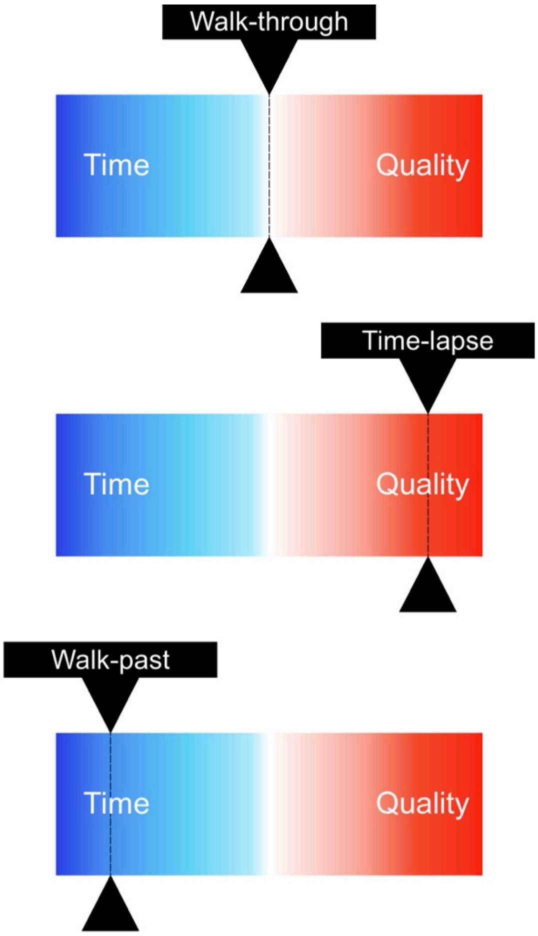


Figure 121. Sliding scale diagram illustrating methodology ability based on time and quality.

If the theme of quantity was left out of the methodology analysis, so that the number of dwellings or defects that are detected was not an issue, then on a sliding scale (Figure 121) it is possible to illustrate the strengths and weaknesses of each methodology in terms of time and quality. From reviewing Figure 121, it is clear that whilst walk-through thermography offers the best balance between time and quality, walk-past and time-lapse thermography offer extremes of either of these aspects. Time-lapse thermography offers greater quality in defect detection/characterisation than walk-through and walk-past, and walk-past thermography offers faster analysis than the other two methodologies. This serves to show how the newer methodologies of time-lapse and walk-past thermography offer niche benefits, which explains why they are currently not as commonly applied in practice.

9.3 Comparison with literature

Having completed first-hand experiential research on three very different thermography methodologies, this chapter has drawn together the benefits and limitations, so that comparisons could be made between each methodology. Comparisons have served to highlight some of the key strengths and weaknesses, focusing in particular on the type of defects detectable, quality/success of defect detection, challenges to conducting the methodology, and ability to inspect multiple elevations, zones (inside and outside) and buildings.

Following comparative analysis between the investigated thermography methodologies researched in chapters 5, 6 and 7 it is also important to link this with literature.

The literature review matrix proved a good basis for investigating the commercial application of different thermography methodologies. By separating the literature into academic, grey and professional use, a clearer understanding of how well used each methodology was. While research undertaken using traditional walk-through thermography (chapter 5) confirmed expectations that this is the most commonly used methodology, time-lapse thermography had not been reported as being used on a commercial basis. This is not surprising given the lengthy set-up time, experimental period and analysis stages that were experienced during chapter 6. The time-scales involved would most likely make time-lapse a more expensive methodology compared with walk-through thermography and is a recognised barrier to the commercial uptake of time-lapse thermography.

At the other end of the spectrum is walk-past thermography. As a relatively recent methodology, pass-by (walk-past) thermography was first discussed in 2009. The commercial application of this methodology has increased over the past six years, and is appears in line with advances in technology (such as digitisation and automation advances). From undertaking three different methodologies, it is not surprising to see how walk-past thermography is becoming increasingly used on a commercial level, since this methodology offers the advantage of increased survey speed. This can help to minimise survey costs, and increase productivity. However commercial organisations should be wary of the limited success found in defect detection and characterisation found from the work in chapter 7. An obvious question that should be asked by professionals is whether the increase in speed, reduction in survey cost can be balanced by the inferior service (compared with other methodologies). Two crucial features of any thermography survey include providing ‘value for money’ and being able to ‘detect building defects’. Both of which could be argued as being absent in fast methodologies such as pass-by thermography.

10.0 Conclusion

Having undertaken primary and secondary research, which addresses the project aim and objectives set out in chapter 1, this thesis has explored the practical benefits and limitations to new and existing passive building thermography methodologies (Objectives 1 & 2). Out of these, three very different methodologies were selected for practical investigation (Objectives 3, 4 & 5). With a deeper understanding of their ability for defect detection and characterisation, proposals have been made (chapter 8), which will help other thermographers and building managers to make improved decisions for the selection of the most appropriate methodology for specific defects or scenarios (Objective 6).

10.1 Summary of the studied passive building thermography methodologies

Before concluding with the key findings and knowledge contributions of this thesis, this section provides a brief summary of the three passive building thermography methodologies that were investigated during this thesis.

Walk-through thermography

Although qualitative thermal patterns suggested that this methodology could detect a broad range of thermally significant defects, ventilation heat loss was the only defect that could be routinely characterised. Whilst other defect types were occasionally characterised, there were occasions when assessment proved inconclusive.

Time-lapse thermography

Results from time-lapse thermography showed that a better understanding of potential defects could be made by observing the thermal pattern evolution from sequential time based images when compared with those captured on a single point in time basis. The lengthy time-scales involved with this methodology were viewed as a key barrier to the commercial application of this methodology.

Walk-past thermography

Whilst offering a very fast method of inspecting dwellings, research into walk-past thermography found that with increased speed came a reduction in defect detectability, both in terms of number of defects detected and the quality of detection.

From each of the three explored thermography methodologies, quantity (number of defects and or properties), time (speed) and quality (spatial resolution) were identified as being the three key themes, which connect or dictate the selection of each methodology. It was found that whilst walk-through thermography adequately balanced time and quality themes, the other two methodologies offered two extremes, which brought added benefits over walk-through thermography.

Identifying the key characteristics, benefits and limitations of each investigated passive building thermography methodology helped understand the most appropriate situations under which they might be used.

10.2 Key findings

Throughout this thesis, a number of key findings were discovered. These findings were decisive in highlighting the main issues and drivers currently influencing building thermography and ultimately helped to shape the overall direction of this project. Key findings included:

- The work in this thesis has clearly established a difference between defect ‘detection’ and defect ‘characterisation’. Although some of the passive building thermography methodologies could detect potential anomalies, which might be classified as building defects, it was not always easy to characterise the defect type. By misunderstanding the precise nature of a defect, it is questionable whether appropriate remediation measures can be proposed/taken based on the results/findings.

- From the literature review, image interpretation was found to be the most significant factor in successful defect detection using thermography in buildings. Contributing factors to the challenging nature of image interpretation were found to include the effects of transient climatic conditions, thermal resolution (including camera specification), emissivity and human camera control. Should any of these factors negatively impact on image interpretation, it is likely that potential defects might be missed or misinterpreted.

- Whilst traditional walk-through passive building thermography remains the most commonly used methodology, a number of alternative methodologies are becoming increasingly utilised. The key driver to methodology development (identified in chapter 3) appears to be speed, with quick methodologies such as pass-by thermography becoming more commonly used compared with those that are slower, such as time-lapse thermography. (See figure 29).

- Single moment in time images cannot be relied upon to provide qualitative image patterns that lead to the conclusive characterisation of defects. This was found to be due to the fact that methodologies using single moment in time images overlooked/did not take into consideration transient climatic conditions and the effects that these had on material properties.

- Because of the known limitations resulting from transient changes in environmental conditions and challenges with spatial resolution, passive building thermography should therefore not be relied upon for accurate quantitative analysis. Whilst this conclusion was derived from work using a time-lapse methodology, those considering quantitative analysis using single moment in time thermography should particularly heed this statement.

- The trade-off between capturing entire scenes/elevations and optimising the spatial resolution of the camera sensor for the efficient detection of received radiation was shown to be a critical consideration for image interpretation/defect detection. As the camera moves further away from the target object, the angle of camera IFOV covers a greater surface area, which means that the smallest discernable signal becomes greater. Therefore leading to some potential defects being missed. This was shown to be a particular problem with those methodologies that needed to capture entire elevations in one FOV, such as some time-lapse and (to a greater extent) walk-past thermography.

10.3 Contribution to knowledge

Based on the key findings from the research project, this thesis was able to bring a number of new contributions to knowledge in this field. These comprise of:

1. Substantiating anecdotal reports in literature, which state that internal thermographic inspections are more successful at defect detection than external inspections.
2. Providing a new methodology for presenting multi-image panoramic thermal images.
3. Providing a new methodology for qualitative time-lapse thermography.
4. Being the first to compare quantitative time-lapse thermography measurements of in situ U-values with heat flux measurements of the same construction.
5. Providing a new methodology for qualitative walk-past thermography.
6. Providing a rational for combining thermography methodologies.
7. Providing a methodology decision-making framework.

Internal thermography is more successful than external thermography

Internal thermography has been proven to be much more successful at defect detection (greater number of potential defects detected) than external thermography (see chapter 5). Before this thesis, this issue saw conflicting anecdotal opinions, both agreeing and disputing the improvement that internal inspections have over external inspections.

Yet observations during the walk-through thermography case studies, found that more defects were detected during the internal inspection than the external inspection (See figure 44).

Additionally, this finding was reinforced by the low detection of potential defects found during the walk-past surveys in chapter 7. This contribution is significant for the future of building thermography, since it underlines the potential inaccuracy and limited benefit to external only surveys such as the walk-past/pass-by survey methodology.

Panoramic images for improved spatial resolution and whole scene views

This thesis provides a new methodology for capturing panoramic images as part of an approach to improve spatial resolution, which will enable improved defect detection and characterisation opportunities. It was observed how single viewpoint images were constrained by both the camera lens FOV and the trade of between distance (to capture larger areas) and spatial resolution (the area size covered by one pixel). To help overcome these constraints, a strategy of forming panoramic images was proposed. Multiple images are recorded and pieced together into panoramic images of entire scenes. This also has the added benefit of placing potential defects in context with other defects or features, which could make post analysis more effective.

Qualitative time-lapse thermography methodology

This thesis provides a qualitative time-lapse thermography methodology for defect detection. This new methodology has been proven to take into consideration the effects of transient changes in climatic and material properties (Chapter 6), something not achieved by others utilising qualitative passive building thermography to date. By observing defect evolution (through image sequences) over a prolonged period of time, transients can be factored into the analysis process so that a better understanding of the potential defect and or characterisation can be made.

This research has shown that time-lapse thermography should be strongly considered as a methodology for inspecting defects (such as moisture ingress) that are particularly hard to characterise using single point in time analysis methods such as walk-through thermography.

Comparison between quantitative time-lapse thermography and heat flux methodologies for in situ U-value measurement

Although others have used time-lapse thermography for the quantitative analysis of U-values, none had compared their data with that from the more commonly used heat flux measurement methodology. This unique comparison of methodologies for in situ U-value measurement was explored through chapter 6, part 3.

When compared against design-based U-value estimates, final U-value measurements from time-lapse thermography varied from between 10% - 72%. This was contrasted with in-situ heat flux measurements, which varied by less than 6% compared with design-based estimates. Greater fluctuations in moving average results and increased uncertainty from the thermography U-value results compared with heat flux results showed that the heat flux methodology was much more effective at measuring in-situ U-values. Thermography based U-value analysis should therefore only be used for estimation purposes in situations where heat flux measurement is not possible, and caution should be taken over the final results.

Qualitative walk-past thermography methodology

This thesis has provided the first practical methodology for walk-past thermography. This was deemed important to investigate due to the rise in demand for fast pass-by inspections (qualitative and quantitative).

The research in chapter 7 found that walk-past thermography was very poor at detecting potential building defects. For example, out of 77 dwellings, only 38 reported signs of potential building defects (29%). In comparison with the 45 walk-through case studied in chapter 4, 100% of properties showed signs of potential building defects.

Whilst walk-past thermography can detect conduction and ventilation heat losses, all other defect groups were missed. Furthermore, this methodology cannot be relied upon to comprehensively characterise potential building defects.

The only positive application for walk-past (pass-by) thermography was found to be using qualitative target comparison analysis of similar dwellings, whereby matching thermal patterns between dwellings might suggest common problems.

This was a benefit not previously discovered by others in the field of pass-by thermography and could help to support existing work in this field.

Combining thermography methodologies

By reviewing all of the investigated passive building thermography methodologies from both primary and secondary research, this thesis has contributed an approach for combining thermography methodologies as part of a phased approach to building/defect inspections. Whilst the benefits from each methodology are maximised it is important that the limitations are mitigated by other methodologies.

Although specifically focusing on passive building thermography, the approach for combining methodologies also makes recommendations for coordination with other NDT methods of defect inspection/building analysis.

Methodology decision-making framework

A key output contributed from this thesis is the creation of a thermography methodology decision-making framework. Presented in the form of a decision tree diagram (Figure 118), this framework has been prepared to help other thermographers, building surveyors and building managers to make improved decisions when selecting the most appropriate thermography methodology for a particular defect or scenario.

The decision making process advocates that quick thermography methodologies are used first, before making use of increasingly slower and more detailed methodologies as and where needed.

In addition to the selection of passive building thermography methodologies, the decision-making framework also makes provision for other NDT methods to be used in combination to detect particular defects.

10.4 Implications for industry

Since the development of passive building thermography has been driven by commercial/industry application, it is important to reflect on the implications of this research for industry.

In industry, it is easy for practitioners to become familiar with typical methods of working. This has been found to be the case within the field of building thermography, with the predominant use of walk-through thermography as the common approach to building inspections. This work however has clearly shown that there are alternative methods of using the same technology for building inspections, and that by making use of new methodologies, added benefits can be provided to clients and building managers.

In a profession, where modern technology is becoming cheaper, more accessible and demanded, it is crucial that trained thermographers are able to offer added value to clients, who might begin to demand greater accuracy in their survey.

This research has clearly highlighted the limited success that walk-past thermography can have for defect detection, and it is imperative that qualified thermographers do not become fixated with such speedy and cheap surveys to the detriment of the primary objective for thermographic inspection: defect detection and characterisation. This work consequently offers a balanced review of very different passive building thermography approaches, which others can use to make informed decisions on the selection of the most appropriate thermography methodologies for a particular defect or scenario.

10.5 Reflections on research

Reflecting on the overarching research methodology for this thesis helps to consider the success or limitations, which might influence future work.

As reported in chapter 4, both experiments and case studies were conducted as part of this overall project. For the work in this thesis, both of these research activities were beneficial to addressing the project aim and objectives. Of particular success was the use of experimentation to test an idea or methodology prior to applying it on real building case studies. This was specifically useful during the development of a time-lapse thermography methodology. Conducting multiple experiments on a laboratory based scenario enabled the methodology to be improved more quickly than if it was practiced immediately on real buildings. Once a robust methodology had been created, the time-scales between conducting case study research with the methodology and obtaining meaningful results was much shorter than if the experimentation phase had been omitted.

Experimentation was only practical for time-lapse thermography, given the static (camera position) nature of this methodology. For walk-through and walk-past, the time-scales involved with one case study meant that the methodology for these approaches could be tried and tested very quickly. With alterations made almost instantaneously or on subsequent case studies. This speed of methodology development was not available to time-lapse thermography. Should other methodologies be investigated, consideration should be made on how each methodology might be developed, used and improved.

Reviewing past literature on different passive building thermography methodologies and the limitations to thermography greatly assisted with the development of new and improved thermography methodologies. This was particularly evident when preparing the overarching research methodology diagram (Figure 31).

It is also important to consider how the research methodology might have been undertaken differently. For time-lapse thermography, longer time scales would have benefited the work by offering a further insight into week or month-long transient pattern changes. It would have also been interesting to conduct multiple (once per month) time-lapse inspections (on the same building/target area) over the duration of one year. This would have enabled a better understanding of the changing transients and how they differ from one season/month to the next. However limitations in the form of tight time-scales and planning sustained periods of adequate weather conditions made these improvements impossible to achieve during the period of this project. Remaining with time-lapse thermography, it would have been interesting to use a second (identical) thermal camera on the opposite side of the wall to the first camera. The results could then be compared to check for correlations.

In part 3 of chapter 6, in situ U-value measurements were made using thermography and heat flux equipment. The results indicated that only night-time measurements should be used to estimate in-situ U-values. This was because night-time periods (20:00 – 07:00) provided more steady/less fluctuating results (about 0.5W/m^{2}K) compared with the more highly fluctuating day-time results (6.3W/m^{2}K) (likely to be due to solar gain, occupancy behaviour etc.). Therefore, it would be interesting to re-assess the final U-values from these case studies based only on the night-time values.

In chapter 8, a strategy for combining thermography methodologies was proposed. It would have been useful to conduct time-lapse, walk-through and walk-past thermography on the same property or properties to demonstrate the benefit from combining thermography methodologies.

Furthermore, there was some disparity between the numbers of dwellings inspected per thermography methodology. While time constraints and weather conditions had dictated the case study numbers for this project. Future work might attempt to conduct an equal number of case studies for all methodologies.

10.6 Future work

This next section lists some of the research avenues, which could not be investigated during the course of this project (Due to the three-year time-constraints associated with this thesis). It is hoped that they might form the basis for further work in the future.

Investigation of the other passive building thermography methodologies.

Having reviewed the existing literature that related to six different passive building thermography methodologies it quickly became clear that only three could be practically explored during this project (walk-through, time-lapse and walk-past). This meant that the other three methodologies (UAV, Aerial and repeat thermography) could not be inspected during this project. UAV and Aerial thermography both required access to expensive flying equipment and repeat thermography required access to a known refurbishment project.

While assumptions on possible performance and defect detection success can be made based on past literature, further research is needed to explore UAV, aerial and repeat thermography. Once this research has been undertaken, it will also be important to update the decision-making process diagram.

Applying different thermography methodologies on alternative building types

In this research project, small-scale residential dwellings formed the focus of thermography inspections. Other types, such as large-scale residential (flats), commercial and industrial buildings were ignored. Further research exploring different thermography methodologies should pay particular attention to how they might benefit other building types. For example, it is anticipated that UAV thermography might be more beneficial for inspecting large buildings by following automated flight-paths.

Other types of building should also include other types of construction. In this thesis, the focus has been on older buildings, which have often comprised of solid or cavity masonry constructions. Further research should expand to include other types of construction, such as timber-framed buildings. It would also be of interest to assess the success of thermography methodologies on new buildings. For example, repeat thermography could be used on a monthly or yearly basis to review the condition of materials (e.g. has cellulose insulation slumped over time?).

Investigating thermography methodologies in other countries/climates

In addition to inspecting other forms of construction and building, it would be of great interest to explore the performance of each passive building thermography methodology under different climatic conditions. For the work in this thesis, a cold climate was explored. Working under warm climatic conditions would not only reverse the expected thermal signature, but might also bring alternative defect, benefits and limitations.

One experiment might use a time-lapse thermography methodology to explore the effects of thermal mass on different construction samples to better understand the most suitable construction build-ups for cool internal environments.

Other defects, uncommon in cool climates might also warrant further investigation with new thermography methodologies. For example rodent or insect (termite etc.) infestation, and the associated damage might be better inspected using transient methods, such as time-lapse or repeat thermography.

It is known that moisture has a higher heat capacity than most building materials. Therefore, moisture surveys are often conducted during the day, after the sun as warmed the water. This aspect of defect detection by different thermography methodologies was not explored through this thesis, and should be investigated in future research.

Engaging with commercial thermographers to gauge knowledge, interest and opinion on existing and emerging thermography methodologies

The work in this thesis has investigated different thermography methodologies with a view to their application under commercial survey activities. Yet this thesis lacks a viewpoint from the commercial building thermographers. Future work should therefore seek to engage (questionnaires and interviews) practicing building thermographers. Key outcomes from this work should include:

- Identifying knowledge, experience and understanding of new thermography methodologies.
- Gauging interest in the possible application of alternative thermography methodologies (to traditional walk-through thermography).
- Obtaining opinions on the potential for new methodologies, methodology development and alternative applications.

This work should also seek to encourage commercial thermographers to utilise the proposed methodology decision-making process diagram, an activity, which would demonstrate robustness of this proposed protocol.

Combining different thermography methodologies with other forms of NDT

As discussed in chapter 8, combining thermography with other forms of NDT on building inspections might help to better characterise building defects or performance issues. Therefore future work should investigate the connections with other methods of inspection. For example, how walk-through or time-lapse thermography can aid in the detection and better understanding of ventilation heat losses during an air-tightness test. Or how time-lapse thermography could be used in coordination with a coheating test and possibly heat flux measurements to better understand as built thermal performance (U-values and thermal bridging, etc.).

10.7 Closing summary

In summary, this thesis contributes to the use of thermography in building surveying. In a context where transient conditions, emissivity variations and low spatial resolutions are limiting/adversely effecting the way that thermal images are interpreted, this thesis offers a way forward for passive building thermography inspection by presenting three very different thermography methodologies, a strategy for methodology coordination, and an approach for improved methodology selection.

Until now, advances in commercial thermography appeared to be focused on the use of existing traditional or faster pass-by methodologies. Both methods firmly reliant on single moment in time image analysis, the effects from transient climatic changes were not being fully understood or accounted for. This thesis addresses this key issue by enabling the observation of transient climatic changes using a time-lapse methodology. By offering a unique opportunity for improved defect characterisation using time-lapse thermography, thermographers, building surveyors, building managers and domestic clients now have the ability to more accurately understand building thermal performance issues, thereby helping to reduce the performance gap between anticipated performance and actual performance.

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Appendices

Appendix A. Supplementary experiments

This appendix lists a collection of supplementary experiments undertaken by the author of this thesis. These experiments have been undertaken to either reinforce a specific aspect of the thesis or to demonstrate/explore a known phenomena/limitation/practical aspect identified during the literature review. The supplementary experiments should be read in conjunction with the relevant sections of the thesis, as indicated alongside each experiment title.

Each supplementary experiment comprises of a description and results section.

The experiments in this appendix include:

> **SUP 1.** An experiment to illustrate the effect that spatial resolution has on image quality and infrared detection. [See Section 2.3]
>
> **SUP 2.** An experiment to illustrate the effect that camera focus has on image quality and infrared detection. [See Section 2.4]
>
> **SUP 3.** In-situ U-value measurement (using Time-lapse thermography) of a known moisture defective construction. [See Section 6.4.6]

SUP 1. An experiment to illustrate the effect that spatial resolution has on image quality and infrared detection. [See Section 2.3]

Experiment description

This experiment made use of three different thermal cameras:

- FLIR i7 (140x140 pixels, 3.7 mrad IFOV) (FLIR, 2013c)
- FLIR T335 (340x240 pixels, 1.36 mrad IFOV) (FLIR, 2009b)
- FLIR T620bx (640x480 pixels, 0.69 mrad IFOV) (FLIR, 2013a)

These thermal cameras were selected because of their different sensor sizes and spatial resolution (IFOV) values. To explore the difference between the three thermal cameras, a mug was filled with hot water. This mug was then thermally imaged using each of the three cameras in turn. The results were then placed together for analysis.

Results

Figure 122 below present the results from this experiment. Despite all three cameras presenting similar overall results, upon closer inspection, subtle differences could be observed. With an increase in pixel size/IFOV, the blurring at the top of the waterline (mid-point on the mug) became more distinguishable. Also edge details around the mug, such as the handle became clearer as the sensor became larger/IFOV smaller.

In summary, smaller IFOV 's and larger the sensor sizes appeared to equal greater clarity in thermal image, as might be expected from higher specification thermal cameras, such as the T620bx.

Lower specification thermal cameras clearly make image interpretation (such as potential defect detection) much more difficult due to undertake.

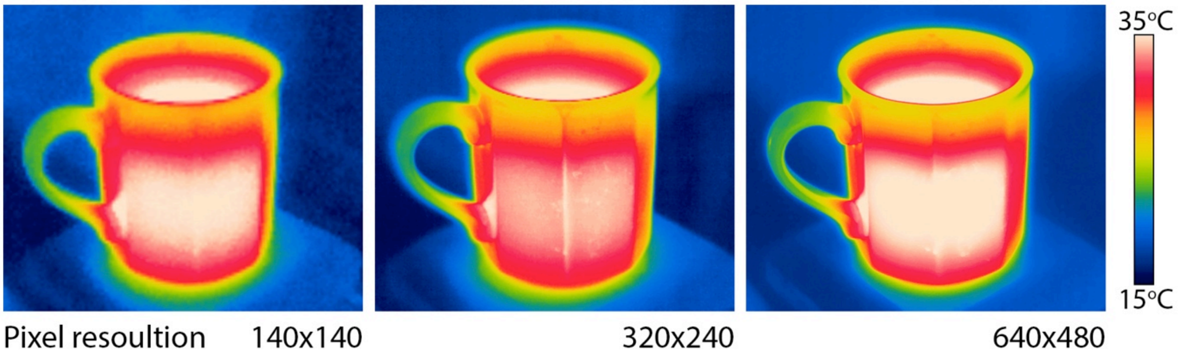


Figure 122. Illustration of different camera resolutions.

SUP 2. An experiment to illustrate the effect that camera focus has on image quality and infrared detection. [See Section 2.4]

Experiment description

All thermal cameras will have some degree of focusing mechanism, whether it is manual or automatic. Focus is one of the key elements (along with range and composition), which cannot be adjusted after the image has been taken (ITC, 2006). This experiment was devised to illustrate/explore how focus impacts upon thermal image results.

The experiment comprised of two pieces of card, placed over the top of a bucket of boiling hot water. A gap between the two pieces of card provided a slotted view of the water below. A T620bx thermal camera was positioned on a tripod to capture thermal images.

Results

Figure 123 below shows two thermal images taken from the experiment. The image on the left has been focused correctly, while the image on the right has been captured out of focus. A thermal transect was taken across the card and slotted view, which enabled quantitative analysis of the two images as shown in figure 124, where the blue line represents the focused thermal image and the red line represents the un-focused thermal image.

From both qualitative and quantitative analysis, it is clear that the out of focus thermal image shows less defined edges to the slot and a lower maximum water temperature compared with the correctly focused thermal image.

This experiment highlights the importance of accurate focus, since any degree of poor focus will result in inaccurate thermal images. This might mean the difference between accurately identifying a defect or misinterpreting is/missing it completely.

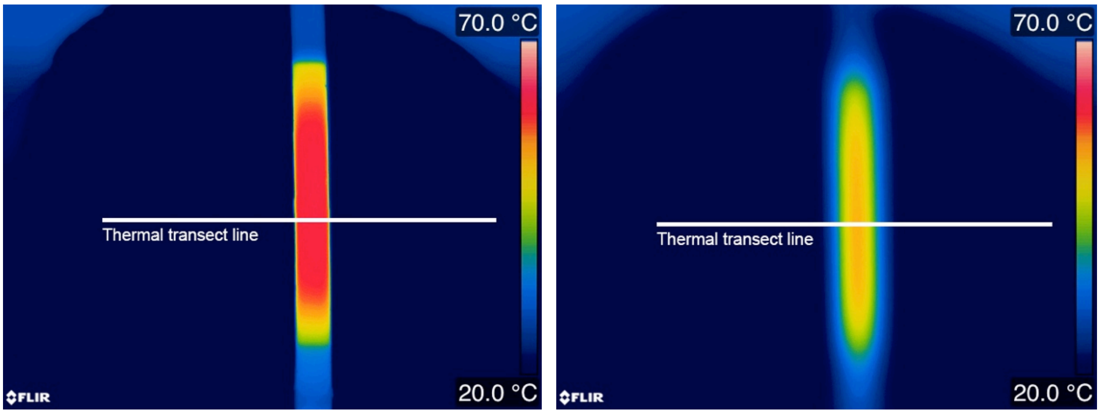


Figure 123. Two images that show the difference between a focused (left) and un-focused (right) thermal image.

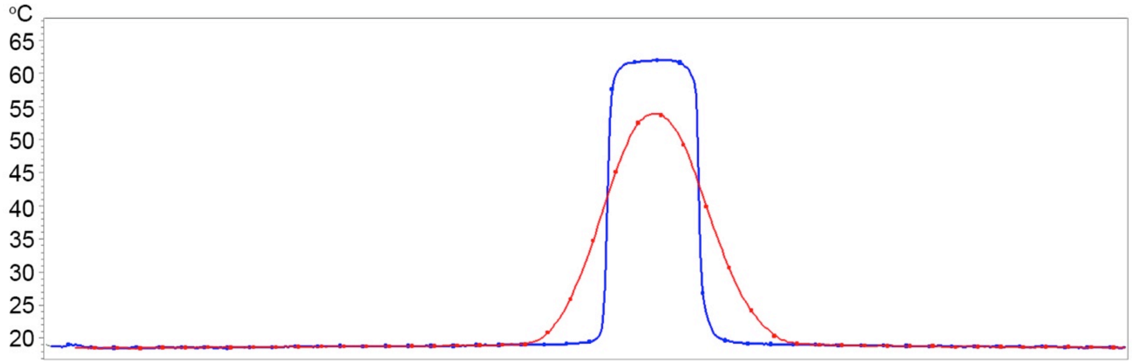


Figure 124. Thermal transect for figure 123 above. X-axis corresponds to length of line.

SUP 3. In-situ U-value measurement (using Time-lapse thermography) of a known moisture defective construction. [See Section 6.4.6]

Experiment description

While part 3 of chapter 6 explored the use of time-lapse thermography for in-situ U-value measurement in real buildings, it was still difficult to determine what impact the effects transient material changes had on results. For example, it was unclear whether any moisture was present within each construction and what impact this would have had upon results. For the case studies in part 3 of this chapter, every effort was taken to find wall samples that were free from cold bridging and apparent fabric defects. Yet, sometimes there will be situations where building defects are present and will greatly impact on the quantitative thermographic results.

It was very difficult to find real building case studies with known/understood building defects. Therefore this supplementary experiment was devised, which made use of a hot and cold box climate chamber to explore the difference between a defective and non-defective identical sample.

The defect, which was explored, was moisture ingress (in wood fibre insulation). Moisture ingress was chosen as it had been acknowledged in chapter 3 as being one of the most difficult defects to detect/characterise compared with others. Also, following experiments in chapter 6 part 1, which explored wetted sample materials, time-lapse thermography was found to be more successful at observing/characterising potential moisture related defects than other (single point in time) methodologies.

Experiment methodology

Sandwiched between two climate chambers, was a sample wall construction, which was formed from typical building materials. The primary material being examined within the sample was wood fibre insulation. This was fitted into a timber frame and had plasterboard on either side, enclosing the sample. Figure 125 shows a sketch illustrating a cut-away section through the hot and cold boxes. By splitting the wood fibre insulation into two sections, this experiment sought to explore the effects that moisture can have on material properties over time. To do this, one section of the wood fibre insulation was moistened and the other kept dry.

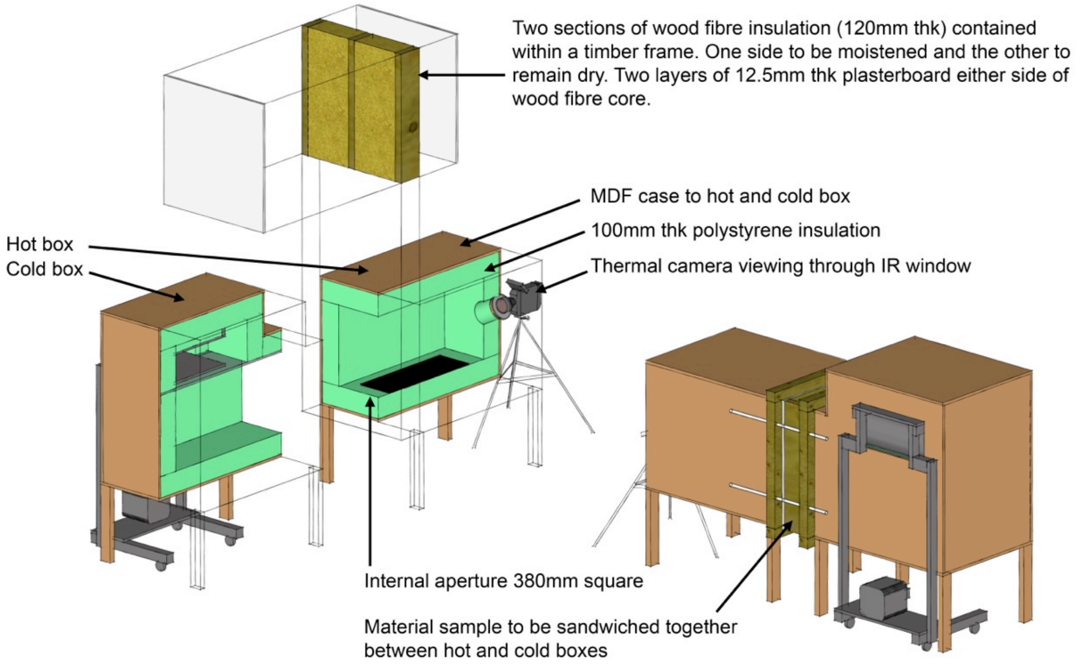


Figure 125. Sketch illustrating the hot and cold box experimental set-up.

Hot and cold box climate chamber construction

While the hot plate experiment was undertaken within a controlled internal room environment, there remained the possibility for fluctuations in internal conditions such as air temperature. To minimise the effects from uncontrollable external conditions, it is important to achieve as close to a steady state environment as possible. To do this, an unguarded hot and cold box climate chamber set-up was developed. The design of these followed guidance from BS EN ISO 8990:1996 (1996) and Asdrubali & Baldinelli (2011) and comprised of the following:

- **Hot box.** This box was constructed out of 100mm thick polystyrene insulation, which was encased by MDF hardwood for rigidity. The box had an internal aperture of 380x380mm. At one end, the hot box was left open, while at the other end, a 150mm diameter circular hole was cut. A highly transmissive infrared window (FLIR, 2011b) was fitted over this opening to allow a thermal camera to view into the hot box. To heat the hot box, a 31W heating mat was laid on the floor of the box. The average temperature of the hotbox climate chamber was: 311.85 K ±1.8K.

- **Cold box.** The cold box comprised of an identical construction to the hot box. To cool the cold box, an old fridge was disassembled to make use of the refrigeration components, which were inserted into the top of the cold box. A plastic sheet with perforated holes was fitted to the underside of the refrigeration unit within the box to help with an even distribution of cool air. Extra insulation was packed around the refrigeration unit, where it entered the cold box. This minimised the opportunity for heat to enter the cold box from the room. The average temperature of the cold box climate chamber was: 262.14 K ±2.5K.

While the hot box simulated an internal environment, the cold box simulated an external environment. It was acknowledged that the internal and external air temperatures were very high and low. The apparatus used dictated these temperatures. Whilst not representative of real building conditions these temperature extremes provided a difference between the internal and external air temperatures of approximately 50K ±3.5K. This proved to be much greater than the recommended minimum of 10K temperature difference (UKTA, 2007) between inside and outside. The greater the temperature difference between inside and outside temperatures equates to an improved resolution in thermal image patterns. This is because greater heat transmission is occurring across the target object.

Diagrammatic sketches of the hot and cold box climate chambers can be viewed in Figure 125 above. This figure also shows how they clamp together around the sample.

Construction build-up sample

Two blocks of 120mm thick wood fibre insulation were fitted within a simple plywood timber frame. The wood fibre insulation comprised of the following properties ('UdiTHERM Wood Fibre Insulation Boards 120mm,' 2015):

- Softwood material with 0.5% paraffin and 2% PVAC
- Design based thermal conductivity 0.040 W/mK
- Specific enthalpy capacity 2100J/kg/K
- Apparent density 140kg/m^3

Either side of the wood fibre insulation, and screwed to the timber framing were two layers of common gypsum plasterboard. Each was 12.5mm thick and had a thermal conductivity of 0.19W/mK ('Gyproc WallBoard,' 2015) (see Figure 126). With an internal boundary layer thermal resistance of 0.13m^{2}K/W and an external boundary layer of 0.040m^{2}K/W (Anderson, 2006), the overall design based U-value (Nicholls, 2002) for this sample (dry) has been calculated as 0.309W/m^{2}K.

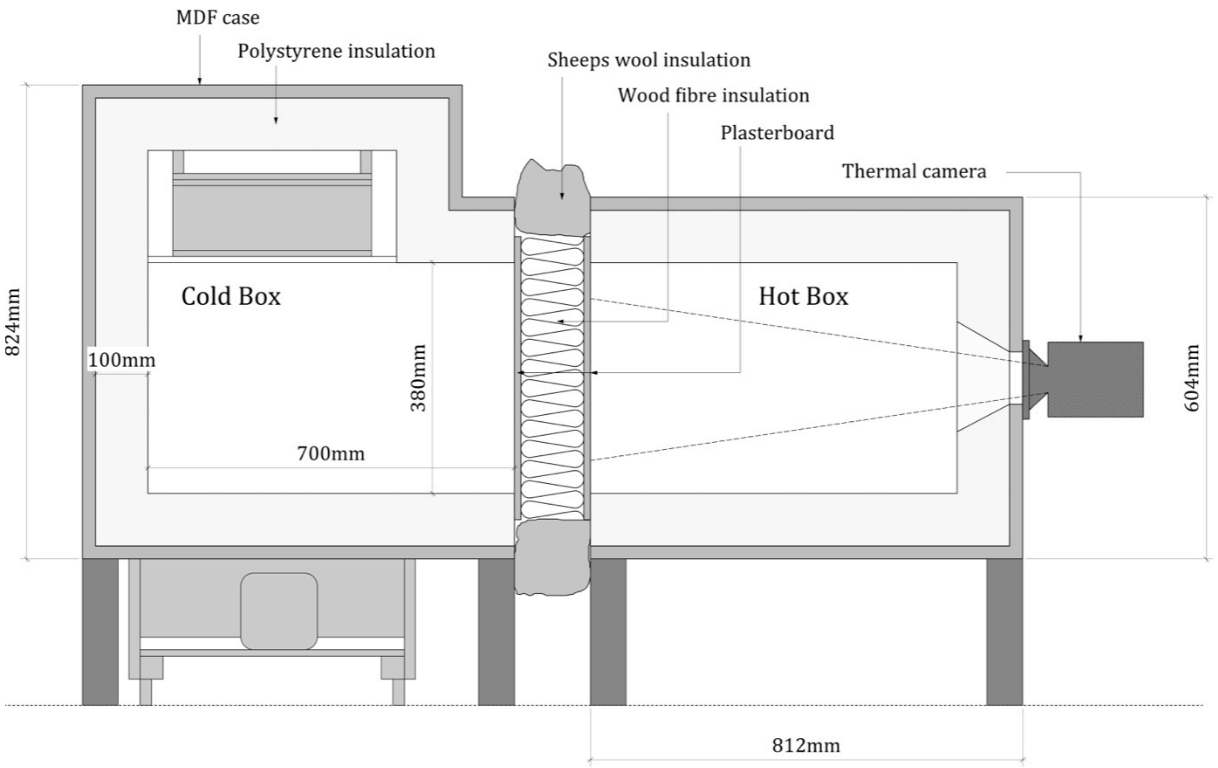


Figure 126. Section through climate chamber and sample set-up.

The objective of this experiment was to examine the transient differences in insulation U-values between a dry and wet construction. Therefore one of the insulation sections was moistened. To moisten the sample, water was continuously poured over the insulation for 10 minutes. To ensure a through wetting, the sample was rotated during the wetting process. After the insulation had been thoroughly wetted, it was stood upright for 10 minutes to allow some of the absorbed moisture to run out. The assembled sample build-up was then clamped between the hot and cold boxes. To minimise the threat of heat loss occurring around the edge of the sample, a 100mm thick layer of sheep's wool insulation was wrapped around the build-up and taped in place.

Figure 127. Four photos showing the sample, hot box, cold box and connected sensors.

Data collection

The data collection methodology for this experiment was identical to the methodology used for the real building case studies in part 3 of chapter 6. This included the collection of:

1. Heat flux measurement
2. Thermocouple surface and air temperature measurement
3. Thermal camera measurement

The heat flux sensors were fixed to the internal face of the wall sample using a heat sink compound applied between the sensor and wall surface. To enable the comparison of U-value measurements between the two samples, one heat flux sensor was placed over the wetted sample area, and the other over the dry sample area. Figure 127 shows photos of the experimental set-up.

In place of the weather station, extra thermocouples were used in this experiment for the measurement of air temperatures. In total, six K-type thermocouples were used for this experiment and were connected to a calibrated Campbell Scientific

CR1000 data logger (Campbell Scientific, 2014). The thermocouples were applied in the following locations:

Thermocouple 1. Fixed to internal (Hot box) surface of dry sample
Thermocouple 2. Fixed to internal (Hot box) surface of wet sample
Thermocouple 3. Fixed to external (Cold box) surface of dry sample
Thermocouple 4. Fixed to external (Cold box) surface of wet sample
Thermocouple 5. Collecting internal (Hot box) air temperature
Thermocouple 6. Collecting external (Cold box) air temperature

Each of the surface mounted thermocouples were fixed to the surface using highly adhesive tape and a heat sink compound to aid conductivity/accuracy.

Although this experiment offered the opportunity for the thermal camera to view the sample from either the hot or cold side, it was decided to set the thermal camera on a tripod to observe the sample from the warm side. This was based on comments/advice from Pearson (2011), Vollmer & Möllmann (2010), and Madding (2008), who explain that quantitative investigations need to be conducted from the inside only. Ideally, a thermal camera would have been positioned on each side of the sample, however only one thermal camera was available for this experiment. Had another thermal camera been available, it would be important to understand the differences in temperature measurement between the two.

The thermal camera used for this experiment was a recently calibrated FLIR T620bx (see Appendix B) for technical specifications).

Sat on a tripod, the thermal camera was located as close to the infrared window as possible. The distance from the thermal camera to the sample was less than 1000mm. Because infrared windows attenuate some of the infrared radiation passing through, it is important to adjust thermal camera measurements to account for this. To do this a separate experiment was performed prior to the experiment in accordance with Orlove (2012), where the transmission value is determined for the infrared window. This is obtained by measuring the temperature of a hot source twice. Firstly, it is viewed without the window, and a surface temperature is measured. The source is then viewed again, though this time through the infrared window. The emissivity is adjusted until the surface temperature matches that of the original surface temperature. This is the transmission value and inserted into the thermal camera (along with window temperature) settings so that this factor can be accounted for during quantitative measurements. The infrared window compensation was measured as being 43% at a window temperature of 304.15K.

A piece of crumpled aluminium foil was flattened out and fixed to the surface of the sample. This enabled the determination of RAT for the sample (Fokaides & Kalogirou, 2011), which was measured as being an average of 308.15K. An average RAT was used for this experiment, because it would have been impractical to measure and adjust this value for all readings. The emissivity for the sample was measured (ITC, 2006) as being 0.90.

As with the experiments in part 3 of chapter 6, data collection was made every 15 minutes for the period of one week. Following this period of data collection, all of the data was uploaded to a computer and inserted into equations based on Madding's (2008) and Baker's (2008; 2011) work as conducted under the experiments in part 3 of chapter 6.

Results

The weeklong experiment was started at 17:15 on the 23rd January 2015 and was ended at 17:00 on the 30th January 2015. During this period, 672 images/measurements were taken every 15 minutes. Figure 128 presents a six hourly-spaced selection of thermal images from this experiment. For this experiment, target comparison methods of qualitative analysis were used to compare the dry and wet samples, and differences between each thermal image. Within each of the thermal images, the insulation sample on the left (dry sample) did not appear to vary significantly throughout the experiment, as seen in Figure 128. Conversely, the wet sample, which was on the right of the thermal images, appeared to start out much cooler than the dry sample before becoming increasingly warmer looking towards the end of the weeklong period.

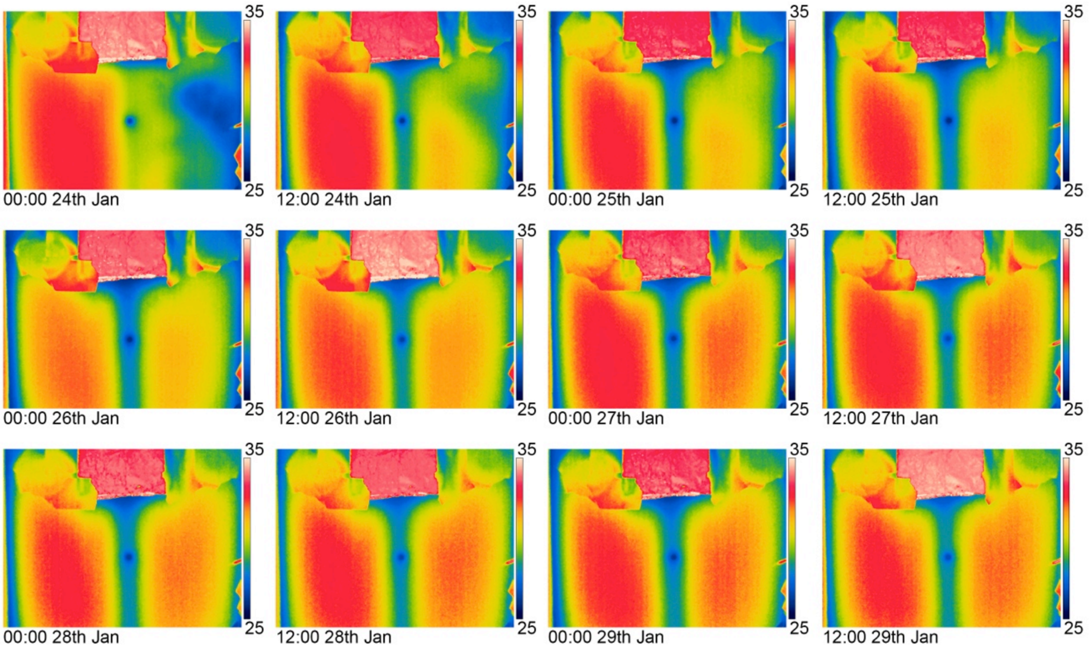


Figure 128. Thermal images recorded at 12-hour intervals from 00:00 on the 24th January to 12:00 on 29th January.

Seeking to determine the U-value for each sample of insulation, quantitative analysis was undertaken, which made use of the thermal images, hot and cold box air temperatures, and heat flux measurements. To generate U-value results using the thermography and heat flux methodologies, equations EQ. 5 and EQ. 6 were used. The quantitative results from the two measurement methodologies are presented in Figure 129, which shows the moving average U-values over the weeklong period for the wet and dry samples. For comparison, the design based U-value for the dry wall sample is also shown in this graph.

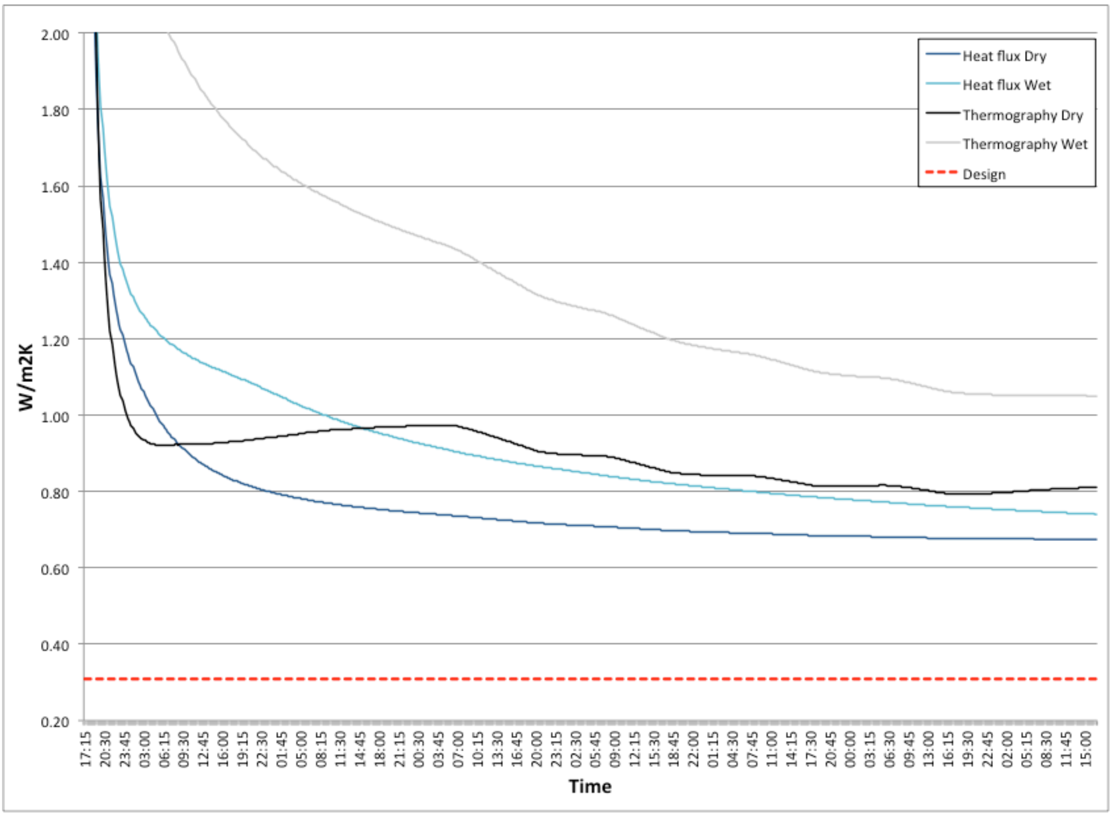


Figure 129. U-value results from the hot/cold box experiment over seven days. Indicating wet and dry heat flux and thermography U-values as well as design based U-value. Note. U-value scale capped at 2.0W/m^{2}K.

The final U-value results for the two samples, recorded at 17:00 on 30/01/2015, and based on the moving average of weeklong data were:

- Heat flux dry sample U-value: 0.67W/m^{2}K.
- Heat flux wet sample U-value: 0.74W/m^{2}K.
- Thermography dry sample U-value: 0.81W/m^{2}K.
- Thermography wet sample U-value: 1.05W/m^{2}K.

Discussion

Having viewed the sample from the hotbox side/theoretical internal space, the expectant thermal patterns would be that properly performing insulation would appear warm, while poorly performing insulation would appear cooler. This was the case in this experiment. As seen in Figure 128, the dividing central timber frame could clearly be seen as acting as a thermal bridge. This might have had an impact upon the results, as Baker (2011) advocates sampling constructions away from potential thermal bridges.

With regards to the wet sample, the qualitative pattern characteristics appeared mottled and patchy (see Figure 128), which aligns with defect pattern descriptions provided by others (Balaras & Argiriou, 2002; BSi, 1999). Over time, these patterns started to disappear, which suggested that the insulation was starting to dry out. The moisture would be moving from the warm side of the insulation to the cooler side. This further confirmed that the defect was moisture related, since had this been missing insulation, the defect would have remained throughout the relatively steady state experiment.

Aside from observing the qualitative difference over time between the dry and wet sample, initial quantitative observations were made from Figure 129. At the start of the experiment, the heat in the hotbox and fridge in the cold box was turned on. This explains the rapid drop in U-value results at the beginning. The real interest in results starts after the two boxes reached a relatively steady state.

Firstly it was important to compare the wet sample U-value results with the dry sample results. For both heat flux and thermography methodologies, a similar pattern in moving average U-values appeared. In both cases, the dry U-values quickly reached a relatively steady plateau U-value, while the wet sample took much longer, or did not reach a steady period. For both methodologies, the wet sample's U-value result was higher than the dry sample. From reviewing Figure 129, it can be suggested that the wet sample U-values were becoming lower throughout the entire experiment period as it was drying out. Had this experiment been left to continue indefinitely, it is likely that the wet sample U-value would have aligned more closely with the dry sample as the moisture was released. However it remains unclear what long lasting impact the moisture would have had on the insulation material properties.

Comparing the results between the measurement methodologies presented further interest. While the heat flux U-value results appeared to be steadier over time, the thermography U-value measurement seemed to undulate slightly. This subtle undulation in U-value results occurred for both the wet and dry sample results recorded by thermal camera. Whilst it is not completely clear why the thermal camera U-values undulated, and the heat flux results did not, past experiences suggest changes in the surrounding environment. Although this experiment was conducted in a more controlled environment to in situ settings, the thermal camera was located outside of the experimental climate chamber. The fluctuations in results occurred at roughly the same time each morning and seemed to correspond with the central heating system (coming on/going off) for the room in which the camera was sitting.

Another factor, which could have caused undulations in thermography U-value results, could have been the infrared window. Although a calibration check of the infrared window used was conducted in accordance with procedures set out by Orlove (2012), adjustments for infrared windows rely upon the input of transmissivity and window temperature values. Both of these values might have changed subtly over the course of this experiment, and would have impacted on results. It was not practical to adjust each thermal image's settings to account for variations in the infrared window transmissivity.

Another observation between the two measurement methodology results was the U-value difference between wet and dry samples (see Figure 130). The difference between the two samples under the heat flux measurement was less than the difference between the samples under the thermography measurement. This was most noticeable at the start of the experiment, when the sample would have been most wet. Towards the end of the week, both differences in measurement started to follow a similar pattern, though the thermography results consistently had a greater difference between wet and dry compared with the heat flux U-value differences.

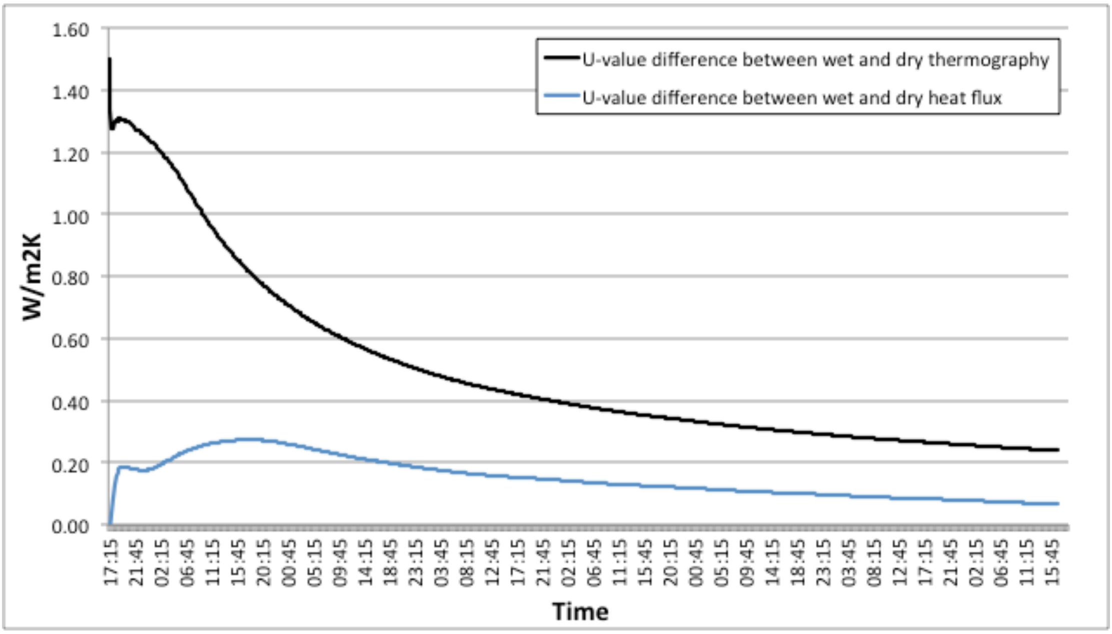


Figure 130. Difference in W/m^{2}K between the wet and dry U-value results for the heat flux and thermography experiments.

Comparing the measured U-value results from both measurement methodologies with the design based U-value (Figure 130) indicated that neither methodology was close to the design U-value based on the manufacturers data. The closest U-value to the design based value was the heat flux measured dry sample, which at 0.67W/m^{2}K was 0.37W/m^{2}K higher than the design value. While there may have been errors in the experiments, these results might also indicate an error in the manufacturers stated thermal conductivity data.

Uncertainty analysis

As with the in-situ experiments in part 3 of chapter 6, both heat flux and thermography measurement methodologies comprised of errors in apparatus, measurement procedure, sample quality, etc. It was therefore important to undertake an uncertainty analysis of results. The methodology for uncertainty analysis used on the hot and cold box experiment was very similar to the in-situ U-value results in part 3 of chapter 6. The only exception was the use of thermocouples (with an error of ±0.5K) to measure the hot and cold box air temperatures.

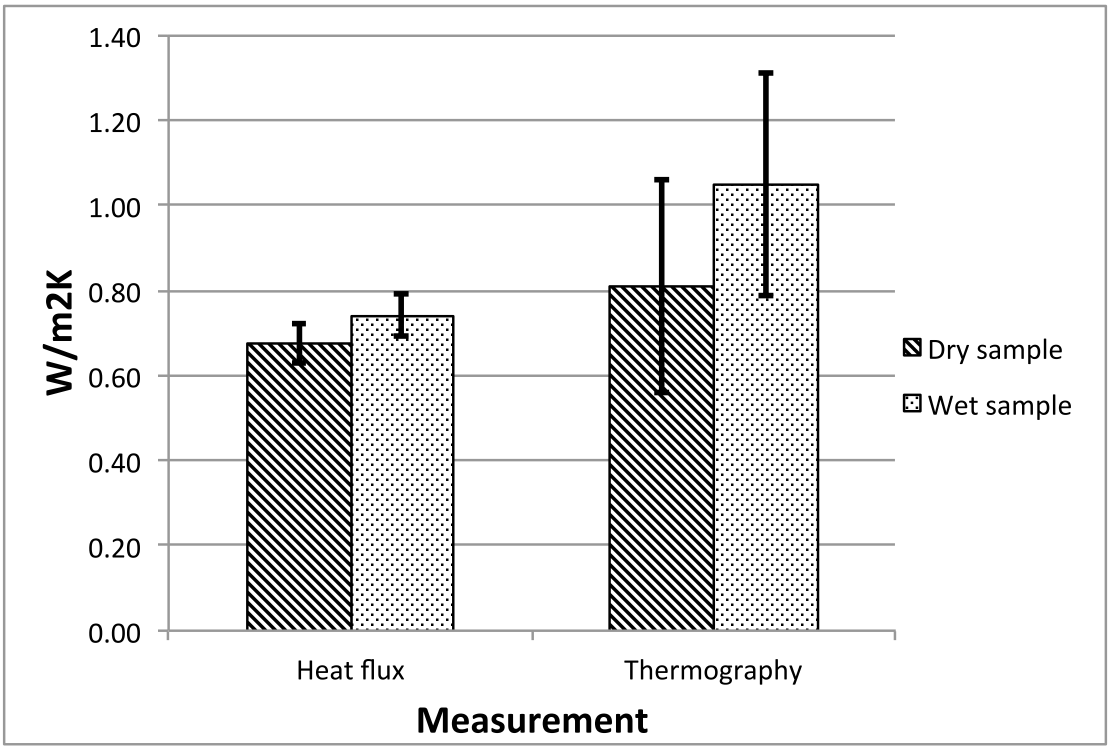


Figure 131. Comparison between measured final U-value results and final uncertainty analysis (±) margins.

The uncertainty analysis was performed on the final U-value result, which were derived from the moving average U-values throughout the weeklong experiment. These have been presented in Figure 131. Also shown in this graph are error bars, which represent the uncertainty of measured results. The uncertainties for each situation were as follows:

- Heat flux dry sample U-value: 0.67 $\pm \mathbf{0.05}$W/m^{2}K.
- Heat flux wet sample U-value: 0.74 $\pm \mathbf{0.05}$W/m^{2}K.
- Thermography dry sample U-value: 0.81 $\pm \mathbf{0.25}$W/m^{2}K.
- Thermography wet sample U-value: 1.05 $\pm \mathbf{0.26}$W/m^{2}K.

In percentage terms, the measured results for the heat flux methodology (both samples) had an uncertainty of between ±6.6% and ±6.7%, while the thermography results (both samples) had an uncertainty of between ±24.0% and ±31.0%.

As found in the results from part 3 of chapter 6, it is clear that the U-value derived from thermography contains a larger degree of uncertainty than the heat flux methodology. Aside from the added complexity in mathematical equation, another possible explanation is the fact that there is no direct connection to the sample during the thermography experiment. This meant that convection and radiation heat transfer mechanisms would be impacting on results (compared with predominantly conduction in direct contact heat flux measurements) as well as conduction. Because of the air gap (and infrared window) between the sample surface and the thermal camera, infrared radiation would have been attenuated before reaching the camera, leading to a reduction in accuracy.

Correlations can be found with the uncertainty results from this experiment and those measured in other literature sources. For heat flux measurements, Baker (2011) and Rhee-Duverne & Baker (2013) list uncertainties of between ±8 and ±10% for brick and stone wall constructions. Whilst this example was neither brick nor stone in construction, these uncertainties offer an indicative range, which the heat flux measurements in the hot/cold box experiment were close to at approximately ±7%.

For the thermography U-value, estimated uncertainties of ±24% to ±31% corresponded with concerns from Pearson (2011), who suggested that U-values measured using thermography would be at best ±25%.

Appendix B. Thermal camera technical specifications [See Section 4.4].

This appendix provides technical specifications for the two thermal cameras used throughout this thesis.

IR resolution	640 x 480 pixels	
Field of view (FOV)	25° x 19° / 0.25m (0.82ft)	
Spatial resolution (IFOV)	0.69 mrad	
Thermal sensitivity (NETD)	<40 mk (<0.04°C) at +30°C (+86°F)	
Image frequency	30 Hz	
Temperature range	-40°C to +150°C (-40°F to +302°F) and +100°C to +650°C (+212°F to +1202°F)	
Accuracy	±2°C (±3.6°F) or ±2% of reading	
Image recording	Simultaneous storage of IR/Visual images Periodic image storage	

Table 10. FLIR T620bx technical specifications (FLIR, 2013a).

IR resolution	320 x 240 pixels	
Field of view (FOV)	24° x 18° / 0.3 m (0.98ft)	
Spatial resolution (IFOV)	1.3 mrad	
Thermal sensitivity (NETD)	80 mk (0.08° C) at 30° C (+86°F)	
Image frequency	50/60 Hz (non-interlaced)	
Temperature range	-40° C to +120° C (-40° F to +248° F), 0° C to +500° C (+32° F to +932° F) and +350° C to +1500° C (+662° F to +2732° F)	
Accuracy	±2°C (±3.6°F) or ±2% of reading	
Image recording	Simultaneous storage of IR/Visual images Periodic image storage	

Table 11. FLIR S65 technical specifications (FLIR, 2006).

Appendix C. Setting the emissivity value [See Section 4.3].

The following is based on ITC (2006) and Level 1 thermography course notes (Walker, 2012).

It is important to set the emissivity value in the camera so that the camera knows what to subtract from the reading in order to give the apparent emitted temperature of the object being observed.

Emissivity figures can be chosen (for input) from emissivity tables. However these are not always accurate and can often not reflect the surface finish variance for each and every material. Therefore it is good practice to measure the emissivity for each material in the field (if you intend to perform quantitative analysis that is).

There are two principle methods for determining the emissivity for materials.
The first is:

1. Ensure that the object to be measured has a different temperature to the ambient temperature of the room / environment. If not you will need to look up a pre-calculated figure.
2. Fix some insulation tape or high emissivity paint to the object (you need to use something with a known emissivity value for this).
3. Take the thermal camera and set the emissivity to 1. By setting 1, you are just telling the camera that every bit of radiation now observed is emitted only (nothing reflected).
4. Put a box tool on the camera and set it to read the average apparent temperature.
5. Get close to the object to be measured and turn your back to it.
6. Point the camera at an inverse angle to that at which you will be pointing the camera. You will be looking to see what radiation will be reflected in the object, so taking an average of the background (T.reflect or reflected temperature) temperature.
7. When you have this figure it should be inputted in to the camera (T.reflect or reflected temperature) setting.
8. Turn to face the object.
9. Set the emissivity value to the known value of the tape or similar material. Tape is usually 0.97.
10. Point the camera at the tape and take a temperature reading.
11. Then point the camera at the actual material, which you require an emissivity value for and adjust the emissivity value in the camera until you get to the same temperature reading as for the tape.
12. This emissivity reading will be the recorded emissivity for the material, and can be checked against published tables if required.

The second method is the same as the first, however points 5 to 8 are different:

5. Take piece of tinfoil and screw it up. Then open it out so that there are lots of bumpy / angular surfaces. This has made a diffuse surface. Its best to attach this to a piece of cardboard for rigidity.
6. Place this tinfoil over the object to be measured.
7. Adjust the focus of the camera so that it is out of focus.

8. Point the camera at the tinfoil (just the tinfoil) and measure the average temperature reading that is recorded. This will give you your T.reflect as it’s reflecting everything behind the object (including you and the camera!). Input this figure into the camera (T.reflect or reflected temperature) setting and remove the tinfoil.

The reflected apparent temperature is vital for accurate temperature measurement, since the camera needs to be told what amount of reflected (environmental) radiation needs to be subtracted from the target emissions if we are to more accurately work out what the targets emissions are.

Appendix D. Climatic criteria [See Section 2.4]

This appendix provides a more detailed explanation of the climatic criteria that should be followed during a thermographic survey. This includes:

- Ensuring minimum temperature differences
- Avoiding solar loading
- Avoiding night sky radiant cooling
- Avoiding the effects of moisture
- Avoiding excessive wind loads

Ensuring minimum temperature differences. The external air temperature should not vary by more than 10 degrees nor be less than 3/U, where U is the thermal transmittance in W/(m^2K), within a 24-hour period prior to the start of a survey (Pearson, 2002). To achieve this, thermographic investigations are typically performed during the cooler months of the year. Furthermore, an air temperature difference between internal and external spaces needs to be maintained at no less than 10 degrees for the duration of the survey (Maldague, 2001a; UKTA, 2007). Throughout the survey, internal temperatures should not fluctuate by more than 2 degrees (Hart, 1991), while external temperatures should not vary by more than 5 degrees (BSi, 1999).

Avoiding solar loading. External thermographic surveys should be conducted during cloud-covered days (Holst, 2000) or within the hours of darkness (Maldague, 2001a). This requirement is in place to avoid interference from direct solar gains (BSi, 1999; Pearson, 2002), which could mask defects due to high temperature reflections and stored thermal mass.

To minimise the effects of thermal mass stored within building components, some (BSi, 1999; Hart, 1991) have suggested that building façades should not have any solar exposure for at least 12 hours before the survey, while Chown and Burn (1983) advocate the following minimum periods after solar exposure before conducting thermographic surveys:

- 2 hours for light weight structures (timber-framing, etc.)
- 6 hours for heavier structures (Brick, precast cladding, etc.)
- 24 hours for very heavy-weight structures (providing the 24 hour period comprises of an overcast sky)

Snell and Spring (2008) also added that solar loadings can sometimes reverse the direction of heat flow through a material and could mask results or lead to misinterpretation.

Avoiding night sky radiant cooling. It is also important to avoid reflecting a clear sky, which can reflect very cold temperatures in the region of -50^{o}C (Pearson, 2011). Considering the differences in material emissivities, extreme temperature reflections, such as a clear night sky, could disguise the emitted portion of radiation from a target, therefore adversely affecting the apparent temperature received by the camera.

Investigations by Möllmann *et al.* (2008) into the impact of night sky radiant cooling suggested that thermographic surveys should be conducted on a cloudy night. Also to minimise the effects of solar gains during the day, the survey should follow a cloudy day. However, some commentators advocate times when a clear sky is not a problem and could be desirable, such as prior to a roof moisture survey (Holst, 2000). Furthermore, McIntosh (2012) argued that where there is a low night sky temperature the thermographer should make camera adjustments (span and level) to see whether the defect signal is detectable or not. Maldague (2001a) suggested that for more accurate thermographic data collection, a clear sky is desirable so as to avoid thermal reflections from clouds.

Avoiding the effects of moisture. Moisture in the form of precipitation can impinge on the accuracy of thermal camera results in two distinct ways. Firstly, moisture in the atmosphere will attenuate the radiation being transferred from the target surface to the camera (Walker, 2004); therefore, it is important that fog, mist, rain and snow should not be present during or leading up to a thermographic survey (Pearson, 2002).

The second way in which moisture can affect thermographic results is through the dampening effect on materials. Unless a moisture survey is being conducted, it is important that all surfaces are dry upon inspection. This is important because surface moisture will have an impact on the temperature reading due to evaporative cooling, when evaporated water vapour takes with it some of the heat from the surface it has left (Brady, 2008; Nicholls, 2002). Also, because water has a greater heat capacity than most building materials (Pleşu, Teodoriu & Ţăranu, 2012), moisture stored within construction materials will change the thermal pattern depending on the time of day that the survey is conducted, which could lead to misinterpretation of performance unless this defect / the physics is understood.

Avoiding excessive wind loads. Balaras and Argiriou (2002) pointed out that increased air movements over a given surface will hasten heat loss due to a reduction in the surface boundary air layer. Vollmer & Möllmann (2010) conducted experiments looking into the effects of wind on thermographic images and discovered that quantitative analysis can be adversely affected as the wind speed increases; this is primarily due to forced convection and lessening of thermal sensitivity. These effects will therefore lower the apparent surface temperature reading.

Additionally, if the surface is damp then increased air movement across it will increase evaporative cooling at a greater rate (Vollmer & Möllmann, 2010), which could lead to further misinterpretation if not fully recognised at the time. In order to minimise the effects of wind cooling a surface, there are recommendations for the maximum wind speed under which thermography should be performed. However, advice varies from a maximum of 1 m/s (Albatici & Tonelli, 2010) to 5 m/s (Balaras & Argiriou, 2002) and 10 m/s (Pearson, 2002). It does, however, appear to be accepted that the effects of wind over a surface are very complex (Hart, 1991; Vollmer & Möllmann, 2010) and can vary more quickly than other conditions due to gusts.

Appendix E. Methodology Checklist [See Section 4.3]

This appendix contains the methodology checklist, which was used during the thermographic surveys for this thesis.

Methodology checklist

Survey Date **Start time** **End time**
Internal air temp **External air temp**

Climatic conditions

General Weather condition	Specific weather condition questions	Answer (circle Y or N)
Precipitation	Precipitation 24 hours prior to survey?	Y/N
	Precipitation expected during survey?	Y/N
	Precipitation present during survey?	Y/N
Cloud cover	Clear sky experienced 24 hours prior to survey?	Y/N
	Clear sky expected during survey?	Y/N
	Clear sky present during survey?	Y/N
Wind	Wind speed >10m/s expected during survey?	Y/N
	Wind speed >10m/s present during survey?	Y/N
	Strong gusts of wind expected during survey?	Y/N
	Strong gusts of wind present during survey?	Y/N
Temperature	External temperature variations >5 degrees during the survey?	Y/N
	Internal temperature variations >2 degrees during the survey?	Y/N
	>10 degree temperature difference in external air temperature fluctuations over 24 hours prior to survey?	Y/N
	<10 degree temperature difference between inside and outside during the survey?	Y/N

Measured emissivity

Comments on climatic conditions

Other factors that have impacted upon thermography results

Photo or Plan cross references with thermal images to be listed on the reverse side of this sheet.

Figure 132. Methodology Checklist.

Appendix F. Walk-through methodology procedure [See Section 5.1.3]

This appendix presents a list of the procedures, which were followed during each walk-through thermography case study survey. The procedure comprised of the following list (based on (ASTM, 1997; BSi, 1999; RESNET, 2012)):

Pre-planning

To begin with, background information was gathered on the dwelling being surveyed. This enabled the thermographer to have a better understanding of the building before undertaking the inspection. This included:

- Address
- Construction
- Age
- Dwelling scale
- View of the dwelling using Google street view
- Request of plans, if available
- Expected purpose of survey
- The site conditions and any other factors the thermographer should be made aware of
- Any defects that the occupants were aware of?

This information was gathered by questioning householders via email or a phone call made in advance of the survey. This also provided an opportunity to ask the householders if they would be at home on the night of the survey and if they would still like to participate in the project. If the householders responded positively, then a survey time was agreed, which allowed for a ±1 hour flexible window in case of delay.

Pre-survey

On the day of the survey, the weather conditions were checked to determine whether the survey needed to be cancelled. The thermographers then travelled to the survey region for that evening, where they met up as a team for a pre-survey briefing. This team was split into smaller two person teams (for safety), who were given a predetermined group of case study dwellings to survey in an evening.

Performing the survey

The thermographic surveys of the case study dwellings were scheduled to commence after sunset, which was approximately 6pm each evening. Once the thermographer had reached a case study dwelling, they introduced themselves to the householder and showed their ID cards for verification. The thermographer then used a predetermined procedure to conduct the walk-through thermographic survey. This comprised of:

- External inspection first
    - Camera acclimatisation
    - Checking weather conditions
    - Measuring air-temperatures
    - Setting parameters
    - Measuring reflected apparent temperature (RAT)
    - Adjusting the camera thermal tuning

    - Scanning and imaging
- Internal inspection second
    - Same procedures as above

Camera acclimatisation. The thermal camera was switched on and left to acclimatise to the atmospheric air temperature for 30 minutes before commencing any thermography (Vollmer & Möllmann, 2010).

Checking weather conditions. Whilst waiting for the thermal camera to acclimatise, field notes were taken, which described the weather conditions during the survey. This included: presence of cloud cover, precipitation and wind.

Measuring air-temperatures. To determine the external air temperature, a post-it note was folded and attached to a wall (which was not part of the dwelling). This was left for a couple of minutes to acclimatise to the air temperature. Because paper is relatively thin, it doesn't take long to match the temperature of its surroundings (Walker, 2012). A spot measurement tool was then added within the camera settings and the emissivity set at 0.90, which corresponded with the paper. The camera was then pointed at the paper and a temperature measurement was taken. This provided a quick estimate of the air temperature without the need for additional equipment.

Setting parameters. Once the air temperature had been estimated, parameters were set within the thermal camera. Because most construction materials have an emissivity of between 0.90 and 0.96 (Pleşu, Teodoriu & Ţăranu, 2012; Ward & Sanders, 2007), it was decided to pre-set the camera emissivity at 0.95. The camera parameters were not re-adjusted at any other time throughout the survey, since the accuracy of these are not deemed significant to defect detection using qualitative analysis (Barreira & de Freitas, 2007; BSi, 1999; Hart, 1991; Mobley, 2002).

Measuring reflected apparent temperature (RAT). Before starting the inspection of an elevation, the thermal camera was pointed away from the dwelling to scan the background RAT. This is advised by the Infrared Training Centre (ITC) (2006) as a methodology to determine whether there are any neighbouring emitters of high or low temperatures that might reflect off the dwellings surface. When extreme contextual temperatures were discovered, surfaces were viewed at angles that did not reflect the emitting source to minimise the risk of image misinterpretation.

Adjusting the camera thermal tuning. To help thermally tune the camera so that the temperature span could appropriately match the dwelling, the thermal camera was pointed at a typical wall surface, set to auto tune and then re-set to manual tune. This locked in the temperature span for all external thermography.

Scanning and imaging. Starting with the front elevation, the entire surface was scanned with the thermal camera to look for temperature anomalies using qualitative thermography methods of measurement (Walker, 2004). The thermographer would stand far enough away to capture as much of the elevation within the FOV. Should a thermal anomaly be discovered, the thermographer would move closer to the location of this and capture one or more thermal images. Notes on the location and characteristic of this defect would be made along with sketches or photos for cross-reference later. One single image of the front elevation was also recorded as a reference image for the dwelling.

The thermographer would then move around the dwelling, scanning each consecutive elevation in turn where possible. Any elevations that could not be accessed would be noted.

Once the external traditional walk-around survey had been completed, the thermographer moved indoors for the walk-through survey. This comprised of the following procedure:

Similar procedures to the external survey were conducted indoors, including: camera **acclimatisation**, indoor **air temperature** measurement, adjusting the camera **parameters** and scanning adjacent surfaces to determine any significant **RAT** issues. As with the external thermography, the procedure for internal thermography started by **scanning** the entrance hallway and front door. The thermographer then moved clockwise or counter clockwise around the entrance level floor, scanning all building surfaces before moving onto other subsequent storeys, if present, to repeat this procedure. Again, using qualitative methods of measurement (Walker, 2004), if any thermally significant anomalies were detected, these were recorded as **thermal images** alongside photos/sketches of the same location for later reference.

Appendix G. Case study parameters

The following appendix presents case study parameter information (weather, dates and times etc.) for each of the case studies conducted during chapters 6 and 7.

Parameters for case study experiments conducted during chapter 6 part 2:

Case study 1 parameters

Survey date	28th November 2012 - 29th November 2012
Survey start/finish/duration	Start: 17:00 (28th) Finish: 08:00 (29th) Duration: 900 minutes (15 hours)
Number of properties imaged	1
Property orientations observed	West external elevation
Camera distance from elevation	20m
Image intervals	Every 30 minutes
Weather two days prior to survey	Dry with periods of cloud cover and direct solar exposure on the target (west) elevation. External temperature range: 0.3°C to 8.1°C.
Weather during the survey	Whilst mostly cloudy there were times when pockets of clear night sky could have been reflecting off the surface. At no point was there precipitation or wind speeds over 1m/s. External temperature range: -3.1°C to 4.5°C Internal temperature range: 17.8°C to 20.3°C

Table 12. Case study parameters for case study 1 (Chapter 6 part 2).

Case study 2 parameters

Survey date	15th January 2013 - 18th January 2013
Survey start/finish/duration	Start: 17:00 (15th) Finish: 08:00 (18th) Duration: 3780 minutes (63 hours)
Number of properties imaged	1
Property orientations observed	North west external elevation
Camera distance from elevation	20m
Image intervals	Every 20 minutes
Weather two days prior to survey	Dry, with periods of changeable cloud cover. External temperature range: 1.3°C and 8.6°C.
Weather during the survey	The sky consisted of fluctuating cloud cover, with periods of clear and cloudy sky, while other times with unpredicted snowfall. There was at least a 10°C temperature difference between inside and outside throughout the survey. External temperature range: -0.8°C to 3.5°C

Table 13. Case study parameters for case study 2 (Chapter 6 part 2).

Case study 3 parameters

Survey date	13th March 2014 - 14th March 2014
Survey start/finish/duration	Start: 17:00 (13th) Finish: 07:00 (14th) Duration: 840 minutes (14 hours)
Number of properties imaged	1
Property orientations observed	East internal elevation
Camera distance from elevation	10m
Image intervals	Every 30 minutes
Weather two days prior to survey	Dry with small patches of cloud cover, though long periods of clear sky during the day and night periods. External temperature range: 11.1°C to 3.8°C
Weather during the survey	Dry with predominantly clear skies. External temperature range: 7.2°C to 3.9°C Internal temperature range: 18.0°C to 13.8°C Internal temperatures were largely dictated by the heating system coming on at 17:30 and stopping at 22:00 on the 13th March 2014.

Table 14. Case study parameters for case study 3 (Chapter 6 part 2).

Parameters for case study experiments conducted during chapter 6 part 3:

Case study 1 parameters

Survey date	5th January 2015 - 12th January 2015
Survey start/finish/duration	Start: 15:15 (5th) Finish: 15:00 (12th) Duration: 10,065 minutes (167.45 hours)
Number of properties imaged	1
Property orientations observed	West internal elevation. Cob construction
Camera distance from elevation	1m
Image intervals	Every 15 minutes
Weather two days prior to survey	For at least two days prior to this experiment starting, the temperature difference between inside and out side was >10°C, furthermore, there had been no precipitation during this period.
Weather during the survey	During the weeklong experiment, the internal/external air temperature difference was almost entirely >10°C. There was no precipitation during the experimental period.

Table 15. Case study parameters for case study 1 (Chapter 6 part 3).

Case study 2 parameters

Survey date	15th January 2015 - 22nd January 2015
Survey start/finish/duration	Start: 16:15 (15th) Finish: 16:00 (22nd) Duration: 10,065 minutes (167.45 hours)
Number of properties imaged	1
Property orientations observed	West internal elevation. Stone construction
Camera distance from elevation	2m
Image intervals	Every 15 minutes
Weather two days prior to survey	There was no precipitation monitored leading up to this experiment, and external air temperatures were less than 5oC two days prior to the survey.
Weather during the survey	During the weeklong experiment, the internal/external air temperature difference was almost entirely >10°C. Only on four occasions (no longer than 5.5hours long) did the temperature difference drop below >10°C. Despite seeking to avoid precipitation, there were short periods of rainfall during these experiments.

Table 16. Case study parameters for case study 2 (Chapter 6 part 3).

Case study 3 parameters

Survey date	28th February 2014 - 5th March 2014
Survey start/finish/duration	Start: 21:30 (28th) Finish: 20:30 (5th) Duration: 7,140 minutes (119 hours)
Number of properties imaged	1
Property orientations observed	North internal elevation. Concrete block, insulated cavity wall construction
Camera distance from elevation	1.5m
Image intervals	Every 15 minutes
Weather two days prior to survey	There was no precipitation monitored leading up to this experiment, and external air temperatures were less than 10°C two days prior to the survey.
Weather during the survey	Weather conditions comprised of at least a >10°C internal to external air temperature difference for much of the five day period. There were very low wind speeds and no precipitation encountered during the survey period.

Table 17. Case study parameters for case study 3 (Chapter 6 part 3).

Parameters for case study experiments conducted during chapter 7:

Case study A parameters	
Survey date	19th March 2014
Survey start/finish/duration	Start: 20:00 Finish: 22:30 Duration: 150 minutes
Number of properties imaged	23 (average of 6 minutes 30 seconds/dwelling)
Property orientations observed	North and South elevations
Average camera distance from elevation	Between 15 and 20 meters
Weather two days prior to survey	No precipitation. Air temperatures ranging from 0°C at night to 15°C during the day. Wind speeds between 2.5m/s and 4.0m/s. Cloud cover unknown.
Weather at the start of the survey	Air temperature: 6.7°C. Less than 50% cloud cover. Less than 10m/s wind speed. No precipitation
Weather at the end of the survey	Air temperature: 7.1°C. Less than 50% cloud cover. Less than 10m/s wind speed. No precipitation

Table 18. Case study parameters for case study A (Chapter 7).

Case study B parameters	
Survey date	7th to 8th March 2014
Survey start/finish/duration	Start: 10:30 Finish: 01:40 Duration: 190 minutes
Number of properties imaged	26 (average of 7 minutes 18 seconds/dwelling)
Property orientations observed	East and West elevations
Average camera distance from elevation	Between 6 and 10m
Weather two days prior to survey	Light rain forecast for the day prior to the survey. Air temperatures ranging from -2°C at night to 14°C during the day. Wind speeds between 2.2m/s and 4.8m/s. Cloud cover unknown.
Weather at the start of the survey	Air temperature: 3.0°C. Close to 100% cloud cover. Less than 10m/s wind speed. No precipitation
Weather at the end of the survey	Air temperature: 2.8°C. Close to 100% cloud cover. Less than 10m/s wind speed. No precipitation

Table 19. Case study parameters for case study B (Chapter 7).

Case study C parameters	
Survey date	10th March 2014
Survey start/finish/duration	Start: 00:30 Finish: 01:45 Duration: 75 minutes
Number of properties imaged	13 (average of 5 minutes 48 seconds/dwelling)
Property orientations observed	North, East, South and West elevations
Average camera distance from elevation	15m
Weather two days prior to survey	No precipitation. Air temperatures ranging from 0°C at night to 14°C during the day. Wind speeds between 2.5m/s and 4.8m/s. Cloud cover unknown.
Weather at the start of the survey	Air temperature: 3.5°C. Close to 100% cloud cover. Less than 10m/s wind speed. No precipitation
Weather at the end of the survey	Air temperature: 3.9°C. Close to 100% cloud cover. Less than 10m/s wind speed. No precipitation

Table 20. Case study parameters for case study C (Chapter 7).

Case study D parameters	
Survey date	2nd March 2014
Survey start/finish/duration	Start: 10:30 Finish: 0:45 Duration: 135 minutes
Number of properties imaged	15 (average of 9 minutes/dwelling)
Property orientations observed	North and South elevations
Average camera distance from elevation	15m
Weather two days prior to survey	Light rain forecast for during the day of the survey. Air temperatures ranging from -2°C at night to 16°C during the day. Wind speeds between 1.4m/s and 6.1m/s. Cloud cover unknown.
Weather at the start of the survey	Air temperature: 4.7°C. More than 50% cloud cover. Less than 10m/s wind speed. No precipitation
Weather at the end of the survey	Air temperature: 4.4°C. More than 50% cloud cover. Less than 10m/s wind speed. No precipitation

Table 21. Case study parameters for case study D (Chapter 7).

Appendix H. Research Ethics. [See Section 4.5]

This appendix lists the accepted research ethics forms for this thesis.

FACULTY OF ARTS

Faculty Research Ethics Committee (FREC)
APPLICATION FOR ETHICAL APPROVAL OF RESEARCH

ALL PARTS OF THIS FORM MUST BE COMPLETED IN FULL IN ORDER TO GAIN APPROVAL

1.	**Title of Research Project:** A comparison of passive thermography methodologies for the detection of defects in buildings.		
2.	**Principal Investigator/Applicant's Name:** Matthew		
	School: Environmental Building Group, School od Architecture, Design and Environment		
	Are you	**STAFF?** No	**ResM/MPhil/PhD STUDENT?** PhD
	If you are staff, are there any other researchers involved in your project? Please list who they are, their roles on the project and if/how they are associated with the University. Please include their email addresses. *Note: Principal Investigators are responsible for ensuring that all staff employed on projects (including research assistants, technicians and clerical staff) act in accordance with the University's ethical principles, the design of the research described in this proposal and any conditions attached to its approval.		
	Are you in receipt of any funding for this project (especially for which ethical approval is required – e.g. R1 funding, Research Council funding, etc.)? If yes, please explain. Yes – I am funded by a European Social Fund, Combined Universities of Cornwall grant (ESF-CUC)		
	If you are a student, who are your Director of Studies and Other Supervisors? DOS – Prof. Pieter De Wilde Other supervisors – Prof. Steve Goodhew and Prof. David Coley (University of Bath) Have you discussed all ethical aspects of your research with your DoS prior to submitting this application? Yes		
3.	**Duration of your overall Research Project/Programme of study (with dates):** Jan 2012 – Jan 2015 **When do you need/expect to begin the research methods for which ethical approval is sought?** October 2013 **How long will this research take and/or for how long are you applying for this ethical approval**? * 1 year **Approval is granted for the duration of projects as indicated above, or for a maximum of three years in the case of PGR programmes. Further approval is necessary for any extension of projects or programmes.*		
4.	**Please provide a 200 word description of the project.**		

Currently there are many thermographers utilizing thermal imaging to assess the condition of existing buildings. To do this, many different methodologies are being developed and used, though there is some concern that some of these methodologies have the potential for mistakes or misinterpretation if the limitations are not fully understood or acknowledged.

This project seeks to identify these different passive building thermography methodologies and understand how they are currently being used for detecting building defects and performance.

Some of these methodologies will be tested through practice-based research to observe the benefits and limitations to each methodology, with particular interest in defect detection.

In addition to the testing of existing methodologies, this project will seek to improve and create new passive building thermography methodologies, which aim to address some of the discovered limitations whilst embracing the benefits, which led to their application in the first place.

Once a clearer picture of how these methodologies could be best used, a decision-making matrix tool will be developed to help other thermographers and clients to make better judgments over which passive building thermography methodology to use for certain situations or defects.

5. **Please describe all methods and procedures which involve humans participants in this project** (You should specify subject populations and recruitment method, etc.):

The project methods, which will utilise human participants in this project include:

METHOD 1. Interviews with building surveying professionals (attached question sheet)

- These will be conducted over a selection of less than 5 building surveyors. These will be sourced from within this projects business partner group, which includes surveyors.
- The aim of these interviews will be to determine the most common defects in Cornwall and the current methods they use for detecting defects.
- Interviewees will receive the questions prior to interview and will be recorded using a Dictaphone (if permission granted to do so).

METHOD 2. Thermographic surveys of properties in Devon and Cornwall

- Thermographic surveys will be carried out on residential properties in Devon and Cornwall. The participants for these will be obtained through some of the projects business partners, one of which is a housing association.

  - Surveys will be conducted at night over the winter period.
  - All surveys will be conducted from outside only.
  - Thermal images will be taken of only one external elevation of a property, which will be the front elevation.
  - An information sheet (Attached draft) will be distributed to all house occupants prior to the survey.
  - Information on property age and type (house, flat etc.) will be sought from the business partner contact.

NB: If you have indicated that you are using questionnaires or semi-structured interviews, etc. you are expected to attach indicative samples to this application.

6. **Please answer either YES or NO to ALL questions below by placing an X in relevant box.**

Do any of your research methods include research:	YES	NO
With vulnerable groups – for example, children and young people, those with a learning disability or cognitive impairment, or individuals in a dependent or unequal relationship?		NO
That involves sensitive topics – for example, participants' sexual behaviour, their illegal or political behaviour, their experience of violence, their abuse or exploitation, their mental health, or their gender or ethnic status?		NO
With groups where permission of a gatekeeper is normally required for initial access to members – for example, ethnic or cultural groups, native peoples or indigenous communities?		NO
That involves deception or which is conducted without participants' full and informed consent at the time the study is carried out?		NO
That involves access to records of personal or confidential information, including genetic or other biological information, concerning identifiable individuals?		NO
That may induce psychological stress, anxiety or humiliation or cause more than minimal pain?		NO
That involves intrusive interventions – for example, the administration of drugs or other substances, vigorous physical exercise, or techniques such as hypnotherapy (i.e. interventions that your participants would not normally encounter, or which may cause them to reveal information which causes concern, in the course of their everyday life)?		NO

If you answered yes to any of the above questions, please provide further details of these potentially ethically sensitive aspects of your research.

7. **Ethical Protocol:**

Please write an ethical protocol using the following the headings:
a) Informed Consent; b) Openness and Honesty; c) Right to Withdraw; d) Protection from Harm; e) Debriefing; f) Confidentiality; g) Professional Bodies whose ethical policies apply to this research.

You must include a statement under each heading, indicating how you will ensure this research addresses each clause of Plymouth University's Principles for Research Involving Human Participants. **(Please note that your application will be returned to you if you have not done so, thus holding up the approval process).**

Ethical Protocol
The following statement details the ethical protocol that this project's human participant work will adhere to. See section 5 for detail of **METHODS**.

a) **Informed Consent**
METHOD 1:

The participants for these interviews will be sourced from within this projects business partner group, one of which includes building surveyors. Initial contact will be made through the business partner main contact before consent is sought from the intended participants.

METHOD 2:
The participants for these walk past surveys will be sourced from within this projects business partner group, one of which includes a housing association in Cornwall. Initial contact will be made through the business partner main contact. The survey methodology will be developed in coordination with the business partner contact, who will advise on property locations, occupant sensitivities etc.

All property residents shall be contacted for their informed consent. Also residents will be given an information sheet so that they understand what will occur and that these images will not invade their privacy (infrared is not x-ray for example).

b) Openness and Honesty
METHOD 1:
Initial communication will outline the aims and content of the interviews in as open a manner as possible. Furthermore participants will receive the questions prior to interview and will be asked if they would permit the interview to be recorded using a Dictaphone.

METHOD 2:
The issued information sheet will explain in an open and honest manner how this survey methodology will be performed and for what purpose.

c) Right to Withdraw
METHOD 1:
At every stage of the process participants will be offered the right to withdraw or not answer certain questions if they wish.

METHOD 2:
The information sheet shall outline that residents have a right to withdraw at any time during the process. Residents will be able to email or phone myself to withdraw or find out more information.

d) Protection from Harm
METHOD 1:
At no point in the interview process will the participants be placed in harm. Interviews will be conducted in the participant’s office environment or over the phone.

METHOD 2:
At no point in the survey process will any of the participants (tenants or home owners) be placed in harm. These surveys will undertake external thermography only and not involve any human interaction during the survey process.

e) Debriefing
METHOD 1:
Following the interview process participants will have explained to them again the purpose of the interview and the intended use of their responses in the broader scope of

the overall project.

METHOD 2:
Analysed images will only be shared with the business partner contact (though not the tenants) for their information and potential benefit, though no liability will be accepted, nor advice given for follow up action.

f) **Confidentiality**
METHODS 1 and 2
Participants will be informed of their anonymity and confidentiality. No personal details will be published in any form during this project.

g) **Professional Bodies whose ethical policies apply to this research**
METHODS 1 and 2
Not applicable.

NB: If you have indicated that you will be using Information Sheets or Consent Forms, etc. you must attach an indicative draft version to this application.

Note that deception is permissible only where it can be shown that all three conditions specified in Section 2 of the University's Ethical Principles have been made in full. Applicants are required to provide a detailed justification and to supply the names of two independent assessors whom FREC can approach for advice.

*Applicants **MAY** choose to write "not applicable" under the "Relevant Professional Bodies" heading. However, if based on the information written in other sections of the form, FREC considers a particular professional code to be of relevance, then the Committee may make its consultation and adherence a condition of acceptance. The committee strongly recommends that prior to application, wherever possible, applicants consult an appropriate professional code of ethics regardless of whether or not they are members of that body (for example, Social Research; Market Research Society; Oral History Society; British Sociological Association, etc.)*

6. **Attachments** (please place an X beside all that are relevant):
   a) Information Sheet X
   b) Sample questionnaire(s)
   c) Sample set(s) of interview questions X
   d) Consent or release form(s)
   e) Other (please describe)

7. **Declarations:**

For all applicants, your signature below indicates that to the best of your knowledge and belief, this research conforms to the ethical principles laid down by the University of Plymouth and by the professional body specified in 6 (g).

For supervisors of PGR students:
As Director of Studies, your signature confirms that you believe this project is methodologically sound and conforms to university ethical procedures.

	Name(s)	**Signature** (electronic is acceptable)	**Date**

	Applicant	Matthew Fox		
	Other Staff Investigators			
	Director of Studies (if applicant is a postgraduate research student):	Pieter De Wilde		

Completed Forms should be forwarded BY E-MAIL to Sue Matheron (Susan.Matheron@plymouth.ac.uk) Senior Administrator, Research and Graduate Affairs no later than 2 weeks before the meeting date.

You will receive approval and/or feedback on your application within 2 weeks of the meeting date at which FREC discussed this application.

Appendix I. Information Sheet. [See Section 7.1.1]

This appendix presents the information sheet, which was sent to potential participants of the walk-through thermography surveys.

Plymouth University Research Project using Thermal Imaging

Dear resident,
My name is Matthew Fox and I am a researcher at Plymouth University investigating defects in residential properties using **thermal imaging**.

As part of my research, I would like to have a look at your house from the outside with a thermal camera. The process is very quick and simple!

Thermal imaging needs to be done at **night**, when it is **cold** and **not raining**, so I would plan on viewing participating properties on one evening that has suitable conditions over the next couple of weeks.

On the night one thermal image will be taken of only the front of your house before we move onto the next house, as shown in the diagram below.

You do not need to be in, nor do you need to interact in any way during the process. Though if you do happen to see someone outside your home with a camera, it will be myself and for identification I carry a Plymouth University ID card.

I would like to know if you would be happy to participate in this research. If you consent to having your property imaged with a thermal camera, please email me at matthew.fox4@plymouth.ac.uk or phone me on 07957471025. If I do not hear from you, I will not include you property.

If you would like to participate, I will email a copy of your properties thermal image. The images from this work will form part of my PhD research and all names and addresses will remain anonymous.

If you wish to opt out from this research at any time during the process (even after you have granted consent), you are welcome to contact me via the details below and I will end your participation.

Thank You,
Matthew

Example street view thermal image

What is Thermal Imaging?

While a normal camera looks at light, thermal cameras look at heat. This process is commonly referred to as *'Thermography'* or *'Thermal imaging'.*

Thermal cameras are used for many different applications, including detecting fires in buildings, problems with machinery and for electrical problems.

Thermal imaging is also perfect for helping us to identify problems in buildings. It can show heat lost from walls, windows, doors and roofs as well as many other building related problems.

It is important to note that thermal imaging only measures the surface temperature. It is not x-ray, so cannot see through building materials.

If you would like to know more about thermal imaging, please get in touch via the contact details below!

Matthew Fox
Room 301
Roland Levinsky Building, Plymouth University
Drake Circus, Plymouth
Devon PL4 8AA
United Kingdom
Email: matthew.fox4@plymouth.ac.uk
Telephone: 07957471025

ENVIRONMENTAL
BUILDING
WITH
PLYMOUTH
UNIVERSITY

Figure 133. Information sheet for walk-past thermography surveys.

Appendix J. Copies of publications

COMPARING TRANSIENT SIMULATION
WITH THERMOGRAPHY TIME SERIES

Matthew Fox[1], David Coley[2], Steve Goodhew[1] and Pieter de Wilde[1]
[1]University of Plymouth, Plymouth, UK
[2]University of Bath, Bath, UK

ABSTRACT

Thermography is an emerging technology used by construction professionals focused upon the thermal and condition performance of buildings. However, the interpretation of thermal images is difficult and often misinterpreted. This paper reports on initial work that compares thermographic images from relatively simple experimental setups with transient models of the same experiment. Thermographic images were obtained from a FLIR ThermaCam S65 while simulation was undertaken using the Voltra transient heat transfer program. The work highlights some of the inherent problems with interpreting thermal images of actual buildings, and suggests how these comparisons can provid a better understanding of real-life material performance.

INTRODUCTION

In 2010, the European Union published legislation aimed at significantly reducing the energy use of buildings, which at present are for approximately 40% of the total EU energy consumption (European Union, 2010). This has given significant impetus to improvements in construction and material standards as new and existing buildings endeavour to become more energy efficient than they were in the past.

As more ambitious targets, such as the UK's aim of 80% reduction in carbon emissions by 2050 (DECC, 2011) are unveiled, more stringent building standards have been introduced to help achieve them. Part L of the England and Wales Building Regulations sets out a number of standards dealing with the *conservation of fuel and power in buildings* (HM Government, 2010), including standards related to the thermal transmission of the building fabric and CO_2 emissions. The underlying basis for the assessment of the thermal building performance in these standards is typically a semi-stationary heat flow calculation.

Within this context, building professionals are starting to address the existing building stock. They employ various approaches to assess actual buildings and to identify defects, such as visual inspection and long-term measurement. This work is highly relevant as most of the built environment remains in use for a long time, resulting in a significant impact on overall energy use and/or carbon emissions. However, it takes place in a completely different context, where heat flows are changing dynamically due to continuous changes in weather and operational conditions, where often construction details are unknown, and defects are prevalent. Although calculating the thermal performance of a building based on steady state conditions is useful for assessing design conditions, it is not suitable to assess the actual condition and performance of a real building envelope. Conditions such as moisture in walls or heat stored within thermally massive building components (Hart, 1990) can change the material properties on a dynamic basis, which in the case of moisture in walls, could damage (Mumovic et al., 2006) and reduce the overall performance for a given construction system.

Thermography is an emerging technology used by construction professionals as a non-destructive tool focused upon the thermal and condition performance of buildings (UKTA, 2007). A thermal camera detects infrared (IR) radiation, which is emitted from the surface of an object and converts this into a thermal image (Hart, 1990). Thermographers generally record IR data as single instantaneous images. This aligns with a stationary perception of buildings, where temperatures can be used to assess heat flows. Unfortunately, this leaves the potential for misinterpretation. Transient conditions such as thermal mass and dampening effects are not always visible in instantaneous thermal images (Pearson, 2011) due to time scales for such environmental changes. Some thermal cameras also have the ability to record movie sequences and time-lapse images. This affords the thermographer the ability to observe the change of thermal surface conditions of the structure over a prolonged period (Drollett, 2001). However, the normal approach in building surveying practice is to use single images, which represent only one point in time.

This paper reports on initial work that is part of a research project, which seeks to develop a deeper understanding of thermographic images of buildings, including the relation between single time-frame images and the on-going transient heat-flow process where indoor and outdoor environmental conditions are in constant flux.

OBJECTIVE

Before embarking on the studies of real buildings, which come with complex multi-layered and three-dimensional envelopes that behave dynamically within a constantly changing environment, this paper studies the dynamic behaviour of simple monolithic material samples.

It aims to compare time-lapse thermographic images of four material samples with simulated transient models of the same experiment to observe a correlation between the results. This will help to build an understanding for transient thermographic and simulative investigation, and will then form the basis for future investigations into more complex situations including building case studies.

The use of transient simulation software presents opportunities to observe heat flow through the layers of the model and these layers can reveal hidden components for further investigation. This is in contrast to thermography, which can only assess the surface of an object. At the same time, modelling rests on a number of assumptions, with thermal camera readings pointing out issues that might need further development.

METHODOLOGY

In order to begin comparing transient thermography with simulation, a relatively simple experiment was devised, which enables sample materials to warm up over a period of time and results compared between the two experiments.

The experiment consisted of a physical model, which was replicated in Voltra software; for further details see details below. Materials were chosen that are representative of materials commonly found in UK buildings. The materials used in this experiment were:

- Brick
- Concrete Block
- Delabolle (Cornish) Slate
- Sanded softwood

Physical thermography experiment

Thin slices of the sample materials were positioned within a purpose built timber frame, which allowed the materials to be uniformly heated from behind with a 31W electric heating mat and copper plate to ensure even distribution as shown in figure 1 below. This would provide a sufficient temperature difference across the samples as required for thermographic investigations (BSi, 1999).

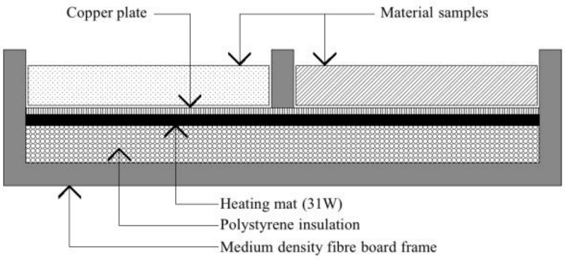


Figure 1 Section through the test board

In order to minimise any adverse environmental conditions that the building materials commonly face, the experiments were conducted in a semi-controlled internal environment, i.e. a room held at constant temperature of roughly 16°C.

Initially all the material samples were at a stable temperature in the 15 – 17°C range. The heating mat was then switched on, providing a continuous power of 31W during the experiment, and a series of thermal images were recorded every 5 minutes to record the warming up of the materials. After a period of four hours, the heating mat was turned off and left for a further hour to record the cooling down of the materials.

A FLIR ThermaCam S65 with a built-in 36mm lens, last calibrated by the UK's National Physical Laboratory in December 2010 across the temperature range of -5 to 100°C, was positioned 500mm from the test board. The internal temperature was recorded at 16°C with a relative humidity of 60% and a reflected apparent temperature of 17°C. To minimise the impact of reflected IR radiation from other sources, the test board was angled slightly so that the IR radiation from the camera (and operator) would not be reflected in the materials, and a fabric curtain was used to cover other potential sources of reflected IR radiation.

Figure 2 Photo of the experimental setup, thermocouples and IR camera

To analyse the samples using the IR camera, a box measurement tool was used for each material, to obtain an average temperature over the area of the box, which was close to (but not over) the area covered by the duct tape.

In addition, thermocouples were attached to the surface of each material with insulation tape to measure the actual surface temperatures (figure 2). To aid the accuracy of the thermocouples, heat sink compound was used between the surface and the tip of the K-type thermocouple.

Each material had its emissivity measured in accordance with the FLIR measurement procedure (FLIR, 2011). These were recorded and inputted into the *QuickReport* analysis software (FLIR, 2009)

The emissivities recorded for each material were:

- Brick (emissivity 0.97)
- Concrete Block (emissivity 0.98)
- Delabolle Slate (emissivity 0.86)
- Sanded softwood (emissivity 0.95)

The dimensions of the samples were 100 x125mm. Each had a thickness of 20mm, apart from the slate, which had a thickness of 5mm. These dimensions are based on practical considerations, with brick, concrete and wood cut to a relatively thin slice, whereas the slate was provided with the thickness given.

Where the first experiment observed the heat transfer through naturally dry materials, a second identical experiment was undertaken using the same materials, which had been moistened for an hour.

Simulated experiment

The environmental modelling software that was chosen for the simulation experiment was the Voltra simulation program from Physibel (Physibel, 2005). Voltra was selected because it is capable of transient analysis for material and construction details in 3D. It is one of very few 3D, transient cold bridge analysis tools presently available (US Department of Energy 2011).

Within Voltra, the test board and materials were modelled to match the experimental setup (figure 3). To simulate the heating mat turning on and off, a step function was set for the power output from the 31W mat. This step function was then applied to a series of node boundary conditions that had been evenly spaced within the heating mat layer on the model to provide a uniform distribution of heat.

Output nodes were positioned centrally at the surface of each material in order to record the temperature outputs from each material.

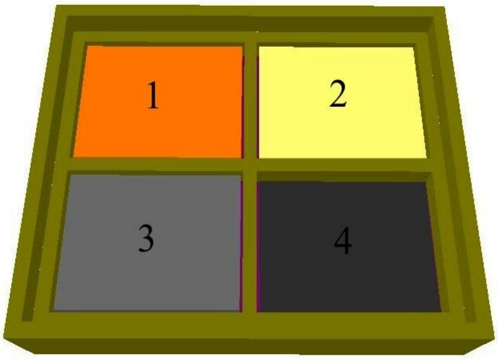
The simulation was then run for the same heating up and cooling time steps as the physical experiments and temperature readings were made every 5 minutes in line with the physical recordings.

Variation and analysis process

The comparison between the thermography experiment and the Voltra simulation was carried out twice: once under typical dry conditions, and once where the material has been made wet. This was done in order to test the generic assumption that thermal imaging of buildings should not take place during when the materials are wet. This yields the following experiments:

- DIR – Dry InfraRed (Physical experiment)
- WIR - Wet InfraRed (Physical experiment)
- DV – Dry Volta Experiment (Simulation)
- WV – Wet Voltra Experiment (Simulation)

Following this approach data was collected (both images and numerical data). The numerical data was then plotted within graphs to illustrate the warming up and cooling down phases of the material samples.



1. Brick, 2. Softwood, 3. Concrete block,
4. Delabolle slate

Figure 3 3D view of test setup modelled in the Physibel Voltra software

RESULTS

The dry experiment was undertaken initially and provided an indication of the thermal performance for each material sample. The samples were left for 20 minutes, before being warmed up for four hours and left to cool down for a further hour. Figure 4 shows the dry IR camera survey (DIR) data for the material samples over this experimental period.

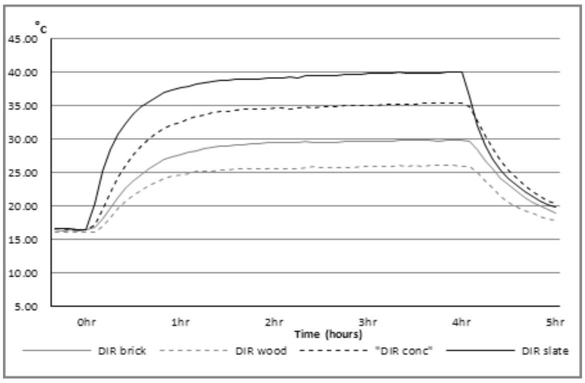


Figure 4 Dry experiment, IR camera apparent surface temperature

Figure 4 also shows the difference in performance between the four material samples.

Thermocouple data also recorded surface temperatures for each material sample, which were consistent with the IR data.

Following the DIR experiment, the same setup and test parameters were modelled and simulated within Voltra to compare with the IR camera results.

Table 1 shows the material properties that were used within the dry Voltra (DV) experiment. Properties for each material were sourced from data contained within the Voltra software, engineering toolbox website (engineering toolbox, undated) and from a BEPAC research report (Clarke, 1990).

The specific properties, thermal conductivity, density and thermal capacity for each material were chosen in order to best allow a comparison to the DIR experiment.

Table 1 Material properties used in Voltra

	Thermal conduc.	**Mat. density**	**Specif. heat capaci.**
Material samples	W/mK	kg/m^3	J/kgK
Brick	0.340	2403	1050
Softwood	0.180	700	1600
Concrete block	1.000	1400	1000
Slate	1.500	2700	1000
Test board			
Fibreboard	0.070	250	1700
Heating mat	25.000	7850	480
Polystyrene	0.035	25	1400
Copper plate	401.000	8930	390

The internal room environment was also modelled within Voltra, with a boundary temperature of 16°C and surface heat transfer coefficient of 17.5W/m^{2}K. Again, the heat transfer coefficient parameter was adjusted several times before a situation arose that emulated the physical experiment.

Figure 5 illustrates a selection of key time stages of visual data within Voltra and captured with the IR camera. Although the colour coding representing the temperature gradient is different between the two, (the ability to directly match the colour coding is limited by the thermographic software and the limited pallet available from the simulation software), there is a visual correlation between the experiments. This correlation was further investigated through the production of graphs.

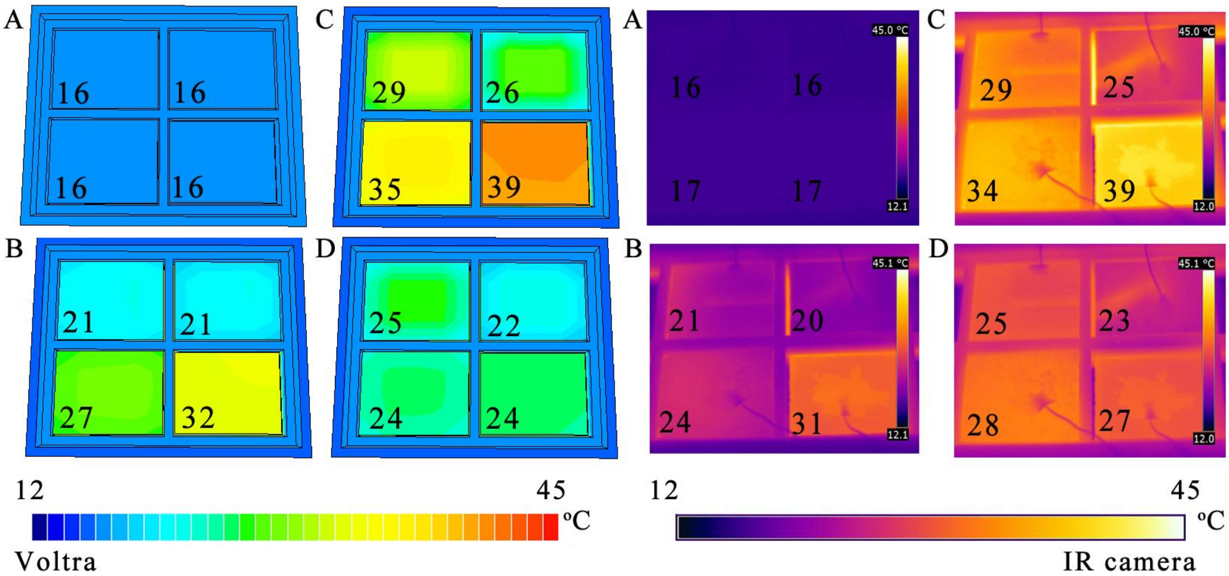


Figure 5 Comparison between Voltra and IR camera image data. Measured temperatures given for each material square. Time periods: A – 0 minutes, B – 40 minutes, C – 100 minutes, D – 280 minutes.

To explore the effects of moisture within the selected materials, a second physical experiment was conducted once the material samples had been moistened for an hour. The data from this wet IR experiment (WIR) was then plotted along side the data for the DIR and DV experiments, so that comparisons between the three could be made. Figures 6, 7, 8 and 9 show DIR, WIR and DV data for each sample and also include the dry thermocouple (DT) and wet thermocouple (WT) data for each sample, which was recorded as a check of the IR data.

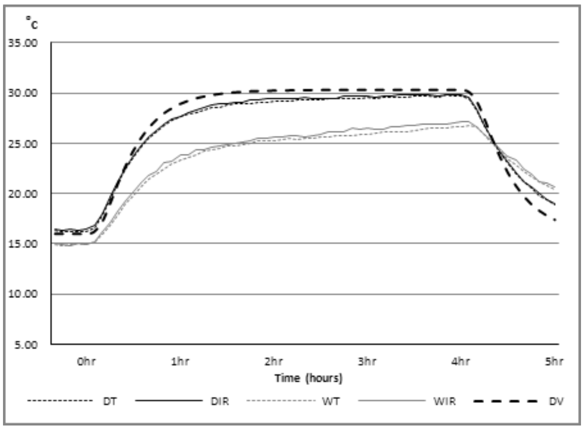


Figure 6 Brick material sample surface temperature

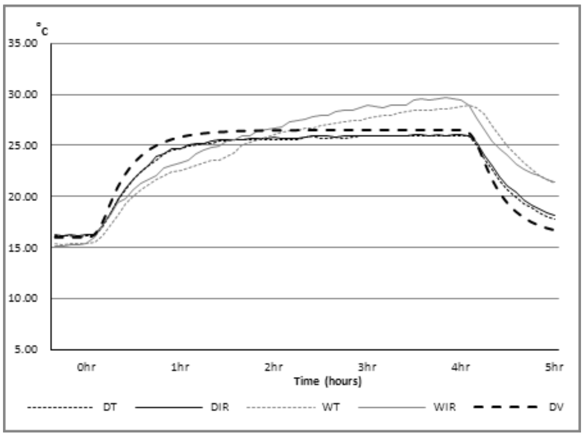


Figure 7 Softwood material sample surface temperature

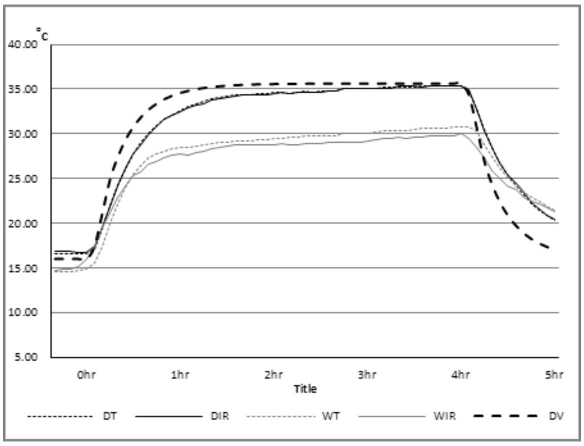


Figure 8 Concrete block material sample surface temperature

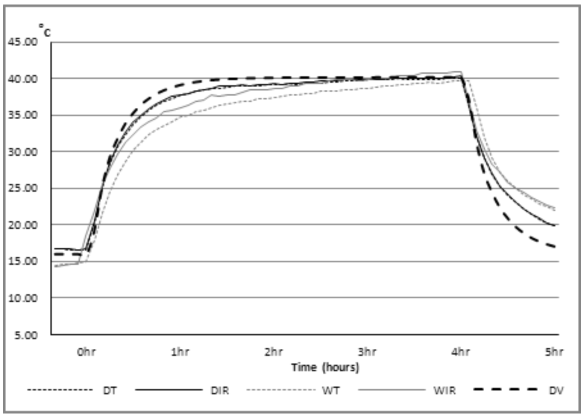


Figure 9 Delabolle slate material sample surface temperature

Comparing the DIR and DV results

Comparing figures 6, 7, 8 and 9, patterns within each experiment could be observed between the material samples. For each material the DV samples appeared to warm up at a faster rate during the initial heating phase than the DIR samples.

Once the DV sample had reached its highest temperature, it maintained this until the heating mat was turned off. The DIR samples however showed a small steady rise in temperature once they had past the initial rapid heating phase.

At the end of the 4-hour heating phase, the mat was turned off and a cooling period of an hour was recorded. This cooling phase showed that the DV samples cooled at a faster rate than the DIR samples.

The faster warming up and cooling phases for the DV samples suggest that some of the material and environmental properties used in Voltra may not correctly simulate the actual properties of the physical experiment. This observation highlights an issue when comparing real experimental data with software., The level of match between the experimental material and environmental properties with the software's possible choice of parameter values will need to be further investigated in light of these findings.

Another observation was related to the softwood timber sample. As the sample reached a higher temperature, the thermal image (figure 10) showed a brighter patch within the sample. This was actually a knot within the sample and would be difficult to accurately model within the software.

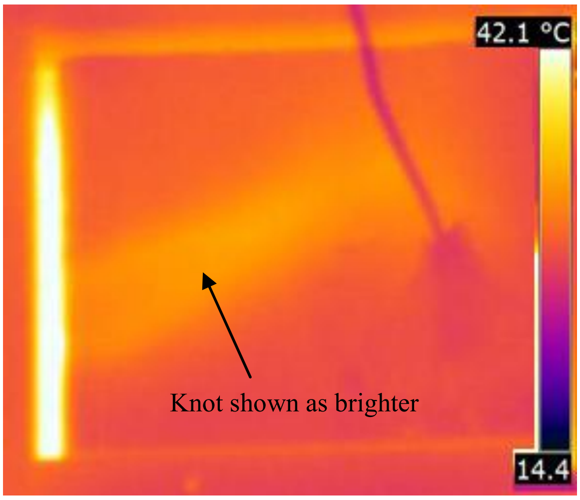


Figure 10 IR image of softwood material sample showing anomaly due to knot within the sample.

Comparing WIR with DIR results

Reviewing the data from the WIR experiment, it can be observed from figures 6, 7, 8 and 9 that when the samples were damp, the initial heating phase took longer than the DIR experiment. Actual results depend on the amount of water that is present in the sample, with brick and concrete showing a different pattern from wood and slate. Following this phase, the WIR samples showed a sharper rise in temperature over the 4-hour heating period than the DIR samples, this was due to the materials drying out over the heating period.

Brick (figure 6) and concrete block (figure 8) show a lower temperature over the duration of the heating phase for the WIR. It was observed that these materials were still damp at the end of the heating phase and account for this lower temperature.

Although having a longer initial heating phase, the WIR delabolle slate sample (figure 9) showed a temperature profile that ultimately matched the DIR data, which would suggest that the moisture on top of the slate had evaporated. Due to the impervious nature of slate, this would seem plausible.

The cooling down phases for all of the WIR samples was shorter, and had a steeper gradient, which would be expected from damp materials in comparison with their dry counterparts.

Attempts were made to try and simulate the WIR experiment within Voltra. Material properties were adjusted to replicate the moisture within the samples, however it was assumed that over the duration of the WIR experiment that the samples material properties would be constantly changing as they dried out from their initial damp state, and that certain parts of each sample would dry out differentially.

CIBSE applications Manual, AM11: 1998 describes this variance in material thermophysical properties as a source of uncertainty within modelling software, and this did indeed prove to be a limiting factor within the Voltra software, which was unable to replicate the drying out conditions, and therefore ruled out this proposed experiment.

CONCLUSION

This paper presents a comparison of simulation efforts with the results of time-lapse thermographic images. In both cases four simple material samples where heated and both warm-up and cool-down behaviour was observed. This comparison was undertaken in order to better understand thermal images, and is stage one in a broader project that looks at identifying the performance – and potential defects – in actual buildings.

The results demonstrate how undertaking simulation in combination with thermography might help thermographers and building designers to better understand the complex behaviour of building fabric, even for simple monolithic material samples under known conditions.

From the perspective of a thermographer, the level of information that can be gained from thermal images is important. Much of the industry perceives thermography as a 'relative' tool (Pearson, 2011), observing colour gradients through the IR camera and using their experience and best judgement to interpret what they are seeing. However, the work presented here hints that it might be possible to use thermography to quantify thermal behaviour far better than this, especially if coupled with simulation expertise.

The experiments presented highlight the difficulties in selecting accurate parametric data to enable precise analysis. Not only in terms of environmental conditions, but also in relation to material properties, which could have anomalies such as fractures or areas of non-homogeneousness within them, such as the softwood sample in this experiment (figure 10).

Furthermore, since difficulties were encountered when selecting parametric data for this relatively simple experiment, a larger scale real life building would present more issues related to refining parameters for circumstances where there will likely be multi-layer elements.

In relation to effective thermographic work using thermal cameras to conduct comparable experiments alongside simulations will enhance the understanding of the thermal processes and assumptions underlying both approaches.

From the perspective of transient analysis, this study demonstrates the importance for longitudinal investigation of material behaviour over a prolonged period, where there are changing conditions. The thermographic experiments in this study proved successful in demonstrating the transient heat flow from both the dry and wet samples.

Voltra proved useful in simulating and assessing the heat flow through the dry samples, and presents a strong case for undertaking transient simulation of materials and constructions for analysis and design.

The actual software used in this work appeared less able to simulate dynamically changing conditions such as the wet experiment, where moisture had a non-stationary impact on the materials properties. Other transient thermal analysis software such as WUFI could offer an alternative. In this context, it is worth noting that other dynamic environmental conditions such as thermal mass changing under moisture content might also present difficulties for transient simulation.

Overall, this study demonstrated that although it is difficult to model a real life situation, doing so presents great benefits to better understanding the performance of a material or building fabric, when used in combination with measurements such as thermography.

Caution should be urged when scaling this experiment up to real life building examples, since other parameters might begin to feature that are not present in semi-controlled conditions. Conditions such as changes in occupancy and weather might combine in a cocktail of parameters that have an impact over a multi-layer structure.

It is this precautionary warning that makes such transient analysis through thermography and simulation even more important. Specifically for construction professionals, if they are to gain a deeper understanding of the thermal performance for their buildings, this is particularly important, since more common design based ‘steady state’ fabric analysis belies the real life performance of the building during frequently changing environmental conditions. Therefore this work has the opportunity to raise awareness of transient analysis and some of the methods available to observe and understand this.

FUTURE WORK

Having reviewed the outcomes from this study, there are a number of areas for potential further investigation that this wider project might follow.

The relatively simple experiments undertaken for this study have proved to be very useful for determining base-line calibration data for single layer samples that can be used in future work. Additionally this experiment has also provided a methodology, which could be replicated for multi-layer material build-ups using a similar experimental procedure.

Another area of future work would be through scaling up these experiments to observe transient effects on real life construction case studies as discussed in the conclusion.

Where this study looked at using the Voltra transient simulation software for comparing with thermal data, it would be useful to compare with other, similar, software. In particular it would be useful to identify whether there is a transient simulation tool currently available, which is able to observe transient environmental conditions such as moisture or thermal mass in walls. Other forms of software might include ‘Therm’ (Lawrence Berkeley National Laboratory, 2012) or ‘MATLAB’ (Mathworks, 2012).

ACKNOWLEDGEMENT

The research reported in this paper is funded through an ESF-CUC (the European Social Fund – Combined Universities of Cornwall) Studentship Grant, Project Reference 11200NC05/CUC/Phase2.

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Title: *Thermography Methodologies for Detecting Energy Related Building Defects*

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Abstract

Thermography is becoming more widely used amongst construction professionals for energy related defect detection in buildings. Until quite recently, most of the research and practical use of building thermography has centred on employing a building walk-around or walk-through methodology to detect sources of unacceptable energy use. However, thermographers are now creating new building thermography methodologies that seek to address some of the known limitations, such as camera spatial resolution, transient climatic conditions and differences in material properties. Often such limitations are misunderstood and sometimes ignored.

This study presents a review of the existing literature, covering both well-established and emerging building thermography methodologies. By critically appraising techniques and observing methodology applications for specific energy related defects, a much clearer picture has been formed that will help thermographic researchers and thermographers to decide upon the best methodology for performing building thermography investigations and for the invention of new approaches.

Whilst this paper shows that many of the different passive building thermography methodologies seek to address particular building issues such as defects and energy use, it has also demonstrated a lack of correlation between the different methodology types, where one methodology is often chosen over another for a particular reason, rather than making use of several methodologies to better understand building performance.

Therefore this paper has identified the potential for using several passive building thermography methodologies together in a phased approach to building surveying using thermography. For example, a less costly and faster survey could be conducted to quickly identify certain defects before enabling more time consuming and expensive surveys to hone in on these with greater detail and spatial resolution if deemed necessary.

Key Words
Building thermography methodology, defect detection

1. Introduction

Buildings are estimated to be responsible for 40% of the EU's total energy consumption [1]. Legislation has given greater impetus for improvements in construction and material standards, as new and existing buildings endeavour to become more energy efficient. This is further strengthened through the UK government's carbon reduction targets of 80% on 1990 levels by 2050 [2]. Although this target aligns more with energy performance than building defects, it can be argued that heat loss from defective building components such as thermal bridging and draughts directly relate to a building's overall energy performance [3, 4]. Space heating accounts for over 60% of domestic energy use in Britain [5] and with energy prices rising [6], conserving heat can contribute to improved comfort levels, lower energy bills and fewer households experiencing fuel poverty.

Many non-destructive methods and tools are currently available for building energy use investigations [7], including heat flux measurement, co-heating tests, automated meter reading, air-tightness testing and computational simulation, each one addressing a particular aspect of building performance. As an emerging technology within the construction industry, thermography is another tool which can be used to help identify common sources of heat losses in existing and new buildings, such as those from ventilation and conduction [8]. Figure 1 shows an example thermal image of the Plymouth University campus. Unfortunately, thermal images are often misinterpreted, especially where thermal mass, reflections and moisture might have an impact on readings and thermal performance.

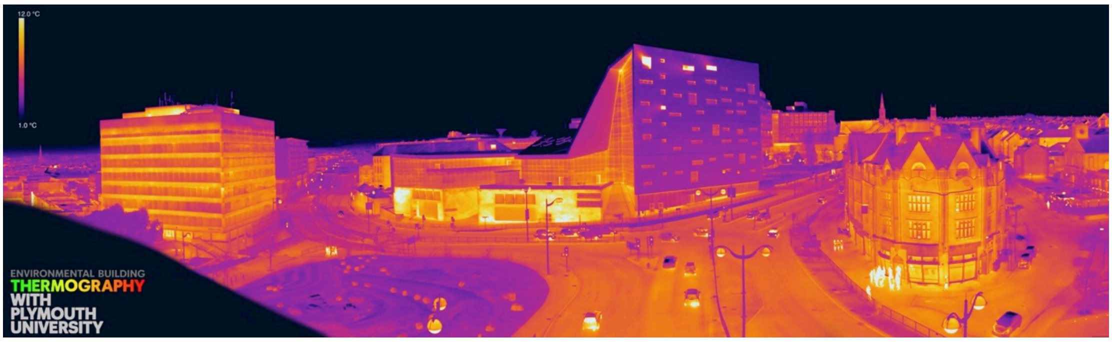


Figure 1. Thermal image of Plymouth University campus.

Currently, thermography professionals and academics are undertaking work which seeks to develop new methodologies for detecting defects and to measure the thermal performance of existing buildings using building thermography. This paper seeks to review and compare the differences between current passive methodologies.

2. Thermography for Building Analysis

In 1800, astronomer Sir William Herschel discovered the infrared portion of the electromagnetic spectrum [9]. This was utilised in 1840 by Herschel's son, Sir John Herschel who utilized carbon and alcohol to record an image called a 'thermograph' [10]. Following this initial work thermographic development was primarily for military purposes [11]. It wasn't until 1966 that the first commercial real-time thermal cameras became available. Being very large and heavy, they required cooling with materials such as liquid nitrogen and compressed gas [12] and were not widely used for construction purposes until the 1970's and 80's [13].

With a reduction in unit size, increased portability, lowering costs and the introduction of uncooled microbolometers in the 1990's [9], thermal cameras in recent years have become less designed with scientific applications in mind and more commercially focused [12], particularly within the construction industry [14].

Thermal cameras are used to detect infrared radiation, which is emitted from the surface of an object and converts this into a readable thermal image [15]. Providing there is a sufficient difference in heat and or mass transfer across a material or building fabric, thermography can be used as a tool to quickly identify building defects without the need to undertake costly and possibly damaging physical exploratory investigations. Other key benefits to modern day thermal cameras include having digital image collection, in camera evaluation, non-contact, real-time and permitting multi-point detection [16-19].

2.1 Scientific parameters

Although thermal cameras measure surface radiation rather than actual temperature [20, 21], it is this processed reading of temperature that is important to thermographers as changes in temperature reading help to indicate potential anomalies. The temperature viewed by the camera is known as the apparent temperature, which is the temperature that is apparent to the camera under the conditions at the time. Furthermore the apparent temperature is only that of the targets surface [22].

The reason why temperature measurement can only ever be apparent is because of several influencing factors, which include differences in surface emissivity, internal and external climatic conditions and reflected apparent temperatures. Much has been written on these the scientific parameters that impact on thermographic results, and for a deeper review of these, documents by BSi [23], FLIR [11], Hart [24], Pearson [25], Vollmer & Möllmann [9] and UKTA [8] should be referred to.

These factors have the potential to cause interpretation challenges since they can contribute to a misunderstanding of thermal patterns in images. Indeed learning how to read, identify and categorise defects based on their pattern characteristics is one of the most challenging aspects of thermography [9, 26]. Gonçalves *et al.* [27] argues that because of interpretation difficulties using thermography, defects cannot be definitively distinguished unaided by other equipment or investigation. Also Brady [28] and Hart [24] urge caution over the reliance on thermal patterns since environmental conditions, building orientation and incorrect camera settings (such as emissivity or reflected apparent temperature) can impact on the quality of thermal images.

2.2 Thermal resolution

In addition to the scientific parameters, the thermal resolution of the sensor dictates the ability for a thermographer to successfully observe and detect building defects. Jensen [29] discusses resolution in terms of data acquisition using remote sensing, such as thermography, and explains that there are four key areas of thermal resolution:

- **Spectral resolution**
- **Spatial resolution**
- **Radiometric resolution**
- **Temporal resolution**

Camera's that are used for building thermography tend to utilise a **spectral resolution** of long wavelength infrared radiation (8-14µm) within the electromagnetic spectrum. This is because this portion is less subject to solar reflectance problems [16].

Spatial resolution refers to the smallest discernable target that the detector can measure [29]. If too small, the target may not be detected or the sensor might not be able to quantifiably measure it well enough [17].

One factor that dictates spatial resolution, is the size of the detector array [30], where a greater number of pixels in the array equal an improved spatial resolution [16]. Typical large detector arrays for construction related cameras hold between 60x60 and 640x480 pixels. Detector field of view is another dictating factor and refers to the total area (horizontally and vertically [31]) detectable by the camera [9]. Yet to determine what the smallest discernable target a detector pixel can perceive [30], a measurement known as the instantaneous field of view (IFOV) is used. Where the smallest value will equal a greater spatial resolution, if an observed target is too small for a pixel with a high IFOV, it is unlikely to be detected [16, 17].

Radiometric resolution refers to the smallest temperature differential, which can be perceived by the cameras pixels [32]. Also referred to as 'thermal sensitivity', measurement is known as the Noise Equivalent Temperature Difference (NETD), which is the temperature sensitivity of the noise from either the detector or measurement system [33, 34] measured in degrees millikelvin (mK). Schwoegler [30] suggests that an NETD of at least 100mK is required as a maximum, though a smaller NETD will equal greater detector sensitivity.

Temporal resolution relates to the image refresh frequency of the camera [29]. Holst [32] recommends a typical frame rate of about 25 – 30Hz, though at low frequencies it becomes harder to hold the camera still, risking camera shake, blurring and reduced image quality.

Costs rise with improved thermal resolution [35]. While a relatively low specification thermal camera of 60x60 pixels might sell for under £1000 [36], it is likely to be too poor for building surveys due to the relatively large distances from camera to target involved, and will likely experience the effects of optical scattering [17], which will make it more difficult to discern small surface temperature differences. Cameras meeting the UK Thermography Association [8] recommended minimum standards of at least 40,000 pixels, such as 640x480 pixel cameras and that hold an NETD of at least 0.2°C currently exceed £5000.

2.3 Determination of building thermography methodology

Before a building thermography inspection, thermographer's first need to question what principle methods they will use for analysis. This decision process will be shaped by the questions posed in figure 2.

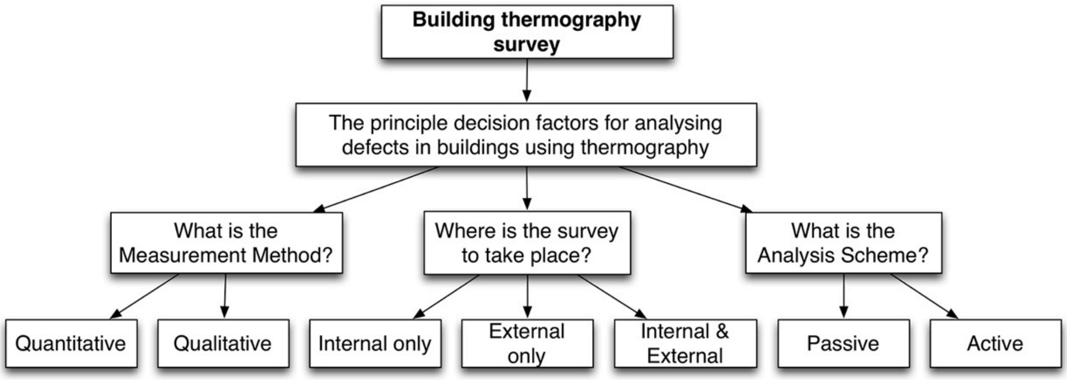


Figure 2. Key decision-making process for the determination of building thermography methodology. This figure has been based upon the author's training and hands-on experience of surveying buildings in the UK.

Analysis Schemes

Two commonly used analysis schemes exist for building thermography: ‘Passive’ and ‘Active’. Active thermography is where an external stimulus, such as a burst or gradual rise in heat is exerted on the object observed [37, 38]. This serves to induce an effect within the material that can help to better visualise a hidden defect [39, 40]. Conversely, passive thermography is where the target being observed is at its normal temperature state [41].

Although active thermography offers a useful insight into sub-surface defects [42], a drawback to this methodology is that prior knowledge of the defects existence is usually required before analysis. Also active thermography tends to focus on detail areas of a building’s fabric, where specific defects are closely examined. Work by Maierhofer *et al.* [43] offers one example where active thermography was used to focus on specific subsurface defect locations within historic buildings. However because most building thermography surveys observe the entire building fabric, looking for unknown defects, without the aid of artificial stimulus (aside from internal climatic control typical of the occupant’s normal behaviour), it is considered [20, 44] that typical building thermography surveys are conducted under a passive scheme.

Measurement Methods

There are two methods of measuring thermal images, ‘Qualitative’ and ‘Quantitative’ analysis. Qualitative analysis in thermography is the visual evaluation of colour patterns within a thermal image, which represent differences in measured radiation [17]. Thermographers need to be able to read thermal patterns in images in order to decide whether these patterns are showing potential problems not.

Quantitative analysis adds to this by seeking to quantify thermal gradients for numerical analysis [16]. This is possible due to the ability for each pixel within a thermal camera to give a calculable apparent radiation value. Although many thermographers use a quantitative measurement method for building analysis, such as the determination of thermal transmittance [45, 46], there are others, who caution against the use of thermography as a quantitative tool [47], stressing the challenges in achieving meaningful, accurate results within environments that are often anything but steady-state.

Location

Building thermography can be undertaken both externally and internally. External thermography is more susceptible to transient environmental conditions than internal thermography, which provides a much more controlled environment that has slower and less significant climatic fluctuations [48]. Internal thermography requires the occupants permitting access to certain parts of a building, and features such as bookshelves and pictures can impact on the ability to obtain useful thermal images. Thermography experts tend to advise that areas of heat loss observed externally will almost always present themselves more clearly on internal thermography [25].

2.4 Detectable defects

Within the field of building thermography there are broadly two applications: existing building assessments and new build / retrofit quality control inspections [32]. With existing building assessments in mind, there are a number of energy specific defects or performance aspects that building thermography has been used for, including the identification of:

- Ventilation losses

  It has been suggested [49] that ventilation losses can account for over half the total energy use in a building. Common areas of air leakage tend to occur around openings (doors and windows) and at the junction between components where gaps might be present [50].

Air-tightness tests are the typical methodology for assessing ventilation losses [51]; though these can struggle to indicate exactly where the losses are occurring. Thermography however holds the ability to qualitatively pinpoint ventilation leaks [52].

- Conduction losses and thermal bridging
  All building components will incur a degree of conduction heat losses, as heat flows from one side of the construction to the other. The amount of heat loss through conduction depends on how insulative the construction is and the temperature difference between internal to external environments. Thermography can be used to check for insulation continuity (in walls, roofs etc.) [24, 53]. It can also detect thermal bridges in buildings, which usually occur at junctions and corners [54].

- Defective services
  Titman [53] discusses this application, describing the usefulness of building thermography for detecting buried and or defective services within old buildings particularly where little or no record is kept.

- Moisture condensation
  Identifying the extent of surface condensation risk is one area of moisture detection amenable to thermography. Undesired air leakage [52] and areas of poorer thermal conductivity [55] can lead to condensation and mould growth on cooler surfaces, which in turn could degrade a material's performance and overall lifespan.

- Moisture ingress
  Penetrative and rising damp, is often associated with moisture from outside of a building entering either parts of the building fabric or the living space, usually via capillary action or sorption and is another application for thermographic inspection [56]. As moisture passes through materials, penetrative damp is likely to degrade materials [57] and impact upon the building's thermal performance through an increase in conductivity and evaporative cooling [9, 58].

  To help overcome problems in differentiating moisture defects and to validate thermographic results, some [28, 41, 59] advocate the use of additional tools such as moisture meters, calcium carbide sampling and in certain situations destructive investigation. However thermography can be a useful tool in directing the use of these other tools and inspection work.

- Structural defects
  Detecting structural defects in buildings is another use of thermography. As well as identifying structural failures such as delaminations [16], locating thermal expansion defects can help to minimise other subsequent defects that might lead to increased energy loss issues.

- Quantitative Energy performance measurement
  Although not a specific defect, heat losses from buildings within a cold climate are a primary concern amongst occupants and building professionals, and are another common application for building thermography.

Work by Fokaides and Kalogirou [45] is one example of performance-based research, where a quantitative measurement method has been used to determine fabric U-Values through the application of thermography. Another example has seen thermographers estimating CO_2 emissions [60].

3. Building Thermography Literature Analysis Methodology

A preliminary literature review using key-words [61] was conducted to determine the current issues surrounding thermography for building assessment. This helped to define a series of knowledge gaps and research questions that could be further investigated through a focused literature review search plan. Results from the literature research led to a broad range of document types including academic journals, governmental guidance notes and commercial web pages. From these, documented bibliographies and references were followed up for deeper investigation [62].

A total of 160 literature sources were collected between the periods dating 1980 to (the end of) 2013. The literature was obtained for two distinct objectives:

Objective 1. To assess the methodology application specific details.
Objective 2. To assess the methodology application occurrence.

Objective 1 sought to determine what passive building thermography methodologies were currently being used, how they were being implemented and for what purpose they were being used. This investigation aimed at better understanding each methodology and how they addressed known limitations to defect detection.

Objective 2 assessed how frequently reported each passive building thermography methodology was amongst the literature for energy related building defects. This objective utilised a methodology matrix, which focused each source into specific categories that could be counted for occurrence analysis. Each source of literature was read and assigned to a specific category based on which methodology was being used or reported on.

3.1 Focusing The Literature

All collected literature was systematically reviewed and categorised based on a series of defined filters (see figure 3) that formed the basis of the key-word search and helped to classify ideas for analysis and further investigation [63]. Some of these filters were based on the key-decision making process diagram (figure 2); whilst others sought to determine the defect type, document type and application methodology.

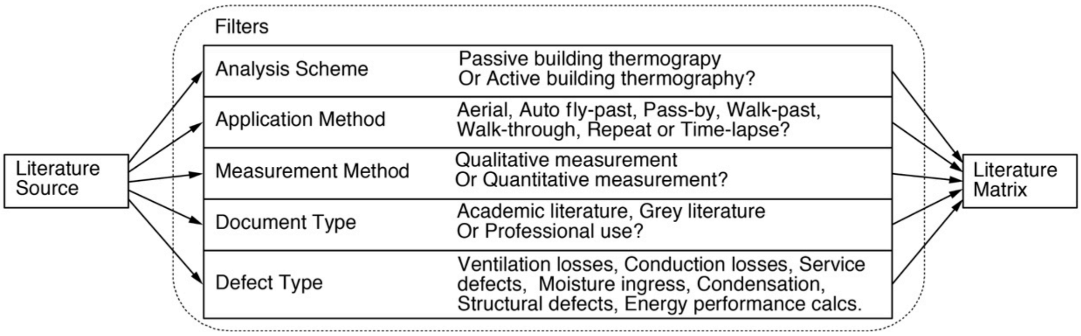


Figure 3. Literature filter diagram.

Analysis Scheme Filter
This filter sought to identify whether the literature was reporting a passive or active thermography analysis scheme. As a result of documented opinions, which state that building thermography employs a typically passive analysis scheme [20, 44], this review specifically sought information on building defects using passive building thermography methodologies. Therefore sources reporting on active building thermography were not included within the literature review matrix.

Application Method Filter
As the main aim of this paper, another filter sought to identify what application methodology the literature was referring to or using.

Measurement Method Filter
An examination of the measurement method looked for indicators as to whether the literature referred to a quantitative or qualitative measurement approach.

Document Type Filter
This filter sought to determine the background to the literature source. Documents were defined as being either from:

- Academic literature. Including published books and peer reviewed documentation such as journal and conference papers. These sources would suggest scientific interest, development and investigation.
- Grey literature. This category deals with informally published literature. Documents such as government or professional guides, legislation or technical reports fall under this category. Grey literature is important because significant developments to passive building thermography have been made under this type of document.
- Professional use. This category collected all the remaining literature sources and specifically included web sites, which report on the implementation of passive building thermography. Because many practitioners perform and help to develop new passive building thermography methodologies, it is important to gain an understanding of their work despite a lack of published material.

Defect Type Filter
Dealing with energy related building defects listed under section 2 of this paper, the aim of this filter was to help indicate which defects were currently being detected by passive building thermography methodologies.

3.2 Literature Review Matrix
Following the focusing process using literature filters, a strategic method of presenting patterns was deemed necessary. For this review a literature synthesis matrix was chosen [64]. This review methodology tool was chosen due to a lack of cross-comparison between much of the passive building thermography literature. Additionally to date there has been no investigation into the effectiveness of detecting defects and how this compares with other passive building thermography methodologies. Using a matrix would allow for a more analytical comparison of each methodology, how they are currently being used, what limitations exist and how comparison links can be made. With reference to work by Klopper

Application method		**Aerial**						
Literature Source		**Academic**		**Grey**		**Professional**		**Total use**
Measurement method	Q1 = Qualitative, Q2 = Quantitative	**Q1**	**Q2**	**Q1**	**Q2**	**Q1**	**Q2**	
Defect type	**Ventilation losses**							
	Conductivity losses							
	Defective services							

Table 1. Cut-away example of the literature review matrix.

et al. [65], who report on the use of a matrix for literature reviews, a specially designed literature matrix (see table 1) was devised that would catalogue and count the occurrences of texts following the filtering process.

The next stage after collecting the matrix results was to critically analyse the findings. This section of the review considers the benefits, limitations and key drivers, which have shaped the development of the different passive building thermography methodologies.

4. Objective 1 Results. Current Passive Building Thermography Methodology Application

Having conducted a detailed literature review into passive building thermography application methodologies for defect detection, a range of seven methodologies were identified. These are (organised from fastest to slowest methodology):

- Aerial surveys
- Automated fly-past surveys
- Street pass-by surveys
- Traditional perimeter walk around surveys (External only)
- Traditional walk through surveys (Internal and external)
- Repeat surveys
- Time-lapse surveys

4.1 Aerial Surveys

Aerial thermography as a methodology has been around for a number of years, with considerable work being undertaken in the early 1980's [26, 66-69]. To perform an aerial survey, a thermal camera is fixed to an aeroplane or helicopter [70], which flies over the target area several times recording thermal images, often of large or multiple buildings rather than singular dwellings. The results present a picture of heat loss from the building's roofs.

Since the aircraft for this methodology usually need to fly at altitudes of 1200 – 1500 feet, the cameras typically used in building surveys do not have an adequate spatial resolution [70], and instead much higher specification cameras or line-scanners are used [71], which offer a greater spatial resolution for discerning detail at high altitudes, This however comes at a greater cost to the user, which under work by Allinson [72] estimated a large urban scale survey costing £50,000.

Benefits of aerial thermography include identifying problems without needing to gain access to buildings and being able to observe problems on large buildings more efficiently [73], however the most significant benefit to this methodology is the speed at which surveys can be conducted, where many roofs can be observed in a night. Because of these benefits, a number of qualitative uses for aerial thermography have been explored, including roof moisture surveys. Stockton [74] reports on such an application and finding show that aerial thermography is well placed for detecting moisture over flat roof surfaces.

Others suggest how aerial thermography could be used quantitatively to determine energy loss from roofs [26], however limitations to this methodology such as roof shape & pitch, image blurring, internal temperatures, climate and emissivity could impact on and require consideration of for qualitative analysis [35, 72]. A clear limitation to this methodology is that it does not seem possible to observe wall or fenestration defects, since these have not been reported on and could be due to the height and parallel angle of the camera from the plane to the building.

4.2 Automated Fly-Past Surveys

A more recent development on aerial passive building thermography has been the use of unmanned aerial vehicles (UAV). Combining thermal cameras with UAV technology has permitted remote and automated fly-by survey opportunities that permit easier access to inaccessible or potentially dangerous areas [75].

Work by Martínez-de Dios & Ollero [76] looked at using UAV passive building thermography for detecting heat loss from windows. However despite seeking to address recognised image stabilisation issues, vibrations from the UAV propellers threatened spatial resolution. It seems that the stability of UAV's is one of the most significant technical issues with this methodology, where effects from wind can also lead to blurred images [77]. Other factors limiting the widespread use of a UAV passive building thermography include equipment costs, with basic UAVs currently starting at around £1,500 [78], and licensing restrictions [79]. The Civil Aviation Authority (CAA) set out regulations, which carefully control the use of unmanned surveillance aircraft and under section 166 & 167 of the Air Navigation: The Order and the Regulations [79] for aerial work, permission is required from the CAA for a person to fly:

- A small unmanned aircraft for the purpose of aerial work,
- A small unmanned surveillance aircraft over or within 150m from a congested area or an open-air assembly of more than 1000 people,
- A small unmanned surveillance aircraft within 50m of a person (while in flight and not including the pilot or others controlled by the pilot), vessel, vehicle or structure that is not under the control of the pilot.

Further to these permissions, other restrictions for small unmanned aircraft include [79] not being permitted to fly more than 400m from the ground, not flying the aircraft unless the pilot is assured of a safe flight, and ensuring that the pilot maintains a direct line of sight to the aircraft at all times.

Despite these restrictions there appears great potential for the application of a fly-by passive building thermography methodology where by a UAV mounted thermal camera could gain a better viewing angle to tall buildings and roofs [80] compared with existing street level surveys. This point is particularly significant, since a UAV could be maneuvered to help minimise the effects of surface viewing angle to the perceived emissivity. Furthermore UAV's can get closer to a target than other aircraft or personnel are able to, which can help to increase defect spatial resolution. Work by Eschmann, *et al.* [77] has also suggested ways in which UAV's can be set on an automated flight path. The recorded images can later be pieced together into a much larger thermal image where the spatial resolution is multiplied over the number images used compared with a single image.

4.3 Street Pass-by Surveys

Following the relatively recent introduction of Google 'Streetview' in 2007 [81] passive building thermography researchers and practitioners have been considering ways of utilising a similar 'pass-by' methodology for building thermography [82].

Work by the Massachusetts Institute of Technology (MIT) has explored a drive-by methodology where several thermal cameras mounted on the roof of a car have imaged properties [35]. MIT's research involves driving through predominantly residential streets with thermal cameras [83] recording images of different sections of a property. The images from each camera are combined into a larger image giving a greater spatial resolution [35, 84, 85]. During the study, approximately 25,000 properties in Cambridge, Massachusetts were analysed, and using software developed by MIT [35] they claim to be able to identify specific features or defects, quantitatively determine the severity and estimate the cost and financial returns of rectifying the defect [86, 87]. *IRT surveys* are commercial thermographers who are also utilising a pass-by methodology [88]. IRT have performed surveys of approximately 30,000 buildings in Scotland using a passive building thermography methodology whereby single elevations are recorded by thermographers on foot [89]. These images are used to quantitatively determine total building heat loss performance as well as locating defects.

A key motive behind IRT's and MIT's work has been to speed up the thermographic analysis process. MIT project leader, Sanjay Sarma suggested that a house energy audit takes too long (approximately 2 hours for a house survey) to be cost effective or practicable [87].

Yet there are some thermography experts, who urge caution over the use of a pass-by passive building thermography methodology. Schwoegler [90] cautions against using a drive-by methodology to *"quantify energy leaks",* citing emissivity variances, changing view angles, thermal mass variations and unknown occupancy habits (providing different internal temperatures) as limitations. A further limitation to a pass-by methodology is that it only appears to capture one elevation, meaning that only part of the dwelling is being observed. Although it could be argued that this elevation could act as an indicator for the remaining elevations, other elevations might harbour different defects (or have a very different construction) to the one imaged. These could subsequently be missed, which could be compounded if the elevations missed have increased exposure to prevailing weather conditions such as driving rain or wind.

Despite the cautions, using a drive-by methodology under a qualitative basis could be useful for quickly identifying specific defects such as ventilation and insulation losses that might be present in a building, and worthy of further investigation [83].

4.4 Traditional Passive Building Thermography

There are two levels of passive building thermography survey that are typically used by practicing building thermographers: Walk-around and Walk-through. Because of their ubiquitous use, they are referred to in this paper as '*traditional*' passive building thermography methodologies. Both forms of traditional passive building thermography methodology involve the acquisition of multiple images from around the building, recording specific areas of interest. Thermographers tend to compile reports [8], which should include information on construction features and environmental conditions recorded during and prior to the survey being conducted [47].

4.4.1 Perimeter Walk Around Surveys (External only)

Whereas a pass-by survey captures only one external elevation, a walk-around survey observes every external elevation. Like the pass-by methodology, it appears that speed is the primary driver behind performing an external-only survey.

Red Current [91] list an external-only, walk-around survey at £250, which is almost half the cost of a walk-through survey (£400). This cost issue becomes more significant when multiplied over many properties and may explain how cost could begin to influence decisions on thermography application. Aside from cost, Holst [32] further identifies that external thermography avoids access issues, particularly with larger buildings, and proposes that internal inspections should only be used to clarify external observations [92].

Yet external thermography can be considered more susceptible to environmental conditions compared with internal thermography [9]. Correspondingly, Hart [24] points out that different façade orientations will deliver different readings depending on solar, wind or moisture exposure.

Although a walk-around methodology minimises the time spent surveying and eliminates issues with access, because it only observes the external façade, there are some defects that cannot be detected using this methodology alone. Loft insulation inspections is one example, where because of the viewing angle from street level to pitched roof, insulation defects are not always detectable [93].

4.4.2 Walk Through Surveys (Internal and External)

A walk-through survey enhances a walk-around methodology as the thermographer performs internal as well as external imaging, presenting a clearer picture of building defects compared with external surveying alone [25]. The procedure for conducting a walk-through survey involves the thermographer inspecting every surface inside and outside of the building, recording potential defects from several different angles and making field notes on the likely observed issues [94]. This increased rigor comes at a cost though, both monetarily as noted through Red Current's [91] service charges, and in terms of time. Westerhold [93] notes the added time-consuming nature of performing a walk-through methodology due to multiple rooms, walls and floors that could require imaging, which contrasts with external only image collection from walk-around surveys.

Adding to Holst's [32] suggestion that internal thermography supports external, it can be argued that external thermography should be conducted first to provide an overview for more detailed follow-up internal thermography [9, 11, 94].

4.5 Repeat Surveys

As with many man-made components, over time building materials will start to degrade [95], a process that will likely occur differentially within different construction components subject to material specification, location, weathering, pollution, construction detail and maintenance [4, 96]. Seeking to address building degradation, some clients and building professionals are now starting to consider the use of repeat thermography as a means for monitoring the continued performance of buildings, and as an early warning tool for detecting developing defects before they present themselves as more serious problems [97]. Such an application could monitor modern airtight and super insulated properties such as those constructed to the PassivHaus standards, since insulation degradation or seal damage could impact on the energy use of the dwelling, which might pose significant problems given earlier suggestions [49] that ventilation losses can equate to over a half of a buildings energy use.

Roof moisture surveys are a common use of repeat thermography [98, 99], where annual inspections are conducted to verify construction condition with particular regards to penetrative moisture.

Before and after surveys offer another application for repeat thermography and are typically performed to identify problem areas and check success of remedial action and workmanship following repairs [16, 100]. Rarely used, this application of thermography can be of specific benefit to both new build and refurbishment through post occupancy evaluation, where recently completed works can be assessed for success and optimisation [4]. Repeat thermography is well placed as a methodology to perform such an assessment, providing not only a tool for helping owners or occupiers to understand when and where defects are occurring [101], but also as a visual feedback tool for educating the design and construction teams as to what they got wrong or right [102].

4.6 Time-Lapse Surveys

As previously discussed, passive building thermography methodologies capture single images, which aligns with a stationary perception of building heat loss, where steady state temperature differences can be used to assess heat flow through building fabric. Unfortunately, this leaves the potential for misinterpretation because indoor and outdoor conditions are often anything but steady state.

Changing conditions such as moisture in walls or heat stored within thermally massive building components [15] can cause material properties to fluctuate, which in the case of moisture in walls, could damage and reduce the overall performance of the construction [103]. Using thermography, such transient conditions are not visible in instantaneous thermal images [25] due to the long time scales involved for some environmental changes to occur.

Some thermal cameras now include the ability to record movie sequences and time-lapse images, enabling thermographers to observe changes in material surface conditions over seconds, minutes or hours [21, 104]. Despite this, the snapshot approach to passive building thermography remains routine. Furthermore, transient climatic changes appear to be ignored, be it purposefully or not. This is despite extensive literature documenting such environmental limitations [8, 23, 105]. An apparent lack of understanding could be detrimental to defect detection particularly in certain buildings such as heavy weight ones, which as reported by Chown and Burn [58] require approximately 24 hours of no solar gain on a wall for an accurate thermographic inspection.

One area of work utilising a passive time-lapse methodology has been moisture analysis, such as work by Grinzato *et al.* [106] who have been exploring the evaporation process and drying periods of different plaster build-ups using passive time-lapse thermography. This resulted in the creation of temperature decay curves that helped to determine differences amongst the samples as they presented their methodology for moisture detection in building materials. Another application of a time-lapse methodology has been to determine the thermal performance of construction

Application method		Aerial thermography							Automated fly-by thermography							Pass-by thermography							Traditional thermography - walk around & walk through							Repeat thermography							Time-lapse thermography						
Literature Source		Academic document		Grey document		Prof. document		Total use	Academic document		Grey document		Prof. document		Total use	Academic document		Grey document		Prof. document		Total use	Academic document		Grey document		Prof. document		Total use	Academic document		Grey document		Prof. document		Total use	Academic document		Grey document		Prof. document		Total use
Measurement method	Q1 = Qualitative, Q2 = Quantitative	Q1	Q2	Q1	Q2	Q1	Q2		Q1	Q2	Q1	Q2	Q1	Q2		Q1	Q2	Q1	Q2	Q1	Q2		Q1	Q2	Q1	Q2	Q1	Q2		Q1	Q2	Q1	Q2	Q1	Q2		Q1	Q2	Q1	Q2	Q1	Q2	
Defect type	Ventilation losses	1	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	2	14	0	20	0	10	0	44	2	0	1	0	1	0	4	0	0	0	0	0	0	0
	Conductivity losses	6	3	0	0	1	1	11	0	0	0	0	3	0	3	1	0	1	0	0	0	2	17	0	20	5	11	0	53	3	0	1	0	2	1	7	0	2	0	0	0	0	2
	Defective services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	0	6	0	12	1	0	0	0	0	0	1	0	0	0	0	0	0	0
	Moisture ingress	15	0	5	0	2	0	22	0	0	0	0	1	0	1	0	0	0	0	0	0	0	23	0	13	0	8	0	44	1	0	1	0	5	0	7	1	2	0	0	0	0	3
	Moisture condensation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	7	4	8	0	26	0	0	0	0	1	0	1	0	0	0	0	0	0	0
	Structural defects	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	8	1	4	0	3	0	16	1	0	0	0	0	0	1	0	0	0	0	0	0	0
Energy performance estimation		0	4	0	0	0	1	5	0	1	0	0	0	1	2	0	1	0	1	0	2	4	0	6	0	5	0	1	12	0	0	0	1	0	1	2	0	8	0	0	0	0	8

Table 2. Completed literature review matrix.

build-ups [45, 46]. Work by Larbi Youcef *et al*. [107] used passive building thermography over a number of days to help measure the performance of insulated building walls. Conclusions from this work suggested that additional parameters were necessary for such a study, which relates back to Hart's [24] recommendation for the additional use of heat flux meters for thermal performance measurements.

Whilst all research using a time-lapse passive building thermography seeks to quantify performance, it remains to be seen whether such a methodology could be successfully used solely as a qualitative tool for defect pattern analysis.

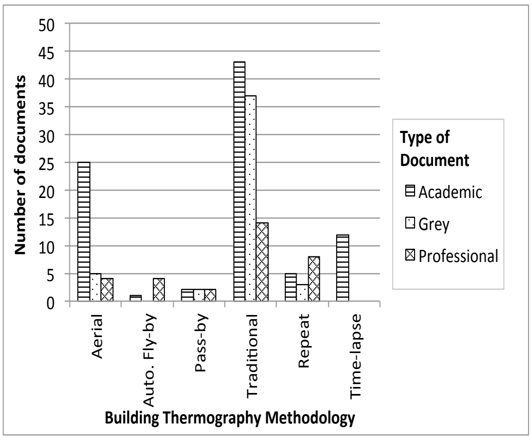
5. Objective 2 Results. Building Thermography Methodology Literature Matrix

Table 2 shows the completed literature review matrix, which includes a categorised numerical record of all the literature sources that were passed through the literature filtration process. For each application methodology, a total number of literature sources were collected irrespective of literature source (type) and measurement method. This provided a quick summary of the most commonly reported defects and methodologies, which proved to be traditional thermography, used for ventilation losses (44 sources), conduction losses (53) and moisture ingress (44) defects.

By further reviewing the data collected within the methodology matrix, a number of interesting patterns started to become apparent, as discussed below.

5.1 Documentation of Methodologies

Figure 4 suggests that while academic work can be observed within all passive building thermography methodologies, a professional application is present in all but the time-lapse methodology. One theory for this may be a limited understanding of this methodology, while another could be because it is more disruptive (to occupants), time-consuming and more complex to set-up compared with the other passive building thermography methodologies.



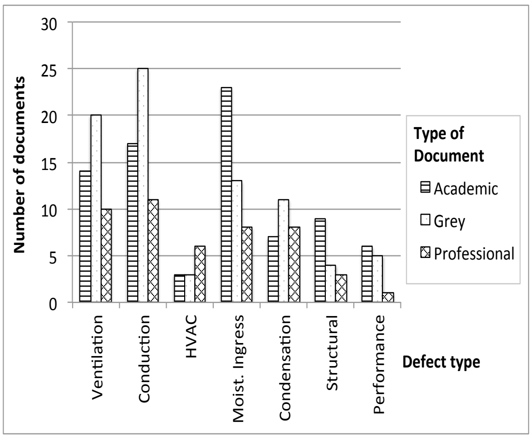


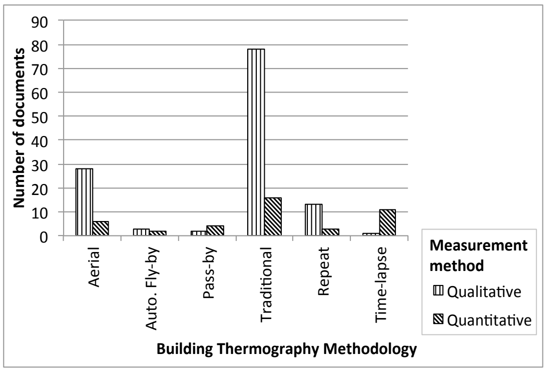
Figure 4. (Left) Literature by source and building thermography methodology. Figure 5. (Right) Literature by source and defect type for traditional passive building thermography methodology.

Figure 4 also reinforces the hypothesis that much of the available literature centres on more traditional methodologies. The automated fly-by and repeat passive building thermography methodologies have seen more professional application than academic research. With regards to the limited academic and grey literature on fly-by thermography, this reinforces findings that this is a relatively new methodology and suggests room for future research.

Focusing on traditional passive building thermography, figure 5 shows that much of the documentation discussing ventilation losses, conduction losses and condensation defects comes from grey literature sources, while moisture ingress, structural and performance related issues appear academic led.

5.2 Qualitative and Quantitative Use of Methodologies

Comparing the data with regards to the measurement method applied for each of the application methodologies, figure 6 provides evidence that supports statements from Kee [108] and Kominsky *et al*. [41], that passive building thermography is primarily performed on a qualitative basis. However this does not appear to be the case for pass-by and time-lapse thermography, which held a greater degree of quantitative application.



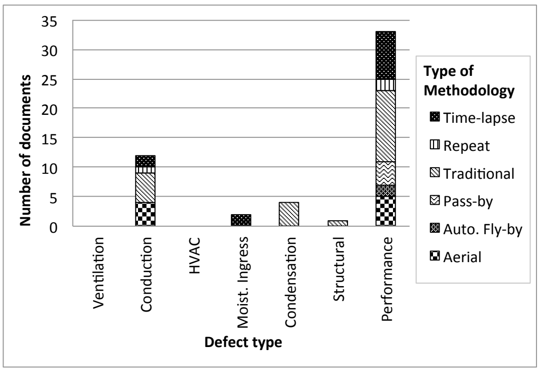
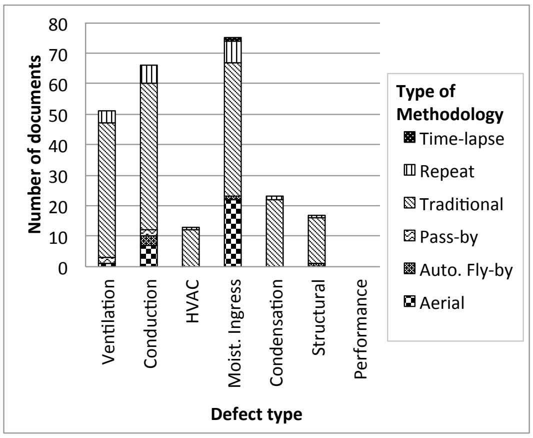


Figure 6. (Left) Literature by building thermography methodology. Figure 7. (Right) Quantitative literature only by building thermography methodology and by building defect type.

However examining quantitative applications within passive building thermography methodologies, figure 7 shows that most of the research in this area targets energy performance estimation, which although not specifically classed as a building defect will largely be effected by other energy related defects such as ventilation and conduction losses.

5.3 Qualitative Application of Passive Building Thermography Methodologies

Figure 8 indicates how each of the passive building thermography methodologies are currently being utilised for qualitative defect detection. Confirming their significance in construction performance, the three defects: Ventilation losses, conductivity deficiencies and moisture ingress can be seen to have had considerable mention within academic and professional literature. Focusing on only the documented professional use, figure 9 shows that conductivity and moisture ingress again seem to be the defects with most focus.



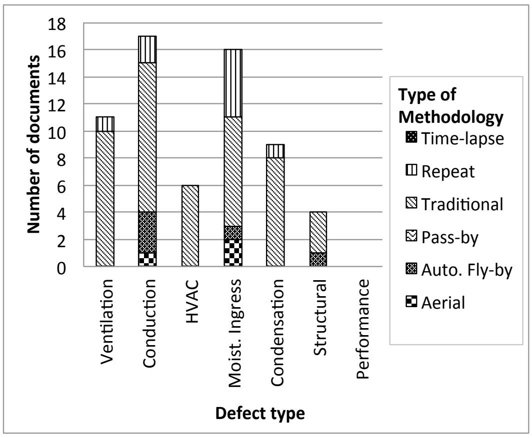


Figure 8 (Left) Qualitative literature analysis by passive building thermography methodology and by defect type for all literature sources. Figure 9 (Right) Qualitative literature by passive building thermography methodology and by building defect type for professional literature source only.

Figures 8 and 9 also show that traditional methodologies are the most common form of defect detection, and that all thermally significant defects have been detected using traditional methodologies. This is possibly due to the frequent use of this methodology, however it could also suggest limitations within the other passive building thermography methodologies. For example, repeat thermography is the only other methodology that has also been recorded as observing condensation defects, which could suggest a difficulty in obtaining a qualitative result using methodologies that are externally focused.

6. Discussing Building Thermography Methodology Drivers And Limitations

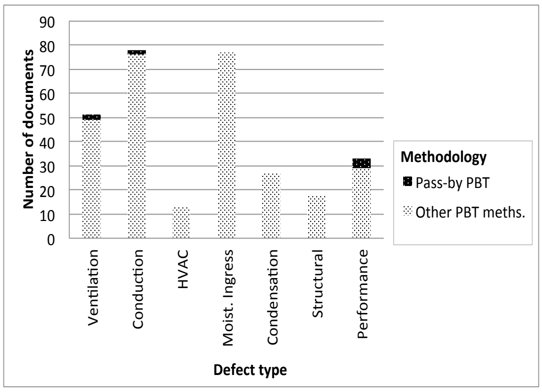
This section seeks to discuss some of the key drivers that appear to be shaping existing and emerging building thermography methodologies. Considering these drivers with potential limitations can help thermographers to understand how new methodologies are being developed, where particular methodologies might be best applied and how they could be combined as part of multiple survey tools.

6.1 Perceived Defect Detection Ability vs. Time

Two of the key drivers shaping passive building thermography methodologies are time and detection ability. Maldague [109] states that internal thermography is more time-consuming compared with external, which when related to costs [91] it is easy to see how lengthier methodologies equate to increased resource demand and cost to thermographer and client. Referring back to figure 4, it can be observed that none of the reviewed professional literature makes reference to using a time-lapse passive building thermography methodology. As well as being a new methodology and holding the potential for further research / use in the future, this pattern could suggest that these slower methodologies are currently prohibitively time consuming and costly for practical use. Continuing this assertion that time-lapse thermography requires longer to perform, other methodologies that are faster than more traditional methodologies could be said to have been developed out of a desire to speed up and lower the cost of performing building thermography for defect detection and thermal performance determination.

Although speed and cost is important when considering the commercial implementation of thermography for building assessment, with greater speed comes a reduction in defect detection ability, which will mean that a less clear picture is made of the overall energy performance of the building. Considering pass-by thermography, a reduction in spatial resolution will become magnified given the likely large distance from camera to target as well as only observing external elevations. These limitations could therefore lead to a misinterpretation of images or missing certain defects.

Figure 10 supports this position, showing that only ventilation and conduction loss defects have been identified to date using a pass-by methodology (in addition to total energy performance estimations), therefore missing one of the main thermally significant defect groups, moisture.



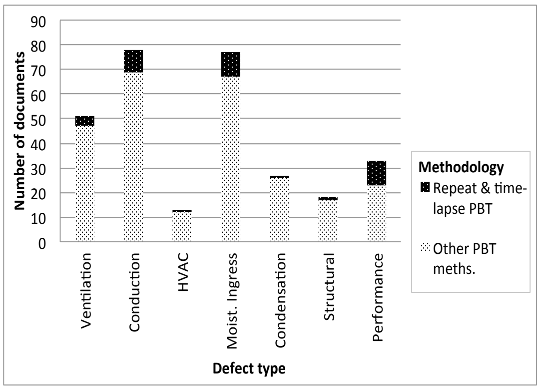


Figure 10. (Left) Literature by defect type with a focus on pass-by passive building thermography. Figure 11. (Right) Literature by defect type with a focus on repeat and time-lapse passive building thermography.

One clear limitation to defect detection using aerial, automated fly-by, pass-by and traditional walk-around methodologies is the absence of internal investigations, meaning that any internal defects are likely to be ignored. This limitation becomes amplified due to construction features such as low emissivity claddings and air gaps between external wall layers, both of which can mask internal defects [110]. Another limitation rests with the camera specification, where even relatively high resolutions of 640x480 pixels appear insufficient for capturing defect detail, within singular image assessments of whole façades, that might involve the thermographer recording images at distances greater than 10m from the target surface.

Add to these limitations differences in emissivity, steep view angles, thermal mass and façade orientation differences, concerns start to be raised [90] over claims [35, 88] that methodologies such as pass-by passive building thermography can be used for quantitative total heat loss and CO_2 estimation. Doubts centre around whether is it possible to determine a building's total heat loss, or energy use based on only partial external information gathered over one single image.

Figure 10 shows that energy performance determination is the most common application of pass-by thermography. Because each of the many pixels in a thermal camera records an apparent temperature reading, comparing a pass-by methodology with collecting surface temperature data from several thermocouples or infrared thermometer readings, pass-by thermography might indeed prove a useful exercise in obtaining fast whole elevation data, which could then be interpreted for energy performance. The concerns and limitations however serve to caution against relying too much on the accuracy of the results, which at best will likely offer an estimation.

However some of the slower methodologies appear to be addressing defect detection in an alternative and more rigorous manner. Figure 11 shows that all of the defect groups are detected using the slower methodologies of repeat and time-lapse thermography, with moisture ingress featuring as a key defect that is more detectable using lengthier analysis procedures. This could be said to be significant since the slower passive building thermography methodologies appear to be taking into consideration the transient environmental conditions acting on a building, and the dynamic changes within building materials.

While much of the passive building thermography research has focused on individual methodologies in isolation, a single paper reports on how different passive building thermography methodologies might work to complement each other. This is work on large building investigations by Brady [111], who conducted an aerial roof survey before following this up with a walk-on roof (traditional) methodology. Results from their work showed that having a larger aerial picture of the roof helped to pinpoint potential problem areas, which allowed for faster and improved staff efficiency when conducting more detailed close up thermography. This research presents an interesting example for future coordination between different passive building thermography methodologies in a phased surveying approach, which could help speed up the detection process.

6.2 Technological Development

Recent advances in thermal camera technology such as the digitisation of image collection [32] have likely helped to shape the way in which passive building thermography methodologies are performed. This is supported by figure 12, which shows the documented patterns of passive building thermography methodology occurrence by documentation publication date. It is interesting to note that early reported methodologies consisted of either aerial or traditional methods for passive building thermography, while newer methodologies have been introduced and most significantly reported on within the past 10 years. It is also interesting to observe the more recent accumulation of literature on passive building thermography, which underlines the growing application of thermography for building assessment.

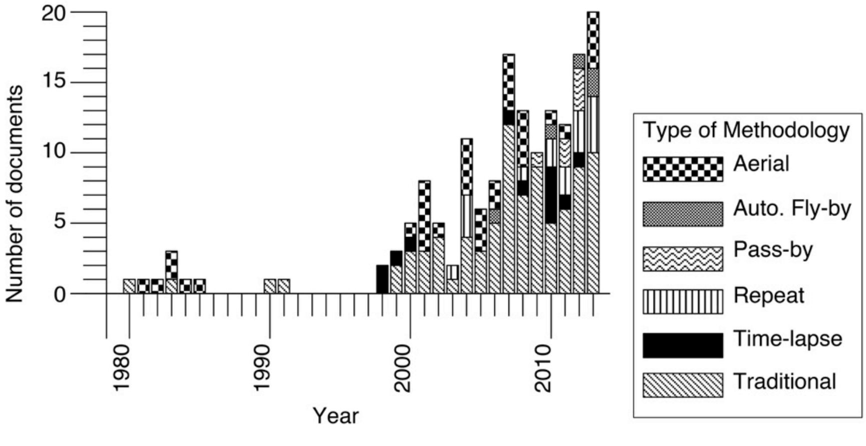


Figure 12. Occurrence of literature by passive building thermography methodology and by date.

Whilst advances in thermal camera technology have enabled more efficient passive building thermography methods, it is also important to note that thermographers have been considering ways of utilising other more recent technological developments. Two examples of these have been through automated fly-by (attaching cameras to small remote controlled aircraft [76]) and pass-by (attaching cameras to cars [35]) passive building thermography.

This combination of technology seems to be opening up novel opportunities for passive building thermography that need further investigation to fully assess the potential benefits and limitations.

6.3 Estimation of Energy use and Thermal Performance

Another driver for passive building thermography methodology development has been the estimation of total façade energy use using quantitative measurement methods. U-Value estimation [45, 46] and CO_2 quantification [88], are two examples, which represent evidence of a growing desire amongst thermographers (and possibly clients) to quantify how a building is performing in terms of energy use.

The literature [60, 88] suggests that some thermographers are utilising a quantitative measurement approach whilst performing traditional and pass-by thermography methodologies, measuring the data obtained from single images to estimate heat loss and energy use. Yet Hookins [112] urges caution over this methodology, arguing that there would be too many variables for accurate quantitative analysis to be conducted on a snapshot basis and adds to the aforementioned concerns by others that buildings are subject to transient changes. Stockton [110] relates this to cost, arguing that obtaining accurate quantitative assumptions on heat loss performance incurs greater costs compared with qualitative image interpretation. This could be said to present a barrier to quantitative commercial application.

Furthermore, by focusing on the estimation of energy use or thermal performance, it is essential to determine the presence of defects. Especially since building defects that permit heat to escape from the building will directly lead to a reduction in energy performance, and might not be fully considered based on simplistic whole-house estimations, which could cause inaccuracies to resultant calculations.

Others appear to be applying quantitative analysis to time-lapse thermography such as the work by Madding [46]. Although their work was primarily conducted under steady state lab conditions, some investigations looked at using a quantitative time-lapse methodology in a real building situation with internal thermography. Set within changing real world conditions, such a methodology could be argued as merely presenting approximations of building performance, however depending on the discrepancy factors encountered, such approximations might be worthwhile exercises in ‘suggesting’ the performance. Discussing discrepancy factors, Pearson [25] states that the accuracy of calculated U-values from thermography are at best ±25%, though values could be less accurate for well insulated walls, and that measurements do not seem to take into consideration stored heat, since they are based on a snap-shot of a wall at one particular time, and might not be observing the flow of stored heat. Madding’s methodology utilised a periodic image collection format from the inside only and would have been subject to far fewer climatic variations than had it been conducted externally. Therefore it could be argued that the discrepancy factor may be less than Pearson’s ±25%. Also by conducting a time-lapse survey a more accurate approximation could be determined by averaging the data from all images as opposed to a single snapshot image under a faster passive building thermography methodology.

7. Conclusions

This review has highlighted the different passive building thermography methodologies that are currently being researched and applied on existing buildings. This includes Traditional perimeter walk around surveys, Traditional walk through surveys, Aerial surveys, Repeat surveys, Time-lapse surveys, Street pass-by surveys and Automated fly-past surveys.

These appear to be influenced by recent key drivers such as increased speed and efficiency, reduction in surveying cost, determination of building performance, improvements in technology and deeper understanding of building defects.

The increased use of passive building thermography for defect detection suggests that building thermography is becoming progressively requested and utilised within building refurbishment work, something that is likely to increase in combination with advancements in technology and cost reductions.

Another observation is that some methodologies are increasingly being used to estimate building energy performance. Yet in doing so some of the past lessons and limitations to thermography such as environmental conditions, emissivity and spatial resolution appear to be forgotten or ignored. This work has also shown that some of the passive building thermography methodologies might be suitable for detecting some defects, but not others, also in some situations defects such as moisture ingress, condensation losses or ventilation losses might be being completely overlooked. Especially when only viewing a building from the outside, which might mean that internal defects such as condensation defects may be missed. Furthermore there might be circumstances where internal defects show on the external elevation during an external only thermographic survey, though these could be misinterpreted due to a lack of understanding of the construction or internal conditions.

Yet failure to recognise the direction that passive building thermography is heading in would also seem to be remiss. Particularly as thermal camera and surveying costs appear to be driving faster surveys. At present, increased speed seems to go hand-in-hand with reduced defect detectability, largely due to a diminished spatial resolution.

Therefore this paper has identified the potential for using several passive building thermography methodologies together in a phased approach to building surveying using thermography. For example, a less costly and faster survey could be conducted to quickly identify certain defects before enabling more time consuming and expensive surveys to hone in on these with greater detail and spatial resolution if deemed necessary.

7.1 Future Work

The results from this research have highlighted a number of gaps in the literature, which suggest that either these methodologies have not been utilised for particular defects yet, or that they are not appropriate for detecting these defects. The authors are currently exploring the defect detection ability of various passive building thermography methodologies. Already work has been undertaken that looks at using passive time-lapse thermography for defect detection in buildings and materials by comparing heat flow simulations with an observed thermography time series [113], and has been followed up by work on *The use of a passive time-lapse thermography methodology to better understand the thermal behaviour of buildings* [114].

Further to the passive time-lapse thermography investigations, work is also progressing that compares the defect detection ability of pass-by thermographic surveys with that of walk-through thermographic surveys. The results from this work will explore baseline data from multiple case study buildings, which will help to better determine the type of defects that can or cannot be detected using certain passive building thermography methodologies and to establish a system of combining different methodologies in order to enhance the defect detection of buildings.

7.2 Acknowledgements

The work presented in this paper has been funded through the European Social Fund – Combined Universities of Cornwall (EU ESF-CUC) Studentship, with Penwith Housing Association and RTP Surveyors, Project Reference 11200NC05/CUC/Phase2

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Title: Time-lapse Thermography for Building Defect Detection.

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Abstract

Building thermography traditionally captures the thermal condition of building fabric at one single point in time, rather than changes in state over a sustained period. Buildings, materials and the environment are, however, rarely in a thermal equilibrium, which therefore risks the misinterpretation of building defects by employing this standard methodology. This paper tests the premise that time-lapse thermography can better capture building defects and dynamic thermal behaviour. Results investigating the temporal resolution required for time-lapse thermography over two case study houses found that under typical conditions small temperature differences (approximately 0.2K) between thermal areas could be expected for 30-minute image intervals. Results also demonstrate that thermal patterns vary significantly from day-to-day, with a 2.0K surface temperature difference experienced from one day to the next. Temporal resolutions needed adjusting for different types of construction. Time-lapse experiments raised practical limitations for the methodology that included problems with the distance to target and foreground obstructions. At the same time, these experiments show that time-lapse thermography could greatly improve our understanding of building transient behaviour and possible building defects. Time-lapse thermography also enables enhanced differentiation between environmental conditions (such as clear sky reflections), actual behaviour and construction defects, thereby mitigating the risk of misinterpretation.

Key Words

Time-lapse thermography, transient behaviour, defect detection.

1. Introduction

According to the United Nations Environment Programme, buildings account for over 40% of the world's energy use [1]. Within the European context, building energy use is rising, with EU dwellings responsible for approximately 70% of all energy use in buildings [2]. Of the 22.4 million dwellings in England, almost 90% were built prior to 1991 [3], a pattern which mirrors the housing trend throughout Europe [2]. Since new build construction in England for 2013 only totalled 109,370 units [4], the aim of the UK government to meet carbon reduction targets of 80% on 1990 levels by 2050 [5] appears unachievable unless widespread action is taken to thermally improve existing dwellings. In addition, increased energy costs are leading to increased levels of fuel poverty [6]. The risk of fuel poverty is typically larger amongst occupants of rural buildings [7] due to a lower uptake of gas central heating and less energy efficient construction. It is therefore important to improve existing dwellings that are energy inefficient thermally and to minimise the energy demand required for heating buildings.

The ability to identify thermally inefficient areas successfully, such as specific thermal defects, is fundamental to the subsequent success of thermally improving existing buildings [8]. Thermography is an analysis technique which is increasingly being used by construction professionals as a non-destructive tool suited for this task [9]. Thermography, also named thermal imaging, uses a special type of camera to detect infrared radiation, which is emitted from surfaces [10] such as the building fabric. Since the infrared radiation relates to temperature, this in turn depends on heat transfer through the building envelope. Providing there is sufficient temperature difference across a construction, thermography can be used as a tool to identify quickly potential building defects, such as moisture ingress, without the need to undertake costly and damaging physical exploratory investigations. However, image interpretation is a key limitation since thermographers need to be particularly mindful of the external conditions and parameters which can inhibit defect detection, such as emissivity, distance, level and span, etc. [11].

At present, building thermographers tend to capture a series of thermal images during a visit to a building but do not undertake any longitudinal studies [12]. Such images have the potential for misinterpretation due to transient effects, such as that provided by thermal mass dampening temperature change over time, which are not always recognised in images taken at a single point in time [13]. Furthermore, internal and external conditions have an impact on the temperature of a construction; the specific effects will vary depending on the ability of the particular fabric to store heat energy. For example, solid masonry walls have a greater capacity to store energy through thermal mass when compared with lighter-weight timber-frame walls. Depending on the internal room temperature and that of the inner wall surface, energy stored in thermal mass might reverse the heat flow direction [14] from that which might be initially expected. Alternatively, some constructions might contain insulation or cavities, which present less thermal conductivity when compared with solid wall constructions such as stone or cob. This will have an impact on heat flow through a wall. As such, low-conductive materials will present a barrier to the flow of heat in either direction and could have an impact on thermal image results.

However, some recent thermal cameras now have the ability to record sequences of images thus creating a time-lapse series and thereby presenting new opportunities for longitudinal building thermography [15] to observe the transient flow of heat through construction over a much longer period. To date, this approach has not been used for thermal studies of whole buildings.

This paper aims to develop and investigate the use of a time-lapse thermography methodology for the inspection of buildings. It seeks to better understand transient thermal changes of the fabric and how these interrelate with the identification of building defects through thermography.
The research has the following objectives, to:

a) Compare and contrast a time-lapse methodology with the more commonly used method of capturing images at one single point in time;
b) Develop a time-lapse thermography methodology, which explores the key limitations and practicalities involved with conducting on-site internal and external investigations;
c) Investigate different temporal resolutions required for undertaking time-lapse analysis, in order to better highlight defects and thermal behaviour.

This paper applies a qualitative time-lapse thermography methodology to three case-study buildings to explore the use of apparent surface temperature changes over prolonged periods of time in order to draw conclusions from transient changes. Although building thermography can also be used to observe the behaviour of and defects within HVAC systems, this work primarily focuses on observing the building fabric.

2. State-of-the-art in Building Thermography

2.1 Traditional building thermography

There are two schemes of analysis by which building thermography can be performed: *active* and *passive*. Active thermography utilises a forced heating or cooling stimulus, which creates an enhanced thermal contrast to locate specific defects such as subsurface cracks [16]. In contrast, passive thermography observes the natural temperature differences of objects which would normally be at a different temperature to each other [12]. Avdelidis *et al.* [17] reported that passive thermography is the most common analysis scheme for building inspections, typically combined with qualitative analysis, since the aim is to detect potential defects in buildings without artificial intervention. In this context, the use of heating systems is not considered to be an active/imposed stimulus since these are a regular part of the building.

Currently, the most common form of passive building thermography utilises a *walk-around* or *walk-through* methodology [18]. In this paper, these are collectively referred to as *traditional* passive building thermography. Given the higher speed and minimal disruption to occupants, authors such as Holst [19] advocate the sole use of a walk-around survey which only observes external building surfaces. Yet the presence of climatic conditions, such as precipitation or wind, during external thermography [11] can hinder external defect detection. Hence there may be the need for the addition of an internal walk-through, where the thermographer inspects internal surfaces [13]. Both approaches require the thermographer to scan each surface systematically with a thermal camera as he/she walks around, or through, the building [20], concentrating on any warmer or cooler spots (compared with the ambient temperature) that might suggest irregularities or defects. As stated, in traditional thermography thermal images are recorded at one moment in time, and not longitudinally. This is significant because the condition of the element being observed is only captured at the specific moment the image is taken. Traditional passive building thermography can be subject to a number of different sources of inaccuracy, such as camera thermal resolution [21], emissivity [22], problems with reflected apparent temperatures [19] and climatic weather conditions [13].

Climatic conditions pose particular problems for thermography. Firstly, climatic conditions dictate when thermography should or should not be undertaken; the recommendation [13] is for dry conditions with low wind levels, cloud covered sky and at least a 10.0K temperature difference between internal and external spaces. However, climatic conditions can also have an impact on the thermal condition of the building fabric. In particular, such changes could alter the apparent properties of materials on a transient basis, particularly when subject to environmental stimulus such as temperature, wind, moisture or solar gain. The impact of varying air movement, for example, is very complex [10] and can vary more quickly than other conditions owing to gusts, which could have an impact on single image results due to forced convection. This can be compounded when coupled with other climatic conditions such as moisture in the material [11].

2.2 Time-lapse building thermography

For the longitudinal application of thermography, the terms 'transient' and 'time-lapse' are important. ‘Transients’ are found when certain factors such as climatic conditions vary over time. ‘Time-lapse’ is the process of capturing spaced data sets (such as images), which can be presented in a sequence to speed up slow processes such as transient changes.

Accordingly, we define time-lapse thermography as a passive thermal imaging methodology, which aims to better understand transient heat flow within a building’s fabric by recording a sequence of images. Time-lapse image capturing is commonly attributed to photography [23] where typically slow or fast events can be accelerated or slowed by saving image frames at different temporal intervals to that of traditional film speeds (25 frames per second). Given the slow nature of transient changes in building materials, time-lapse image recording appears well suited to thermographic investigations.

To establish the current thinking regarding time-lapse thermography, a review of existing literature was conducted. From this, it was discovered that the most commonly reported use of time-lapse thermography involved active thermography. This is exemplified by Hamzah [26] whose work located structural defects hidden beneath material surfaces using forced heating phases prior to thermographic observation over periods no greater than 22 seconds. Avdelidis [17] asserts that time-lapse thermography is in the realm of active thermography. However, work which explored the evaporation process from moistened plaster samples under laboratory conditions by Grinzato, *et al* [27] is one example where a time-lapse methodology has been applied to passive thermography. Also, work by Lehmann *et al.* [28] applied a passive time-lapse methodology to determine the most influential environmental conditions to external thermographic analysis. This study identified solar gain in combination with differences in construction composition (insulated versus uninsulated brick wall construction) as presenting the greatest impact on thermography. Madding [29] and Kato [30] have explored the determination of thermal transmittance (U-value) using passive time-lapse thermography by measuring apparent surface temperatures over a prolonged period of time. Previous research by the authors of this paper [31] studied the warming and cooling phases of sample typical construction materials using time-lapse thermography; analysis compared measured results with simulated results using the *Voltra* transient heat transfer software [32]. Lehmann *et al.* [28], Madding [29] and Kato *et al.* [30] have captured thermographic images at intervals ranging from 5 to 20-minute. For quantitative analysis, Fox *et al. [31]* utilised 5 minute intervals, which served as a useful initial experiment to establish image intervals for measuring finite temperature differences in small samples. For qualitative analysis, Lehmann *et al.* [28] reported using an image interval of 5 minutes; however, when publishing the image data in their paper, images were reproduced at a 60 minute intervals only, which suggests that the images between 60 minutes did not show a discernible difference in the displayed patterns to enable qualitative analysis.

While this existing work utilised passive time-lapse thermography for the study of some transient aspects of thermal building behaviour, there is no evidence in literature on the use of time-lapse thermography to identify building defects. Currently, there is no evidence in the peer-reviewed literature of a practical methodology for time-lapse thermography as applied to the study of whole buildings. Indeed, recommendations regarding temporal resolution for such studies are non-existent.

3. Methodology for Time-lapse Thermography

3.1 Case study buildings

This research explores the application of time-lapse thermography on the study of transient building behaviour, with a view to identifying building defects. In order to compare in-situ time-lapse building thermography with traditional methodologies that only capture images at one point in time, and to explore the practicalities involved with conducting time-lapse thermography, action research [33] was employed on two domestic properties in the south west of England. Building 1 consisted of 18th and 19th century solid cob (natural building construction comprising organic material such as earth and straw) and stone walling respectively, while building 2 an 18th century cottage comprised of solid stone with a 21st century concrete block cavity wall extension. Both buildings offered large back yards, which enabled a thermal camera to be positioned so that entire elevations could be observed. Building selection was based on the need to find contrasting construction methods that reflected existing UK housing stock and contained the likelihood that defects would be present. By investigating a mix of construction types, a broader assessment of temporal resolutions for time-lapse thermography of different scenarios could be studied. Building selection was also based on convenience sampling, given the extended access required internally and externally for these experiments and their proximity to the research centre.

3.2 Hardware

A calibrated FLIR T620bx thermal camera was used for the experiments. Figure 1 provides its technical specifications. Environmental conditions were monitored using a WH1080 wireless weather station, which has an internal and external sensor that measures humidity, precipitation, wind speed and air temperature. Indicative surface temperatures were obtained using simple k-type thermocouples fixed to the wall at head height next to an openable window and readings were noted by hand; these served as a benchmark check for the thermographic results.

IR resolution	640 x 480 pixels	
Field of view (FOV)	25° x 19° / 0.25m (0.82ft)	
Spatial resolution (IFOV)	0.69 mrad	
Thermal sensitivity (NETD)	<40 mk @ +30°C (+86°F)	
Image frequency	30 Hz	
Temperature range	-40°C to +150°C (-40°F to +302°F) and +100°C to +650°C (+212°F to +1202°F)	
Accuracy	±2°C (±3.6°F) or ±2% of reading	
Image recording	Simultaneous storage of IR/Visual images Periodic image storage	

Figure 1. FLIR T620bx Thermal camera technical specifications (adapted from FLIR [34]) and photograph of the device by the authors.

To perform time-lapse thermography, the thermal camera was set on a tripod (approximately 1m from the ground level) facing the target building surface and positioned far enough away so that as much of that surface could be captured within the Field of View (FOV). The camera was tilted to capture the best view of the elevation within the FOV. The angle of tilt was between 0^{o} and approximately 10^{o} (from horizontal). Hart [10] argued that emissivity can vary with angle (depending on the material being observed), though not significantly until angles of more than 65^{o} from perpendicular are exceeded. It is also important to recognise that when perpendicular to a target, the camera can act as a source of reflected radiation, which can impact results [35].

3.3 Experimental conditions

Weather conditions were monitored for two days prior to experimentation commencing, which was determined to be a logical step which stemmed from guidance that called for a steady temperature difference across the built fabric [36]. This period was also chosen to help monitor/minimise the effects of other weather conditions. For example, had there been heavy rain prior to the experiment, this would have been postponed. Experimentation periods were chosen to minimise the likely presence of clear skies, precipitation and wind, and which had an external temperature that remained at least 10.0K lower than internal air temperatures. To ensure that early images were not adversely effected by the camera sensor adjusting to the atmospheric temperature, the camera was turned on 30 minutes before commencing, as advocated by Vollmer and Möllmann [11]. Once acclimatised, the camera was programmed to record periodic images. Emissivity values were measured in situ [37] and selected in the camera settings for the predominant material being observed, which for these experiments was either painted render or plaster.

3.4 Data collection

Images were captured every 20 to 30 minutes. This interval was chosen as a mid point between the 5-minute image interval used in references [28, 31] and the 60 minute displayed image interval used in the work of Lehmann et al. [28]. Following the survey period, all images were uploaded and assessed using the FLIR Tools software [38]. This software enables image adjustment so that each had the same temperature span (between minimum and maximum temperatures). This allows creation of a time-lapse sequence of multiple images covering the same temperature range, which enables the evolution of transient heat losses to be viewed more clearly.

3.5 Practical methodology

There has been no previous research detailing a time-lapse methodology for passive building thermography. This work therefore sought to introduce and explore a practical methodology for this form of thermographic investigation.

Through conducting time-lapse experiments using passive building thermography, practical issues were identified. Limitations to a time-lapse methodology were encountered both internally and externally. External constraints encountered during studies 1 and 2 included:

- The safe and secure positioning of equipment;
- Challenges with monitoring environmental conditions (wind, rain, cloud cover);
- Maintaining power for equipment throughout the survey period;
- Balancing spatial resolution with FOV;
- Minimising unwanted foreground objects.

Pearson suggested [13] that there are fewer limitations to internal thermography than external thermography due to the presence of a more controllable environment. However, the following limitations were encountered during study 3:

- Capturing entire elevations within narrow FOVs;
- Avoiding occupant interference;
- Avoiding unwanted foreground objects.

Once the practical limitations had been considered, a robust practical methodology for time-lapse thermography was developed. Figure 2 demonstrates the equipment set-up for an external time-lapse investigation, and the following aspects detail the practical approach to the acknowledged methodology constraints.

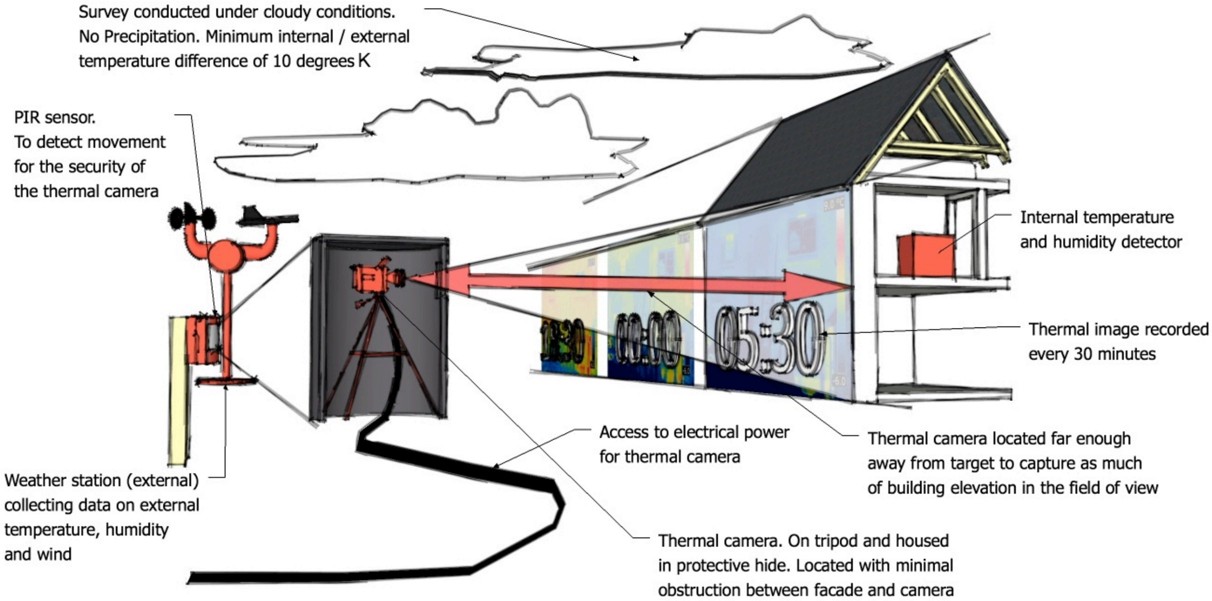

Figure 2. Experimental set-up for external time-lapse thermography showing designed solutions to the methodological constraints.

Safety and security

Although less of an issue during internal investigations, when left outside unattended for prolonged periods of time, the safety and security of the thermal camera (valued at approximately GBP £12,000) was a key concern. Despite positioning the camera in back yard locations, away from public view, the security risk was not completely eliminated. To further aid security, a remote passive infrared (PIR) security alarm device was used to observe the vicinity of the thermal camera during the experiments (figure 2). Weather protection was also paramount. While nights with a cold and dry weather forecast were chosen, care needed to be taken that the thermal camera did not get wet when left outside. To guard the camera against precipitation and frost damage, a simple shelter with a viewing hole was placed over the camera (figure 2), this proved invaluable during the unexpected snowfall experienced during study 2.

Monitoring environmental conditions

Environmental conditions such as temperature, precipitation and wind were easily monitored using a weather station; however, monitoring the presence of cloud cover (which might reflect off the target surface) was very difficult due to the large expanse of sky and the possibility of fast moving and irregular density of cloud cover. Although forecasted cloudy nights were chosen, the actual presence and density of cloud was not observed and might have had an impact on the results of the external experiments. It is therefore important to note such factors and their potential for impacting time-lapse results, which might vary from image to image in a continuous sequence.

Prior to a thermal image being recorded, ITC [37] recommend pointing the thermal camera away from the observed object to identify surrounding sources of infrared radiation (sky, other buildings, appliances etc.), which might reflect off the target surface and could impair measured results. This methodology might work for images captures at a single point in time, however, for automated periodic image recording, a second thermal camera would be required, which if automated would only give data for a comparatively small (compared with the entire background scene) area of sky/background, which might miss many possible areas of potential reflected radiation sources. Internally, an aluminium foil methodology was used to measure reflected apparent temperature [39]. Because of the distances involved externally, the aluminium foil methodology could not be used since a very large sheet of foil would be required and might obscure parts of the observed object.

Maintaining power for equipment

The battery operational time for the T620bx thermal camera is listed as being 2.5 hours long [34]. To avoid reliance on battery power, it is essential to maintain a mains electricity supply throughout the experiment. Alternatively, an additional battery is required; for instance a typical 60Ah automobile battery (using a Buck-boost converter giving 97% conversion efficiency) would power a 3amp rated thermal camera for about 19 hours. Whist it is easy to address internal thermography with mains electricity, it is more problematic for external thermography, which requires long extension leads that place restrictions on camera location and distance from target surface. A source of external mains electricity was available for all studies in this paper, but future studies might not have this luxury. Furthermore, relying upon mains electricity might limit the positioning of the thermal camera (to the yard), as it could be impractical to establish a power supply some distance from the property due to features such as roads. For studies 1 and 2, mains electricity was supplied via a 20m-extension cable. Fortunately in these cases, this distance also corresponded to a suitable camera location to capture as much of the elevation within the FOV as possible. Had either property been larger, it would have been more difficult to locate the thermal camera further from the building surface and reliance on a car battery would have been necessary.

Balancing spatial resolution with FOV

Traditional walk-by / walk-through [18] methodology permits thermographers to scan entire surfaces at relatively close proximities. Multiple views of the surface can then be captured and merged into higher spatial resolution single images of the elevation [40]. Unattended automated time-lapse thermography, however, requires the thermal camera to be fixed on a tripod, resulting in only one view being captured. In order to capture as much of the surface within the FOV as possible, the camera must often be placed at a large distance from the target. This is significant because increased distance equates to reduced spatial resolution. Distance relates to instantaneous field of view (IFOV) [37], which stipulates the smallest discernible target. Yet the smallest target that can be accurately measured is known as the measuring IFOV (MIFOV) and is often three times the IFOV [19]. With greater distance, the smallest discernible target size becomes larger making small details harder to discern [41]. The camera used in these studies held an IFOV of 0.69mrad, which at a 20m distance with a pixel size of 640 x 480, meant that defects smaller than 41.6 x 41.6mm could not be accurately measured due to their falling below the MIFOV. For comparison, had the camera been 5m from the surface, defects as small as 10.4 x 10.4mm might have been detected.

Similarly, by attempting to capture an entire internal wall surface within the FOV, the thermal camera needed to be placed as far from the observed surface as possible. Given the small domestic room size for study 3 (4.5m x 2.5m), the thermal camera had to be located on the farthest opposite side of the room to the target (approximately 4m from the surface). Based on the camera FOV (25^{o} x 19^{o}), this gave an observable area of 2m x 1.5m, which proved insufficient to capture the entire external wall surface of 2.5m wide x 2.8m high. Therefore, only a portion of the wall could be observed at any one time using this camera/lens, as illustrated by the red box in figure 5, which shows the approximate FOV for the thermal camera in context with the surrounding wall area. To help provide a larger FOV, a wider angle lens could be used, though these are costly.

Minimising unwanted foreground objects

During each experiment, unwanted objects such as bushes and pictures obscured surface detail. Internally, every effort was made to remove such items. FLIR [35] recommend that obscuring items are removed at least 6 hours prior to the survey starting; however, in practice this was not always possible, particularly when dealing with large pieces of furniture or immovable planting. Externally, it was important to angle/situate the camera to avoid foliage or garden furniture concealing the building surface. Furthermore, during study 3, all occupants were instructed to avoid entering/using the room whilst the experiment was being conducted as they might have an adverse impact on results.

To mitigate practical issues such as camera security, FOV and power supply, it became routine to locate the camera in back yards. This, however, constrained the studies to the observation of rear elevations only. Therefore, had defects been present on other façades, these might have been missed.

3.6 Case study information

Building 1, study 1

Study 1 observed a Devon vernacular cottage that was formed of two construction types (figure 3). The original 18th century cottage had cob construction with a 19th century, solid, stonewall extension. Both constructions were covered with a cement-based render. Observing the rear (west) elevation, the camera was situated approximately 20m from the dwelling in the back yard.

Survey parameters.
Survey duration: Start: 17:00 on 28th November 2012
End: 08:00 on 29th November 2012
Duration: 15 hours
Image intervals: Every 30 minutes
Weather two days prior to survey: Dry with periods of cloud cover and direct solar exposure on the target (west) elevation. External temperature range: 273.45K to 281.25K
Weather during the survey: Whilst mostly cloudy, there were times when pockets of clear night sky could have been reflecting off the surface. At no point was there precipitation or wind speeds over 1m/s.
External temperature range: 270.05K to 277.65K
Internal temperature range: 280.95K to 293.45K

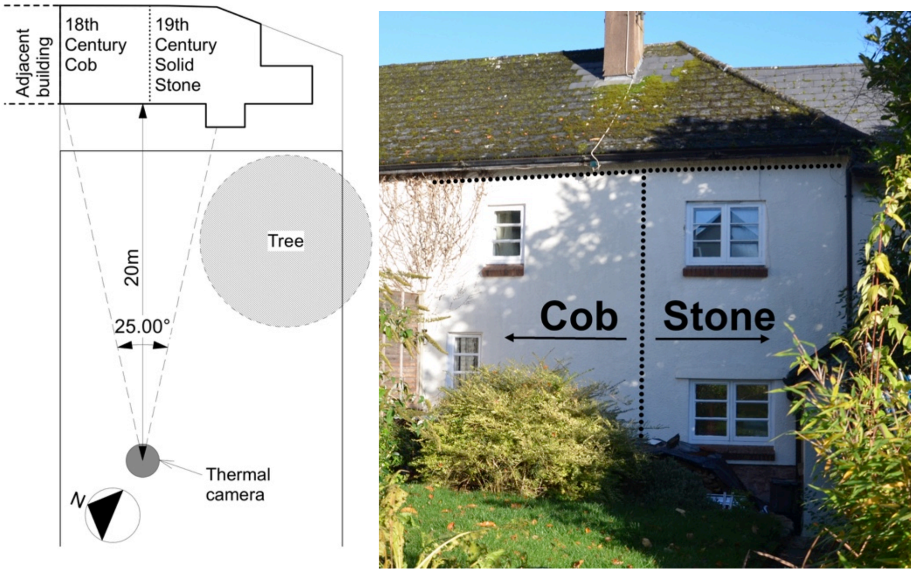

Figure 3. Plan and photo of building study 1

Building 2, study 2
The original cottage was formed of solid stone construction with a 20th century rendered concrete block extension towards the rear of the dwelling. Combining modern with traditional construction, this portion of the dwelling formed the focus of this study. Located in the back yard, 20m from the dwelling, the thermal camera was angled to observe the northwest elevation (see figure 4).

Survey parameters.
Survey duration:
Start: 17:00 on 15th January 2013
End: 08:00 on 18th January 2013
Duration: 63 hours
Image intervals: Every 20 minutes
Weather two days prior to survey: Dry, with periods of changeable cloud cover.
External temperature range: 274.45K and 281.75K
Weather during the survey: The sky consisted of fluctuating cloud cover, with periods of clear and cloudy sky, while other times there was unpredicted snowfall. There was at least a 10.0K temperature difference between inside and outside throughout the survey.
External temperature range: 272.35K to 276.65K

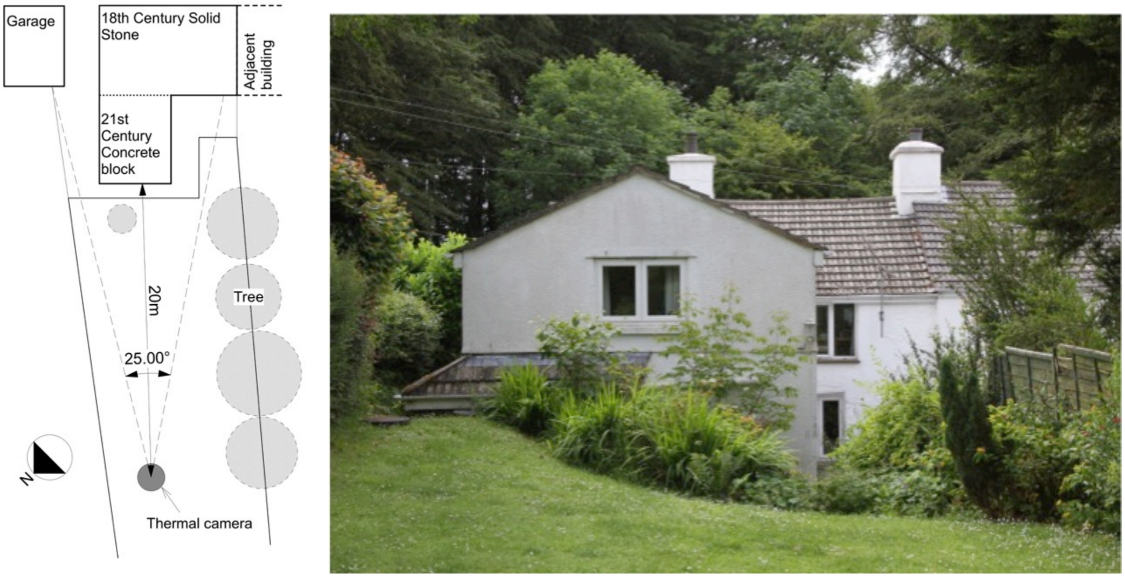

Figure 4. Plan and photo of building study 2

Building 1, study 3

Using the same building as used in study 1, this experiment explored internal time-lapse thermography. Located in a bedroom to observe an east facing external wall (figure 5), the construction observed was predominantly solid cob with a thinner section of brick infill above a window.

Survey parameters.
Survey duration: Start: 17:00 on 13th March 2014.
Finish: 07:00 on 14th March 2014
Duration: 14 hours
Image intervals: Every 30 minutes
Weather two days prior to survey: Dry with small patches of cloud cover, though long periods of clear sky during the day and night periods.
External temperature range: 284.25K to 276.95K
Weather during the survey: Dry with predominantly clear skies.
External temperature range: 280.35K to 277.05K
Internal temperature range: 291.15K to 286.95K
Internal temperatures were largely dictated by the heating system coming on at 17:30 and stopping at 22:00 on the 13th March 2014.

Figure 5. Plan and photo of building 1, study 3. Red box shows limit of thermal camera FOV.

4. Results

4.1 Building 1, Study 1: External time-lapse study

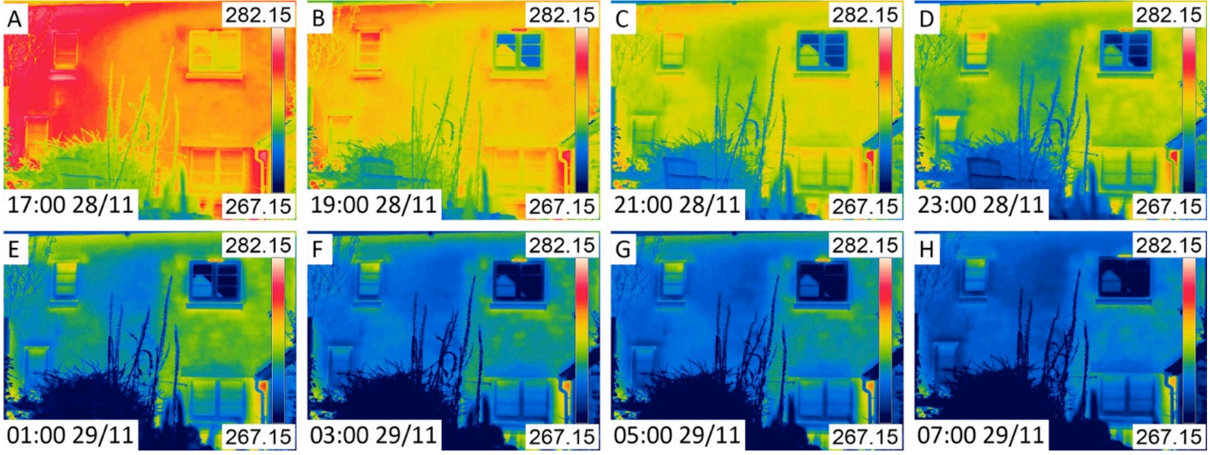

Figure 6. Top left to bottom right (A-H). Study 1. Displayed every 120-minute interval image only (every 4th image).

Differences in image colour patterns were qualitatively analysed (Figure 6A-H) as time-lapse sequences, leading to the following observations:

a) The cob and stone portions of the dwelling showed different thermal behaviour. Figure 6A shows the initial effects of solar exposure during the day, with higher surface temperatures for the cob walling (278.35K) noticed at the start of the survey that progressively cool down throughout the study into the morning, which ended at 269.65K. It can be noted (figure 6H) that the render over the cob had a lower surface temperature overall (269.65K) to that of the render over the stone (271.45K).

b) An approximately 1m diameter warmer patch became increasingly notable over time below a window in the cob walling (figure 7). Although the specific detail of this patch could not be distinguished by thermography alone, quantitative analysis of the thermal images was undertaken over the potential defect and normal cob areas, which has been illustrated in figure 8. At the start of the experiment, the temperature differential between the suspected cob defect and surrounding 'normal' cob was approximately 0.1K; this differential increased throughout the experiment to 1.0K by the end, and suggests that the patch represents a defect rather than an image anomaly due to emissivity or climate.

c) Adjacent to this patch, a hairline crack (figure 7) was observed as being cooler than the surrounding area and could be a related issue.

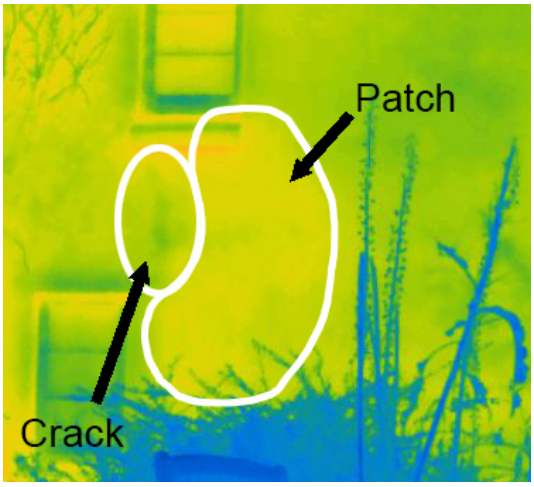

Figure 7. Locations of identified crack and patch

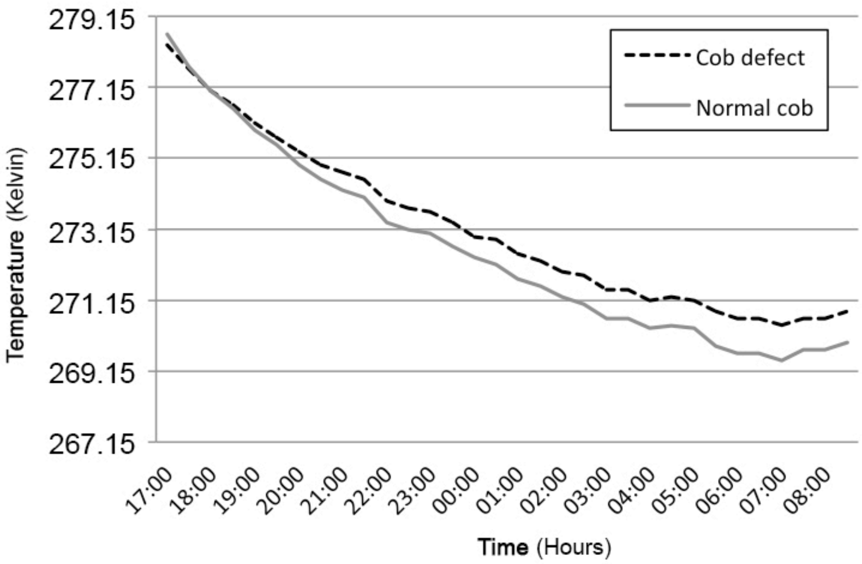

Figure 8. Graph showing temperature difference between normal cob and cob warm patch (defect).

4.2 Building 2, Study 2: External time-lapse study

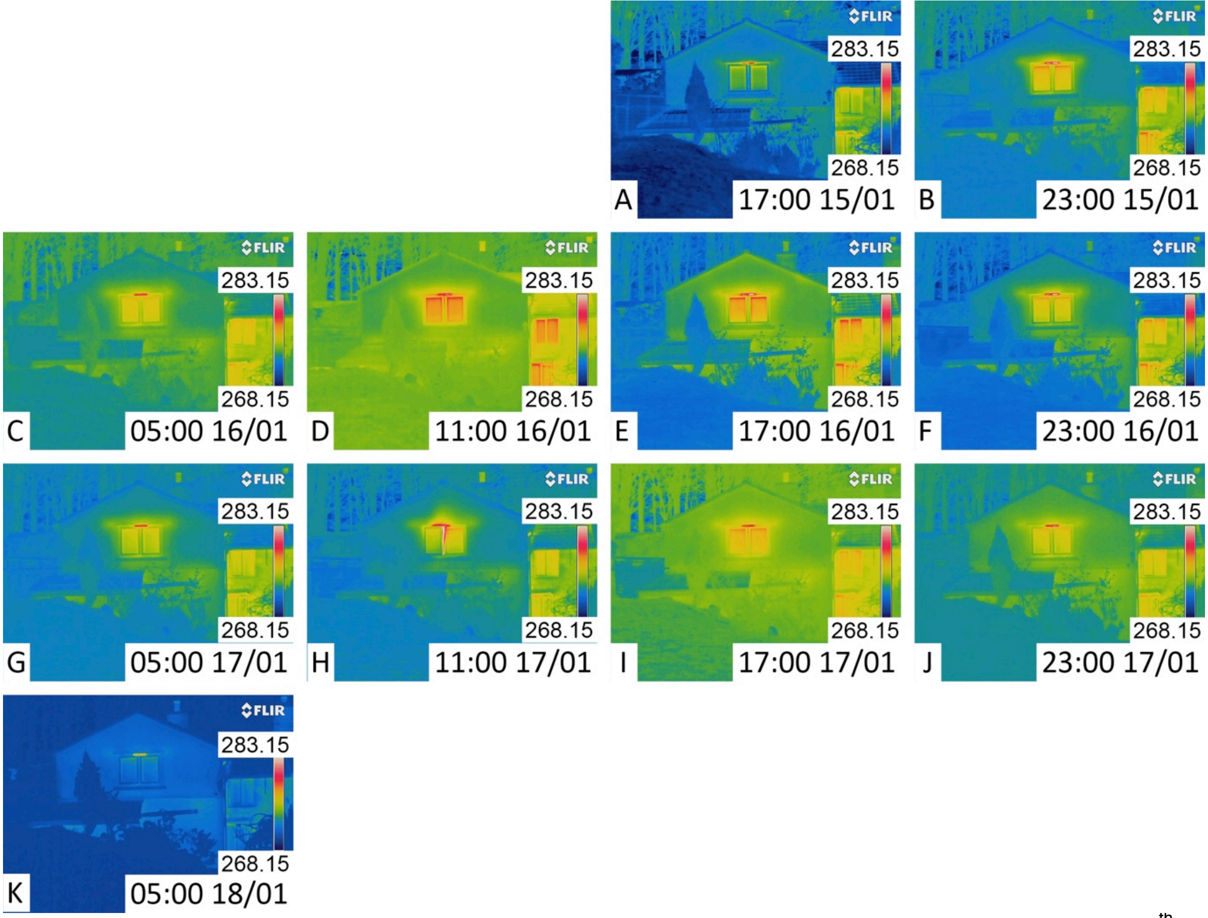

Figure 9. Top left to bottom right (A-K). Study 2. Displayed every 360-minute image only (every 12th image).

From figures 9A-K, several areas of interest can be observed, including differences in surface temperature between the original stonewall construction (back right of images) and the newer rendered concrete block, cavity wall extension (foreground building). Above the window of the extension, a warmer patch was identified, which marks the location of a lintel. Within this patch was an even warmer feature (6.0K greater than the average surrounding wall temperature), which shows internal heat escaping through air leakage from a trickle vent.

Recorded at 17:00 over three days, figures 9A, E & I illustrate qualitatively how thermal patterns appeared to fluctuate from day-to-day during study 2. Measured apparent temperatures recorded at this time fluctuated from 273.25K to 274.95K. In order to minimise the effects of thermal mass from the day before, generic wisdom states that building thermography should be conducted in the morning, before sunrise [11, 42], yet further comparisons between figures 9C, G & K recorded at 05:00 over three days again show discrepancies with measured apparent temperatures ranging from 272.05K to 274.25K. At both 17:00 and 05:00 time intervals, a temperature difference of about 2.0K was experienced over three days.

4.3 Building 1, Study 3: Internal time-lapse study

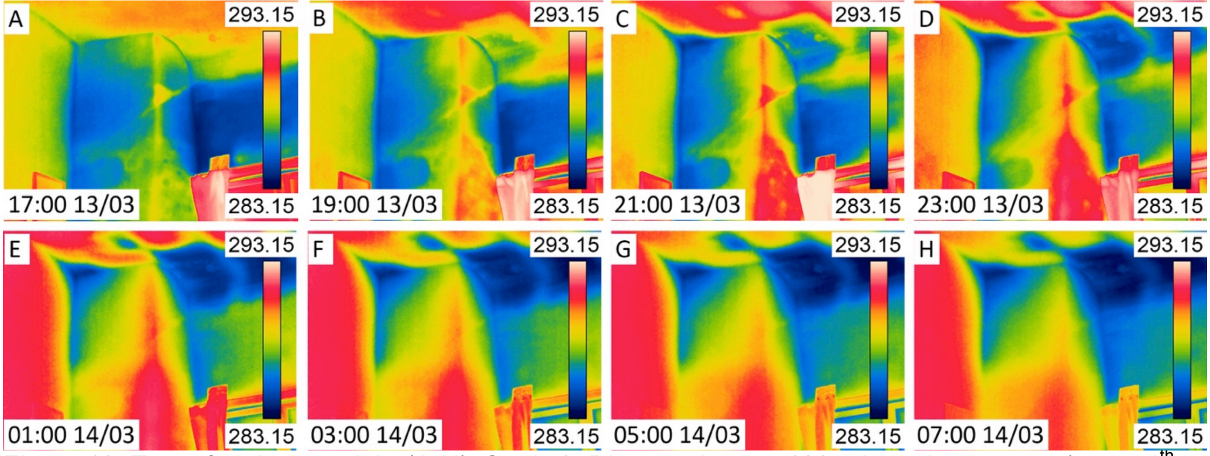

Figure 10. Top left to bottom right (A-H). Study 3. Displayed every 120-minute image only (every 4th image).

Qualitative interest included noticing unidentified features that were seen as bright markings within the cob. These patterns were clearly visible at the start of the investigation (figures 10A–C), though diminished in clarity as the survey proceeded throughout the night, before becoming completely indistinguishable by the end (figure 10H). Above the window was a patch of solid brick walling that appeared cooler than the adjacent cob. Above the brick was a patch located within a corner of the eaves and which appeared even cooler than the brick and other parts of the eaves.

4.4 Temporal resolution exploration

Seeking to investigate the most appropriate temporal resolutions for time-lapse thermography, a series of movies were created of the case studies at different temporal resolutions. The movies used for this analysis can be observed in gif format. Movie: 1 (Building 1, study 1, 30min temporal resolution), 2, 4 & 5 (Building 2, study 2, 20, 120 & 360min temporal resolutions) and 3 (Building 1, study 3, 30min temporal resolution) (Insert links to movie files) uploaded to the Elsevier website. These time-lapse recordings have been processed in the following way. Initially, the movie sequences consisted of each recorded frame, giving the full 20 or 30-minute temporal resolution. To begin with, these were reviewed using qualitative analysis techniques [43], including target signature, target symmetry and target comparison. From this investigation, it became apparent that some images in the sequence were very similar to subsequent images. This is best observed through movie 2, which shows a 20-minute temporal resolution for building 2. In this movie, very little colour change over the concrete block cavity wall between images was discernible. Seeking to address this, further movies at longer temporal resolutions were created for building 2, which included 120 (movie 4) and 360-minute (movie 5) intervals. At 120-minute intervals, the colour change between surface temperatures was much more discernible than at 20-minute intervals, while at 360-minute intervals the spacing did not appear to offer any greater contrast than the 120-minute temporal resolution.

Following qualitative analysis, quantitative analysis was used to measure the change in target apparent surface temperature between images. Figure 11 shows a thermal transect graph, which was plotted for the cob and stone portions of study 1. The apparent surface temperature difference between 30-minute spaced images for the cob gave an average of 0.3K, while for the stonewalling the temperature difference was 0.2K. At 120-minute intervals, the average apparent temperature difference for the cob was 1.2K and for the stone, 0.8K (figure 11).

Comparing the measured apparent surface temperatures of different constructions at 60-minute image intervals, the average temperature differences between images were:

- Cob (study 1): 0.5K
- Stone (study 1): 0.4K
- Concrete block cavity wall (study 2): 0.2K

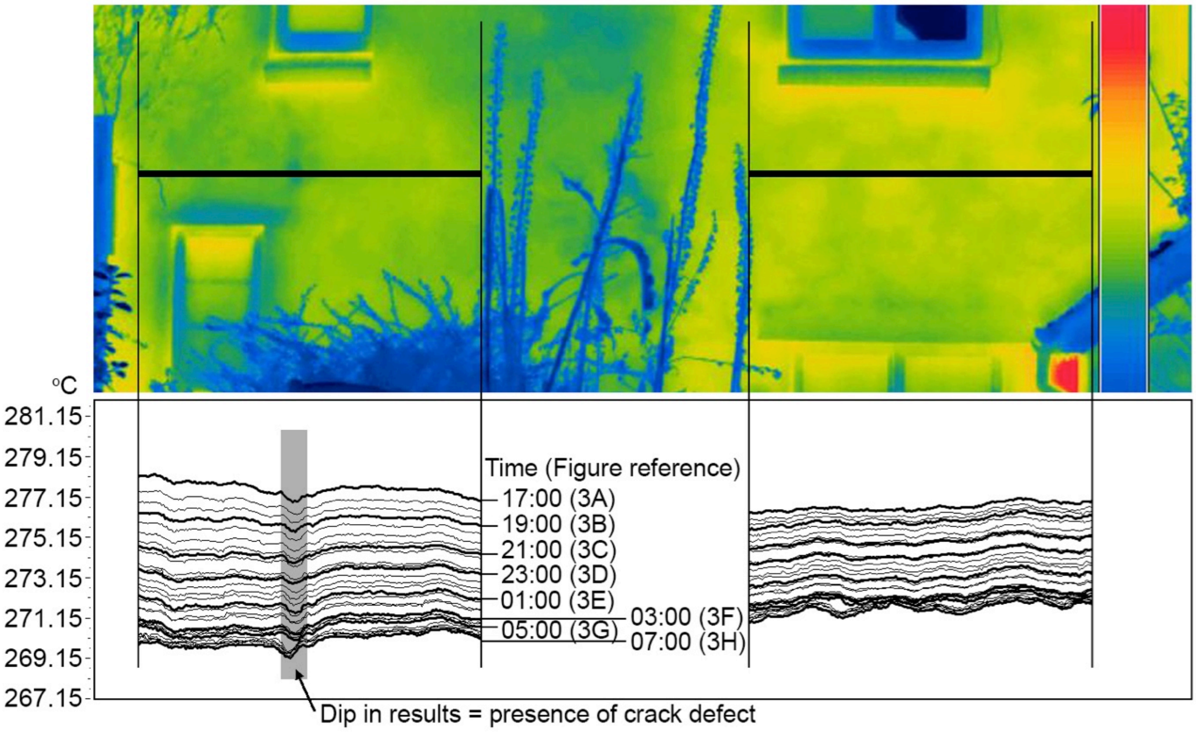

Figure 11. Graph showing thermal transects (taken along the two lines indicated in the thermal image above) plotted for each 30-minute interval thermal image for building 1. Bold lines highlight 120-minute image intervals and correlate with thermal images displayed through figures 6A – H. The grey block within the graph indicates the presence of the crack defect.

5. Discussion

Results shows that time-lapse thermography offers deeper insights into how unknown constructions might be behaving when compared with traditional analysis using thermal images taken at one single point in time. Once a better understanding of how a construction might be behaving (over time) is made, behavioural nuances can be factored in so potential defects become more straightforward to identify and diagnose. Observe study 1, where a warmer patch was identified within the cob walling (figure 8). In this specific case, delamination was identified through gentle tapping of the identified area, which gave a dull hollow sound. It was unclear whether moisture was present beneath the cement render, though Keefe [44] suggests a common failure with cob arises when moisture enters cavities behind cement render via hairline cracks (also observed in building 1). The temperature effects captured through the time-lapse thermography could result from the presence of moisture, because water holds a higher specific heat capacity than other common building materials and will retain heat longer than materials surrounding it [21].

Although the defects identified in study 1 might have been detected using single point in time thermography (following a reduction in thermal mass stored from the previous day), time-lapse thermography enables an assessment through image evolution. Such evolution can be seen in figure 8, which displays the increased temperature difference from approximately 0.1K at 17:00 to 1.0K at 08:00. Giving a time related enhancement of a static technique provides a greater insight into the size of a defect over time. Furthermore, viewing the time-lapse images in a motion sequence helps to qualitatively review the evolution of heat losses, which also indicates how materials respond to changes in transient conditions[1]. This extra layer of information is devoid from single point in time analysis.

Study 1 showed that the effects of solar gain presented a significant limitation to thermographic results. This corresponds with findings by Lehmann *et al*. [28], though largely depends on the elevation viewed, as study 2 was not subject to solar gain in the same way. Once stored, solar energy had been released (study 1), the heat flow from inside to outside became increasingly apparent, leading to a clearer picture of potential defects later in the investigation. Conversely, the internal investigation (study 3) presented clearer images at the start, prior to the introduction of artificial domestic heating. As the wall surfaces warmed up through domestic heating the heat appeared to dissipate through the construction and led to a reduction in image clarity. Had study 3 been undertaken using a single point in time methodology following a period of domestic heating, potential subsurface defects might have been missed or misinterpreted. It is therefore critical to consider the effects different heating sources might have on how a construction might behave, whether from previous solar irradiation or from internal appliances.

Work to develop a time-lapse thermography methodology has shown that there are more practical limitations to overcome externally than experienced within internal investigations. In particular, attention needs to be taken over the security, weather proofing, monitoring of environmental conditions and power supply for the thermal camera. In light of these key limitations and methods for overcoming these, the time and effort required to setup and maintain a time-lapse investigation for prolonged periods of time are quite considerable and might prove prohibitive for non-specialist commercial application. Also, it should be remembered that at distances of approximately 20m from the target surface, defects smaller than 41.6 x 41.6mm will have been missed. This is potentially significant since not only will small defects be missed, but the edges of detectable defects will not necessarily be accurate. For example, the assessment of the perceived crack in study 1 (figure 7) might not have been very accurate due to its width being less than 41.6mm.

With regards to the selection of temporal resolution for time-lapse analysis, results from the three studies showed that a greater accuracy in surface temperature difference (lower temperature differences between consecutive images) was gained from shorter temporal resolutions. Whilst a high degree of temperature accuracy, such as a difference of 0.2K between image intervals, might be required for quantitative analysis, for qualitative analysis such low differences were not visually discernible. Instead, temporal resolutions that gave approximately a 1.0K surface temperature difference between images seemed more appropriate.

Temperature variations between each of the observed construction types tended to be greater or smaller when viewed at the same temporal resolution. This suggests that the temporal resolution selected will largely depend on the type of construction being monitored, where, for example, more modern and highly insulated constructions will show less heat flow (from inside to outside) compared with older solid masonry constructions.

Further analysis of temporal resolutions showed that apparent surface temperature differences between consecutive images could fluctuate significantly, as seen through the thermal transect in figure 11. For example, temperature differences between 60-minute image intervals for the cob in study 1 started at 1.4K between 17:00 and 18:00 before ending at 0.2K between 07:00 and 08:00 the following morning. This result was most likely due to transient changes in environmental conditions, such as the thermal mass experienced in study 1. The impact of this is significant because if a temperature difference of no greater than 1.0K is desired between consecutive images, then a temporal resolution shorter than 60-minutes might be required to ensure that all temperature differences are below 1.0K.

This work has demonstrated how environmental conditions and building properties can fluctuate over multiple days (study 2), giving a surface temperature difference of about 2.0K between images recorded at identical times over three days. This was as a result of transient environmental conditions such as air temperature, precipitation and cloud cover, which had an impact on the apparent surface temperature results during the entire study period. Consequently, if thermography were conducted

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[1] *This paper shows a small selection of the experiment images. All of the thermal images will be uploaded to the Energy and Buildings Journal website.*

externally on just one of these days, the results would be different to that undertaken on another day. This, therefore, questions the ability to obtain accurate results from relatively short time-lapse investigations and particularly from single point in time images, indeed Biddulph *et al.* [45] recommend in situ investigations of at least 3 days for better estimation of u-values using heat flux sensors. Therefore, if quantitative analysis using time-lapse thermography were to be pursued, it would be advisable to conduct investigations over at least 3 days before taking averages from the results and drawing conclusions on how environmental conditions are impacting the results.

6. Conclusions

This paper has explored the practical application of time-lapse thermography for building defect detection. Contrasting time-lapse thermography with traditional single-moment-in-time methodologies, it was evident that although traditional studies might be useful in capturing particular defects at one moment in time, this methodology is often constrained by physical limitations, such as reflected radiation and the interaction between transient weather conditions and materials (solar gain and moisture). This makes the process of formulating assumptions related to defect behaviour or thermal transmittance using single-point-in-time images particularly challenging. Passive time-lapse thermography, however, has been shown through this paper to enable the evolution of heat loss to be observed and thus better understood.

Through the application of time-lapse thermography, a methodology for such an investigation has been developed in this paper. This addresses practical limitations, comprising of safety and security concerns, spatial resolution / FOV limitations resulting from camera distance to object surface, unwelcome foreground objects, difficulties observing front elevations and challenges involved with supplying continual power to the thermal camera.

The work also investigated the different temporal resolutions required for time-lapse analysis of different building constructions. Qualitative analysis of the time-lapse movies recorded at 20–30 minute image intervals showed that some images in the sequence were visually identical to others, not helping to discern variations within thermal patterns. These studies found that the apparent temperature difference between consecutive images varied with construction type, indicating that no single temporal resolution would fit all circumstances. Because assumptions are sometimes made on constructions, it seemed appropriate that the thermal camera should capture images over a short time frame using temporal resolutions of less than 30 minute intervals, before analysing and reducing the temporal resolution depending on initial results. Quantitative analysis, such as U-value determination, might require more accurate / lower temperature differences between images compared with qualitative analysis, and may therefore require shorter temporal resolutions.

On-going work is currently reviewing the use of time-lapse thermography for quantitative analysis, and specifically the determination of U-values, through work that combines in-situ observations with observations made in a controlled environment (hot/cold box set-up).

7. Acknowledgements

The research in this paper has been funded through a European Social Fund – Combined Universities of Cornwall (EU ESF-CUC) Studentship, with DCH Group and RTP Surveyors as industrial partners. Project Reference: 11200NC05/CUC/Phase2.

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