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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.

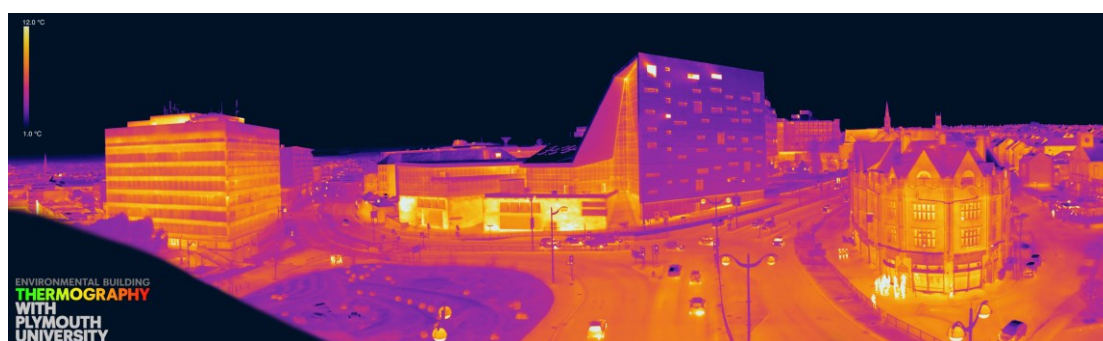


Figure 1. Thermal image of Plymouth University campus.

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 (8-14 μ m) 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.

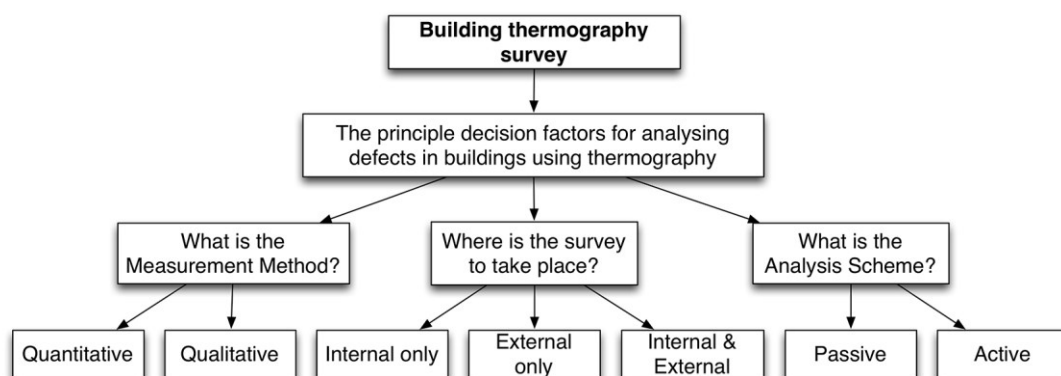


Figure 2. Key decision-making process for the determination of building thermography methodology. This figure has been based upon the author’s training and hands-on experience of surveying buildings in the UK.

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 CO₂ 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.

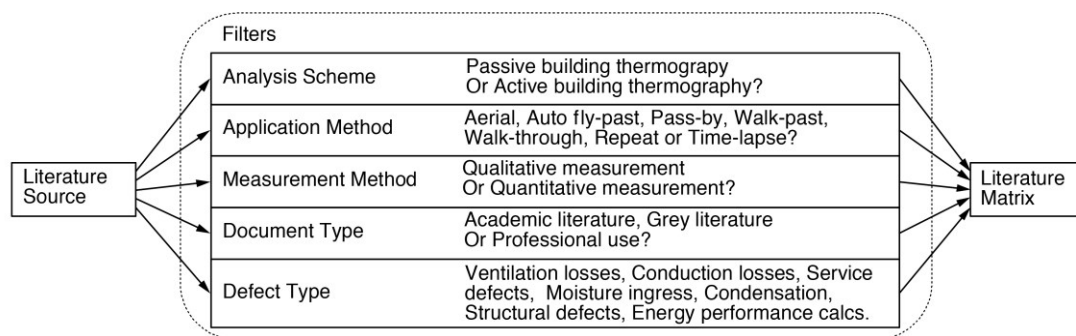


Figure 3. Literature filter diagram.

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	
Measurement method	Q1 = Qualitative,	Q1	Q2	Q1	Q2	Q1	Q2
	Q2 = Quantitative						
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 (walkthrough)										Repeat thermography										Time-lapse thermography																																																																																																																																																																																																																																																																																																																																																																																																																																		
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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.

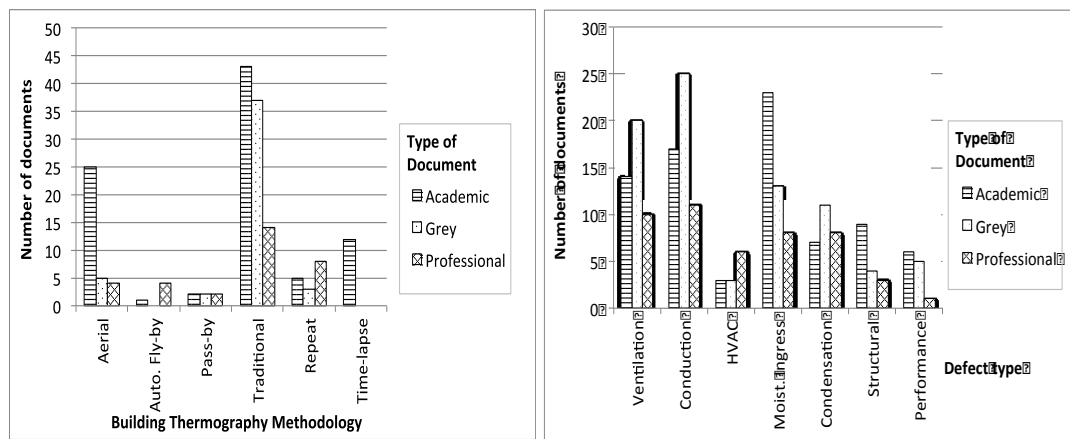


Figure 4. (Left) Literature by source and building thermography methodology. Figure 5. (Right) Literature by source and defect type for traditional passive building thermography methodology.

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.

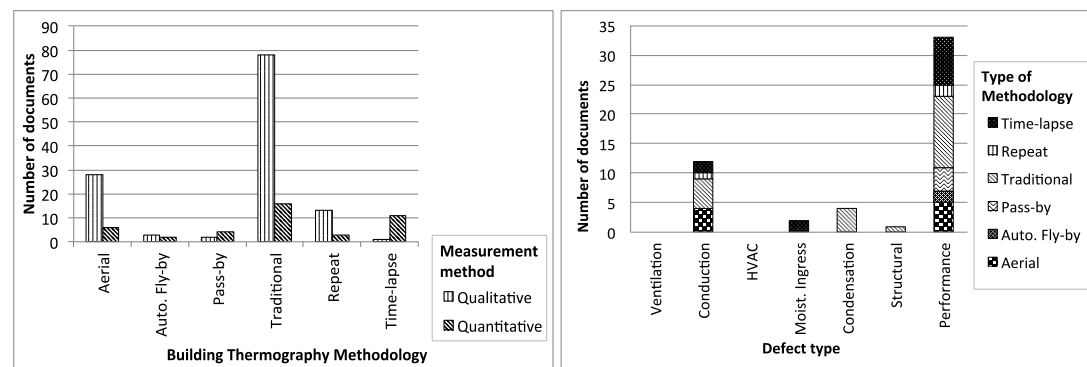


Figure 6. (Left) Literature by building thermography methodology. Figure 7. (Right) Quantitative literature only by building thermography methodology and by building defect type.

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.

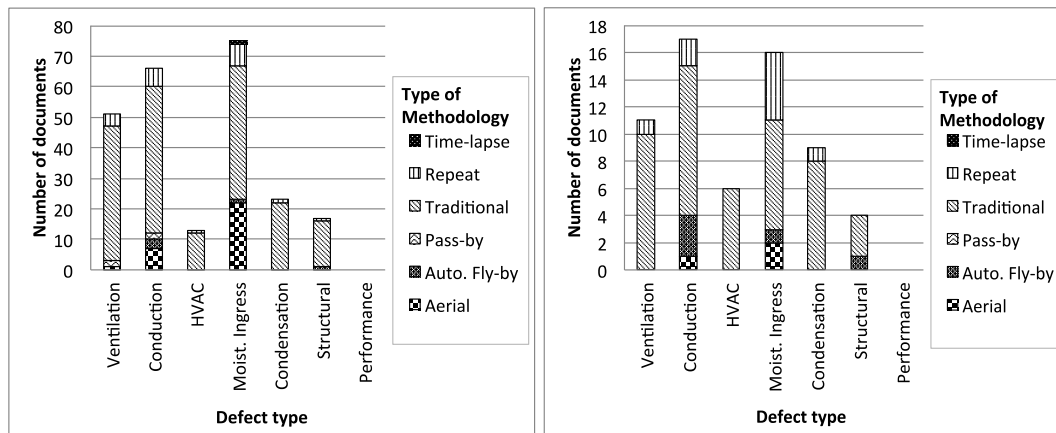


Figure 8 (Left) Qualitative literature analysis by passive building thermography methodology and by defect type for all literature sources. Figure 9 (Right) Qualitative literature by passive building thermography methodology and by building defect type for professional literature source only.

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.

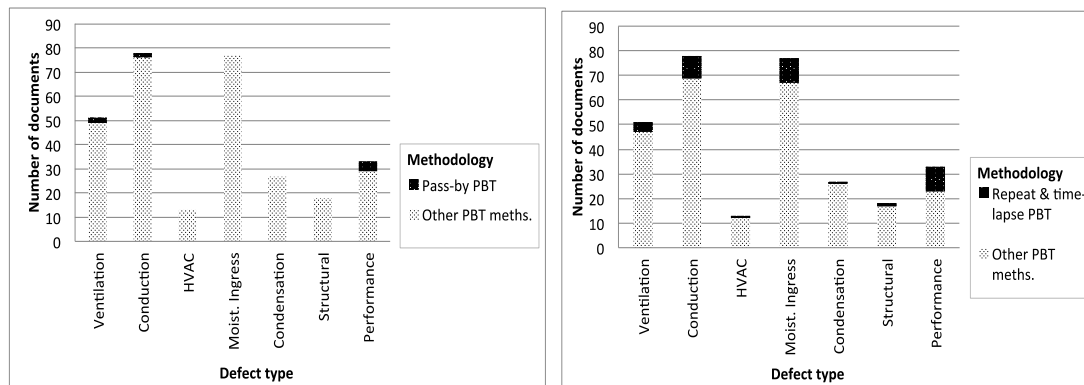


Figure 10. (Left) Literature by defect type with a focus on pass-by passive building thermography. Figure 11. (Right) Literature by defect type with a focus on repeat and time-lapse passive building thermography.

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 CO₂ 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.

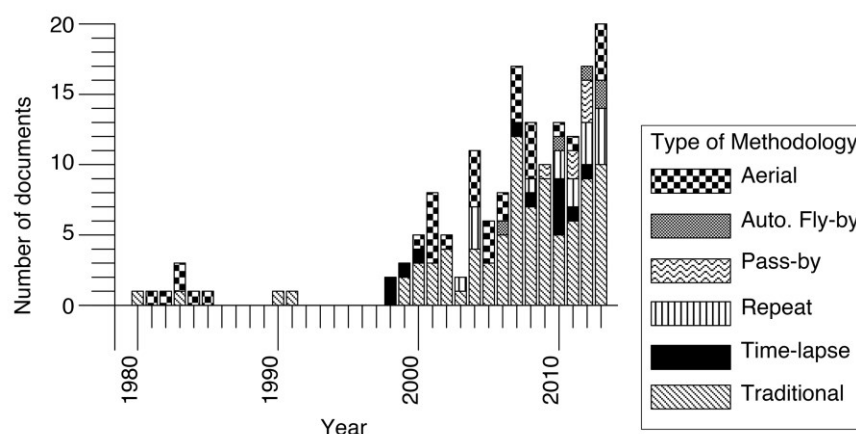


Figure 12. Occurrence of literature by passive building thermography methodology and by date.

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 CO₂ 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 $\pm 25\%$, 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 $\pm 25\%$. 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

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