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Julie Goodhew

Steve Goodhew *School of Art, Design and Architecture*

Matthew Fox *School of Art, Design and Architecture*

Joao Alencastro *School of Art, Design and Architecture*

Gavin Kilip

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Goodhew, Julie; Goodhew, Steve; Fox, Matthew; Alencastro, Joao; Kilip, Gavin

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Visualising Defects via Thermography (DeViz): A combined technological, behavioural and quality systems approach to achieving near zero defect buildings.

Dr Julie Goodhew
School of Art, Design and Architecture, University of Plymouth
Plymouth
PL4 8AA
UK
Email: julie.goodhew@plymouth.ac.uk

Professor Steve Goodhew
School of Art, Design and Architecture, University of Plymouth
Plymouth
PL4 8AA
UK
Email: s.goodhew@plymouth.ac.uk

Dr Matthew Fox
School of Art, Design and Architecture, University of Plymouth
Plymouth
PL4 8AA
UK
Email: matthew.fox4@plymouth,ac.uk

Dr João Alencastro
School of Art, Design and Architecture, University of Plymouth
Plymouth
PL4 8AA
UK
Email: joao.alencastro@plymouth.ac.uk

Dr Gavin Killip
Environmental Change Institute
University of Oxford Centre for the Environment
South Parks Road
Oxford
OX1 3QY
UK
Email: gavin.killip@eci.ox.ac.uk

Abstract

To achieve carbon reduction targets the emissions from buildings need to be near zero. Thermal defects in buildings pose a significant risk to this goal and contribute to energy performance gaps for space heating. A high-performance building envelope is a fundamental requirement towards meeting emissions targets and providing comfort and affordable warmth. Defects in design and installation (e.g., discontinuity of insulation, incorrect detailing, incompatible building systems) can lead to high rates of heat loss, structural damage from moisture build-up and poor user satisfaction. Many defects are invisible upon completion but can be made visible through the correct use of thermal cameras (thermography). Thermal images can help to improve site operatives' awareness towards defects, due to their visual appeal. The DeViz research project trains and guides site supervisors, on UK based construction sites, to use thermal cameras at the 'first fix' construction stage, when there is still time to remedy defects quickly and cheaply. The aim is to provide new, engaging feedback loops to improve quality control in designing and constructing energy efficient building envelopes and close the design-energy performance gap. DeViz pilots a protocol for overcoming the challenges of; a) achieving the required 10ºC temperature difference for imaging, in a mid-construction space, b) accessing the site at the mid-construction point where measurements are meaningful (with the potential for cost effective rectification). Acknowledging the reluctance of some construction professionals to focus on what could be perceived as their mistakes, DeViz, instead frames defect identification as a 'normal' pathway towards better quality, rather than 'blaming the operative'. We investigate the acceptance of and potential barriers to this intervention with construction professionals, using focus groups and survey methods. We present our learnings to date and discuss the implications for continuous improvement quality systems.

Introduction

To achieve ambitious carbon targets, emissions from buildings will need to be reduced. Yet despite efforts to reduce energy demand in buildings (and thereby reduce carbon emissions), there remains a performance gap between the anticipated and expected performance of buildings (Zero Carbon Hub, 2014). For example, one study on new housing in the UK found that energy for space heating could be 50-100% higher in reality than intended (Johnston et al., 2016). A high-performance building envelope is a fundamental requirement towards meeting emissions targets and providing comfort and affordable warmth. There are many factors that contribute to the performance gap but those that are easy to overlook are undetected defects occurring in the build process which confound efforts to reduce energy demand. The occurrence of quality defects in buildings therefore pose a significant risk to the effort of bridging the building's energy performance gap and reducing the energy used for space heating (Topouzi et al., 2019; Palmer et al., 2016, Bell, Wingfield et al., 2010). Defects are defined here as 'physical features of the construction process which are imperfectly designed or installed, and which lead to reduced building performance, occupant satisfaction or both'. By this definition, a defect is physically observable and remediable within the building itself; it is different in kind from other known causes of design-performance gaps, such as poor commissioning, changes of use, occupant behaviour, and inaccurate computer models and design tools. Many defects in the construction of building envelopes are invisible or hidden, but the correct use of thermography can render them visible and, if located in time, remediable with a minimum of extra time and expense (Figure 1). DeViz aims to address the identification, detection and remedy of defects on UK based construction sites, taking a multidisciplinary, technological, behavioural and quality systems approach.

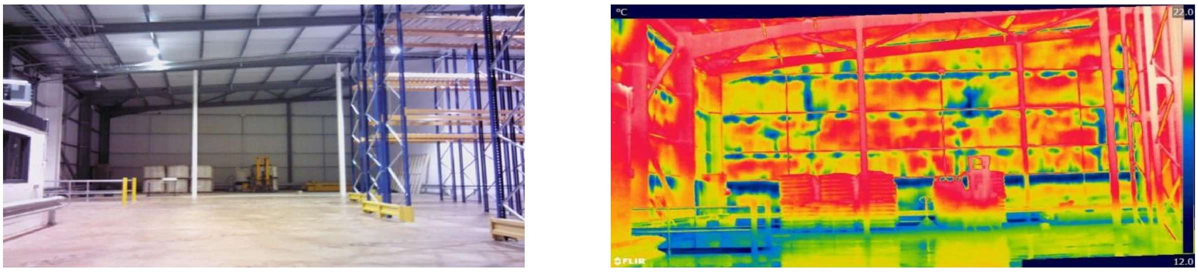

Figure 1: A mid-construction building, early in the build process, in photo and thermal image. The blue areas (cold, according to the temperature scale to the right of the thermal image) show where insulation has slumped within the wall, after installation. This is a defect that can be seen clearly only in the thermal image which has been thermally tuned.

Background/Literature

A Technological Approach: Defect Identification

In terms of a technological approach, thermography can identify a range of defects in buildings which may be invisible/hidden. Defects in buildings can take a variety of forms and might become apparent immediately or later, following a series of subsequent events that alter the condition of a construction component. For many defects, there are visible clues that indicate their presence. However, some defects go undetected due to their nature and or location. While some defects relate to cosmetic (surface finishes) or systems based (services) issues, many building defects, such as cold bridging, potential for water ingress, construction movement and delamination will not only manifest through cosmetic imperfections but are also likely to lead to thermal weaknesses; for example, increased heat transfer via draughts, cold bridging and moisture transference. A study by Forcada, et al. (2014) investigated 68 dwellings in Spain to determine the type and number of construction stage defects detected prior to handover. Results from this work found that of all defect types, the most common (24%) resulted from incorrect installation. Another finding from this study was the low occurrence or observation of possible thermal related defects. Finally, the paper by Forcada et al. (2014) compares construction detected defects with post-handover detected defects. It is reported that post-handover defects commonly concerned cosmetic issues rather than installation or structural defects. Whilst clients value cosmetic quality many thermal defects in the building fabric are concealed by finishes prior to hand-over thus rendering them invisible. The findings from Forcada et al. (2014) (not directly generalisable to DeViz and its UK based location) are particularly interesting when compared with thermal imaging results from a study by Fox et al. (2016), who found that in forty-five occupied dwellings, every dwelling had a thermal related defect, which was difficult to detect without the aid of a thermal camera. Thermography is a common methodology for detecting thermal building defects; however this has tended to be conducted on occupied buildings, with very few studies reporting on mid-construction thermographic inspection (Taylor et al., 2012a, b).

A Technological Approach: Thermography and Defect Identification

The use of thermography and thermal cameras to identify defects in buildings requires specialised knowledge and training. Thermal cameras are specialist cameras, which are constructed to detect infrared radiation. Infrared radiation is emitted from sources depending on their state of heat transfer. A thermal camera is able to measure infrared radiation from an object and transform this signal into a visual image, which a trained thermographer can interpret to determine possible thermal defects or anomalies (Vollmer and Möllmann, 2010). It is important to note that the camera can only detect surface temperatures, though the surface temperature will be influenced by heat transfer mechanisms/paths deeper in the construction.

Defect detection usually involves qualitative thermography, although thermography can take the form of quantitative analysis. Qualitative detection methods involve the analysis of thermal signatures in thermal images. Protocols previously established (Balaras and Argiriou, 2002) indicate typical defects and their pattern characteristics. Some typical pattern characteristics include:

- Ventilation heat loss / draughts. These present a graduated pattern, where the heat loss patterns diminish the further they are from the source (Figure 2a).
- Conductivity heat loss. Patterns present more clearly defined patches of temperature variation. These patterns usually correspond to specific construction features, such as missing insulation or cold bridging through a structural component (Figure 2b and c).
- Moisture ingress defects. These patterns present a mottled heat loss appearance, which varies depending on the moisture quantity in the material (Figure 2d).

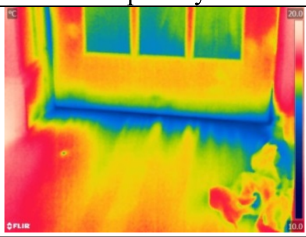	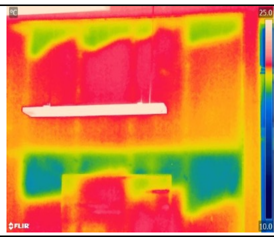
Figure 2a: Ventilation heat loss below a door.	*Figure 2b: Conductivity heat loss*
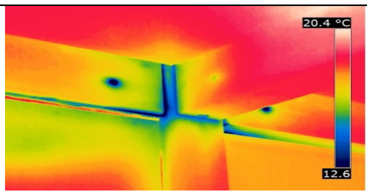	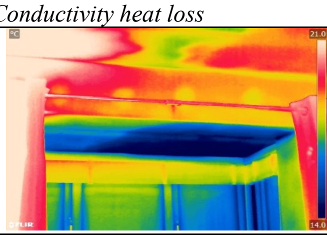
Figure 2c: Cold bridging heat loss	*Figure 2d: Moisture ingress*

Figure 2a -d: Typical thermal defects detected using a thermal camera

The images in Figure 2, taken by the authors of this paper, illustrate typical thermal defects detected using a thermal camera. Aside from the moisture ingress example, it is important to note that none of these defects were visually detectable, nor were they detected prior to inspection with a thermal camera. This further supports the objective to increase opportunities and success at detecting defects early in the construction phase of a building, before thermal related defects are covered up.

In summary, there is a menu of building defects observable via thermography. Training construction site staff to use thermal cameras to identify these defects early in the build process (when the defect is more easily remedied), could improve the final building performance.

A Quality Systems Approach: Defects and Continuous Improvement Quality Systems

The identification and remedy of build defects lies within the existing quality system on construction sites. Whilst the occurrence of defects in construction projects can undermine the achievement of thermal performance targets, it can also undermine the achievement of defined performance indicators such as client satisfaction, budget, and programme. Therefore, over the past decades the construction industry has relentlessly applied a number of management processes and procedures to enable and facilitate the achievement of defined quality standards (Harris et al., 2013). However, even though the theoretical basis for effective quality assurance is well established, actual quality management practices in the construction industry often fail to deliver expected outcomes related to thermal performance. According to Zero Carbon Hub (2014), the construction industry has already many quality management programmes in place; however, they can prioritise other issues above energy performance. This is mostly because many projects aim to solely achieve statutory approval in regard to thermal performance, where quality compliance is awarded by a third party, i.e., building control bodies, thereby diluting the responsibility of contractors to provide evidence of compliance. Therefore, an intervention which brings thermal performance into the quality system and highlights thermal defects may be able to raise the priority of energy performance within the quality management programmes.

There are several reasons why existing quality management practices might miss energy critical defects. Firstly, the main effort of quality management practices tends to focus on mitigating visual defects; those which are likely to raise warranty claims and cause occupant dissatisfaction in the short term (Tofield, 2012, Auchterlounie, 2009). Secondly, defects that impair the ability of buildings to achieve the expected thermal performance quality criteria (such as the discontinuity of the insulation layer or gaps in the vapour/air barrier which enables heat loss) are often taken for granted as an acceptable outcome of the construction process (Tofield, 2012). Thirdly, implementing quality management practices in the construction sector has often proved challenging. The challenges emerge from the nature of the construction industry itself, where projects are one offs and implemented in unique circumstances, built and managed by a transient group of companies, including a high level of organizational and technical complexity (Jraisat et al., 2016, Tofield, 2012). Fourthly, the lack of substantial procedures for sharing learned lessons between and with other projects impacts on potential continuous improvement. As identified by Gorse et al. (2012), Jraisat et al. (2016) and Alencastro et al. (2018), the construction industry lacks continuous and consistent quality appraisal. A standardised and robust quality assessment and reporting process could facilitate benchmarking across different projects within companies, contributing to continuous improvement towards achieving buildings' thermal performance.

However, assessing the quality of build often goes beyond the currently used technology and quality systems, instead residing with site supervisors (on large sites). Achieving a high-performance building envelope for new build or retrofit raises the importance of the site staff as it requires the elimination of build defects by site staff (Topouzi et al., 2019). Indeed, quality systems (e.g., PAS 2035, Soft Landings, BSRIA) recognise this. Achieving zero build defects at a single build level requires (and assumes) that site supervisors be skilled and able to know, understand and assess their own sub-contractors' work. Therefore, upskilling site supervisors to better identify invisible defects can support better quality and building performance. Indeed, there are calls for an overall improvement in quality of building, one that integrates feedback loops that support site supervisors and incorporates a '*knowledge, management and communication* approach into quality (Killip et al., 2018, p.10; Zero Carbon Hub, 2014). Achieving a near zero building requires a zero-defect culture on site and authors have also called for a general increased culture of quality, one focused on firstly evaluation & then enforcement of quality in construction (Fawcett and Topouzi, 2019).

A Behavioural Approach: (Thermal) Images and Behavioural Determinants

A change in culture towards defects and quality implies a behavioural change approach for site operatives. Thermal images, used as a behavioural intervention, have already been seen to have a motivational quality; the images providing new goals for individuals where they can relate them to their previous actions/behaviours (Goodhew et al., 2015; Boomsma et al., 2016). Earlier research suggests that thermal images are vivid and more readily recalled (less easily forgotten) compared to other mediums of communicating energy reduction issues. When thermal images were tailored to the viewer (personalised) they attracted increased attention and were more likely to be shared, discussed and elaborated (Boomsma et al., 2016). Taken together this drives motivation, aiding the formation of goals which in turn prompts behaviour (Pahl et al., 2016). However, most research has measured the behavioural response of homeowners and less is known about the different context of a construction site.

However how an individual reacts to an image (thermal or not) depends on psychological factors, prior attitudes, perceptions and beliefs. Having seen a defect, how an individual feels about their capability to address that defect also affects their behaviour (perceived self-efficacy). The thermal images of defects might assist the site supervisor with this aspect as they do to a certain extent communicate specific action that needs to be taken (replacing the insulation in Figure 1). However, it is important that individuals know 'what' to do or how to rectify a situation (action related knowledge) and also know the benefits of taking that action (effectiveness knowledge) (Steg et al., 2015). These can be seen as preconditions that are needed to drive the behaviour that is desired. Additionally, feelings of pride in work and the perceived respect of others (see Tracy and Robbins, 2007) may affect how images are interpreted. These behavioural determinants can therefore underpin the achievement of quality standards, the acceptance of a building defect identification intervention and attitudes towards continuous improvement quality systems. We return to this discussion later, under challenges.

The focus of the DeViz Project is different from standard research programmes in that the research needed is to test and develop a protocol for using thermography to identify defects on site, mid build. Therefore, this paper is structured to firstly explain the challenges faced and then propose a protocol that will be the focus of investigation. How DeViz will assess the impact of using the protocol, on behaviour, on quality and on the quality culture is explained in the methodology section.

Challenges to Methodology

There are a series of methodological challenges which we divide into two branches: technical challenges around using thermography in mid construction; and behavioural challenges.

Technical Challenge of Surveying for Defect Identification

There are technical challenges in using thermal imaging on site and especially in this novel manner; during mid-construction.

Firstly, a key outcome is to develop a robust and practical protocol for undertaking thermography inspections during the construction phase of a building project. Thermal imaging of buildings has been proven to detect a variety of potential thermal defects in buildings (Brady, 2008), however it is not without limitation. Such limitations include emissivity variations and surface finish, climatic conditions and user application (Hart, 1991).

Material emissivity is a known limitation in thermography inspections of buildings (Walker, 2004). For completed buildings, internal painted plaster surfaces tend to have emissivity values >0.9, which means most infrared radiation received by the thermal camera is emitted rather than reflected. Prior to the installation of finished surfaces, it is not uncommon to find a variety of construction materials. Some of which contain low emissivity materials such as aluminium foil. Low emissivity materials are those with an emissivity value <0.5, which means that surfaces will reflect more radiation (from surrounding sources) than is emitted from the object being inspected. When this occurs, it is possible to miss or misinterpret potential defects unless proper understanding of emissivity and material properties is gained. Externally, emissivity can be equally challenging, especially given the greater pallet of facade treatments available, many of which comprise metal or glass materials. Whilst emissivity can be mitigated by adopting awareness of material properties, climatic conditions can prove to be particularly challenging and unpredictable during a thermography survey (Pearson, 2011). Some of the key climatic conditions that need to be considered to use thermal imaging on the construction site (mid build):

- Ensuring at least a 10ºC temperature difference between internal and external environments to the construction being viewed.
- Avoiding the effects of solar exposure and stored thermal mass.
- Avoiding the effects from moisture on surfaces and precipitation in the atmosphere.
- Minimising the effects of wind movement.

Although most climatic conditions can be mitigated through attention to their possible effects on the building, the 10ºC temperature difference between inside and outside spaces is most critical to inspection. The greater the difference, the more pronounced the thermal signature, as conductive paths (cold bridges etc.) will be subject to higher temperatures. To help achieve this temperature difference, thermal imaging is usually conducted early morning or late evening (hours of darkness) and during the winter months / "cold" season (October to March) when active heating systems are more likely to be on, and external air temperatures are at their lowest. In completed buildings control of the internal thermal environment is relatively easy. However, for buildings mid construction, internal climate control is more challenging. Additional limitations include:

- Difficulties in sealing incomplete buildings

- Construction programmes might not coincide with the “cold” season
- Active heating systems are rarely operational prior to hand-over

Another limitation to thermography inspection is foreground obstructions (Colantonio & McIntosh, 2007). In completed buildings, foreground obstructions might include tables, pictures, equipment, trees, cars etc. which can make inspection of all external surfaces difficult. For buildings under construction, foreground obstructions are also likely to limit the ability to detect potential defects. Taylor et al. (2012b) discusses this issue with regards to scaffolding, which can obscure views of the building. There is also likely to be stored material, equipment and other temporary works that might obscure inspection.

Underpinning each of these limitations is the most critical factor in thermography, which is user ability (Mauriello et al., 2015). In recent years thermal cameras have become much smaller, improving resolution and cheaper, which has led to a greater awareness and accessibility of thermography as a technology. However simply possessing a thermal camera does not make someone a thermographer. There exists a significant risk that those using a thermal camera might mistake or misinterpret thermal signatures. This is if the user is unaware of heat transfer physics and key thermography limitations. The ability to interpret and correctly diagnose defects is therefore limited by user ability. Addressing user ability, there exists three levels of thermography training (BINDT, 2017). These courses guide users on infrared and heat transfer physics, camera control and defect identification, however these courses are not mandatory and there remains the possibility that few with lower cost thermal cameras will wish to invest in costly training. In conclusion, training is important.

Behavioural Challenges

Using thermal cameras affords the opportunity for site supervisors to learn and have new information tailored to their build process, in so doing there is the potential to empower the site supervisor towards improved remedying of defects and improving quality/energy efficiency. But construction professionals may be reluctant to focus on what could be perceived as their mistakes and might react to the images of defects in a negative or defensive manner. How do we address this?There are various reasons why site supervisors might react in a negative manner to seeing defects during the build; the idiosyncratic reaction of individuals to images, the way the images are communicated (i.e., ignoring behavioural determinants that are preconditions) and the prevailing environment.

Firstly, images are subject to alternative interpretation (not always perceived in the way the communicator intended). Images ‘stand in’ for meanings and can be emotive stimuli, where viewers find themselves forced to engage or disengage (Joffe, 2008). They can trigger negative responses of unease, thereby generating defensive psychological reactions (Nicholson-Cole, 2005). The interpretation of images is shaped by viewer’s beliefs, perceptions and ideas. Herein lies a potential for site supervisors to feel wary of the use of thermal images on their construction work. An example in a different domain serves to illustrate. Images showing hydraulic fracking were interpreted differently by individuals depending on their prior attitude towards fracking. Those who already supported fracking were more likely to interpret the images in terms of positive economic gains, whereas those who already opposed fracking interpreted images in terms of negative environmental concerns (Krause and Bucy, 2017). This is important as it illustrates that images can reinforce prior attitudes. In other words, images intended to motivate the building of high quality, high performing buildings, could demotivate, depending on prior attitudes.

Therefore, framing may be important. ‘Framing’ refers to the way that information is presented and in the DeViz context relates to how identified defects are communicated. Famously, Kahneman and Tversky (1985) identify that individuals respond to information using cognitive biases or heuristics; with affect (emotion) and to avoid loss. Seeing (or having another colleague see) a defect in work which you have completed has the potential to feel threatening, for example a) if one feels the potential for loss as a result (e.g., loss of future work, loss of ‘face’ or respect) or b) if negative emotions are triggered (e.g., embarrassment, self-esteem, perceived self-efficacy). Therefore, it is important that information about defect identification does not inadvertently trigger these reactions. Yet we have seen above, that build defects are common, are not easy to see and are not always due to workmanship. Therefore, the dominant frame should be motivational rather than that of ‘blaming the operative’ or ‘policing’. Instead, the occurrence of defects can be deemed normal and their identification as part of the normal pathway towards a better-quality approach. In this sense more positive emotions of pride, perceived respect of colleagues and professionalism might be triggered. However, even then, viewers can understand the dominant message in a communication but still the meaning they take from the image can be coloured by their prior experiences and beliefs, especially Difficulties in sealing incomplete building if those beliefs conflict with the dominant message (Krause and Bucy, 2017).

It is often assumed that individuals know what to do to achieve set goals (e.g., of build quality). However, it is important not to ignore the behavioural determinants that underpin desired behaviours and goal achievement. For example, 'action related knowledge' and 'effectiveness knowledge' (knowing 'what' to do and knowing the benefits of that action) can be seen as a pre-condition for how an individual responds to an image of defects. These two determinants directly predict pro-environmental behaviour (Steg et al., 2015). Therefore, it is important that site supervisors and operatives understand the images and can connect them with the quality standard that is the end goal. Training in understanding the images and the type of defects, can be one way to raise action related knowledge and effectiveness knowledge. Also modelling can help (i.e., having example thermal images of defects available for site staff, alongside information about how to rectify those defects) and showing the exact desired standard of work required. Checklists can help and can be used to guide standards of work.

The prevailing environment is important. Behaviour change is more likely within a supportive motivational and contextual environment (Steg et al., 2015). In other words, site supervisors need to feel motivated and able to engage in the desired behaviour (identifying and remedying defects mid build) after seeing the images. So, what is an (un)supportive environment on a construction site? Feeling able to engage in the desired behaviour might involve allowing time for the process of defect identification and making this an expected, active part of the job role. Ensuring that all site staff understand the quality standard prior to starting work can also be supportive.Even providing examples of the required standard of work (modelling the required goal), may help. Being involved in the process too can enhance the feeling of being able to identify and rectify defects. Finally, providing a supportive environment might mean the removal of perverse rewards or practices on site which might inadvertently act as barriers towards a defect identification and early rectification practice.

From a best practice behavioural perspective therefore, the first step is to research and identify any such barriers to an intervention in the first phase of a project (Steg and Vlek, 2009; MacKenzie Mohr, 2008). Additionally, the challenge is to monitor for unintended psycho-social consequences. Focus groups and observations can be used to explore behavioural and situational barriers both to the intervention and its expected success. Appeal and acceptance issues can be investigated, and findings used to inform the design of an intervention. Further, relevant behavioural determinants can be identified pre intervention and can be used to assess whether and how an intervention leads to changes in an individual's behaviour. Measures that are important are those that focus on engagement with the images (on recall, elaboration, new goal setting, self-efficacy) and on attitudes/behaviour/practice (self-efficacy, 'action related knowledge' and 'effectiveness knowledge' aspects of pride and respect of colleagues) amongst site supervisors.

In conclusion, identifying defects in buildings through an image has the potential to cause unease amongst those individuals involved in the workmanship under inspection. However, understanding the images, understanding reactions to the images and enabling the rectification of defects is important.

Rationale

Combining a technological (thermal defect identification), behavioural and quality approach into a protocol that is effective in using images to show defects, identifying and rectifying defects mid build has the potential to improve the thermal performance of new buildings. In parallel, thermal images utilised in a manner that enhances self-efficacy is more likely to motivate. Measuring the impacts of the images and the changing behaviour and approaches to quality systems and cultures on site can inform continuous improvement quality systems.

Towards a Protocol for Mid Build Defect Identification Using Thermography.

The thermal imaging protocol comprises the training of site supervisors and the establishing of parameters by which defects mid build can be imaged and identified. The Protocol has two stages: training of site supervisors and thermal imaging.

Training of Site Supervisors

The methodology proposed by Taylor et al. (2012b) makes use of trained thermographers to inspect a live construction site. The DeViz project differs from this, by proposing that construction workers use thermal cameras to review, detect and understand their own defects. The aim being that through deeper understanding of the defect, the operative will improve their practice. Aware of the limitations with user ability, the DeViz approach will be to train contractor thermographers to use TG165 thermal cameras (FLIR, 2017). These cameras have been specifically selected based on their robust nature and ease of use. As part of this training, contractor thermographers will be taught the principles behind infrared physics, emissivity, camera use, potential limitations and defect characterisation. It is not expected that contractor thermographers will attain the same level of training provided by a registered thermography course.This is recognised as a potential limitation to the project, since degrees of understanding and skill might vary between contractor thermographers. This could lead to scenarios where some potential defects are missed or misinterpreted depending on the user. To help mitigate for user error during this project, two level 2 qualified thermographers will train, mentor and review contractor thermographer images.

Thermal Imaging

The most common methodology used by thermographers is the walk-through survey (Fox et al., 2014). The walk-through survey involves a systematic inspection of all external building features (walls, roof, windows, doors, ground floors etc.) whereby the camera is used to scan for possible thermal anomalies. Thermographers will conduct both an internal and external inspection using this methodology and any findings will be recorded for later analysis. The benefit of this methodology over others, such as time-lapse thermography is the ability to quickly inspect all parts of the building fabric during a single survey session (Fox et al., 2016). This key attribute therefore lends itself to the DeViz project.

To date, most walk-through thermal imaging inspections have been conducted on buildings in-use or post completion, with few studies exploring thermography for mid-construction use. One such study by Taylor et al. (2012a) outlines a methodology for inspection of buildings mid-construction. This is a useful basis for the DeViz approach, which shall include this methodology:

Utilise an active heating system.

Addressing one of the key limitations to thermography inspections, the DeViz approach shall make use of an active heating system to warm the internal environment of the building. Taylor et al. (2012a) discuss this at length and propose three options for heating the building prior to inspection. These are:

1. Utilise the installed and commissioned buildings heating system.
2. Use electric radiant heaters to spot-test specific building components.
3. Use electric fan heaters to bring the entire building envelope or zoned areas up to a suitable air temperature for thermal imaging.

However, heating a live construction site is not without limitation. Taylor et al. (2012b) indicate practical concerns, such as raised insurance premiums due to the potential added fire risk, and the need for heating systems to utilise 110V power supplies. It is judged that it is likely that heaters will need to be active for 24 hours prior to inspection.

For thermal anomalies to show clearly, the temperature difference between indoors and outdoors needs to be 10°C, which will be possible using active heating systems in the winter / cooler months. However, it is acknowledged that there will be scenarios, such as outside of winter months, where external air temperatures will be relatively high (above 10°C), making artificial heating challenging. Seeking to mitigate such scenarios, the DeViz team plan to monitor weather forecasts for the coolest period within any given month. Active heating systems will be deployed and where necessary thermal imaging inspections shall be undertaken late at night or early in the morning, when air temperatures will be at their coolest. For the warmest months, the DeViz team will experiment with air-conditioning units to cool internal spaces, thereby reversing the flow of heat from that expected during the cool season. These methods will be further investigated over the coming months.

Selecting an appropriate date for inspection.

As previously indicated, live construction projects operate to tight timescales. It is not always possible to align the thermal imaging “cold” season with construction programmes (Plowright, 2016). It is therefore important to consider key milestones in a construction programme from the outset, carefully planning when thermography can be best undertaken. For this project construction sites have been selected that will be under construction during the winter months. By pre-planning target dates in advance, contractors and researchers can more carefully plan for the setup of electric heaters.

While optimal thermal imaging is undertaken during the hours of darkness, using contractor thermographers to inspect their work will likely mean inspections being undertaken during the day. It will therefore be important to plan dates in line with weather conditions. For example, cold, cloud covered, windless days can offer good conditions for daytime thermal imaging. Daytime thermal imaging will also minimise the risk to health and safety identified by Taylor et al. (2012a), who found increased risks from site hazards at night.

Selecting the appropriate stage of a construction project to inspect.

When planning the thermography inspection within a project programme, it is important to consider at what stage the building should be inspected. All projects are different and have unique programmes depending on the construction system and design. However, since the aim of thermography inspections is to observe thermal anomalies, the DeViz approach will be to inspect buildings after the insulation has been installed.

Sealing of external fabric.

To ensure minimal heat loss from the building during the heating phase, all windows, doors and other openings should be sealed at all times during the heating phase.

Minimising site obstructions

Obstructions on site are to be expected. However, to minimise the impact of obstructions masking defects, the DeViz approach requires easy to move obstructions to be relocated away from external wall surfaces at least 24 hours prior to the thermal imaging inspection.

Methodology for Behavioural Assessment and Assessing the Efficacy of the Protocol.

Working alongside construction companies and site supervisors involved in large construction projects, the ‘intervention’ is the training of site supervisors in the use of thermal cameras, the interpretation of images and the subsequent use of the thermal cameras to identify defects on site and mid construction.

Preparatory Engagement with Construction Site Staff and Intervention Design

Focus groups with site supervisors can explore how thermal images are interpreted and any potential barriers to the intervention, also the appeal and acceptance. When using images as a behavioural antecedent, focus groups are a useful method of testing or capturing individual’s pre-conceived attitudes, perceptions and interpretations (Nicholson-Cole, 2005). Example thermal images or images related to workmanship on site can be shown in a neutral environment and reactions to these captured. These reactions are likely to affect how site supervisors respond to the images. Similarly, exploring site supervisor’s prior attitudes, knowledge and feelings of self-efficacy (the ability to achieve near zero defect, high performing buildings) will be important in designing the manner in which thermal images are presented, the training and the necessary quality assessment context. Attitudes to quality assessments and to building performance can also be captured as these attitudes too may be the same attitudes through which images are interpreted. Therefore, these findings can inform how thermal images can be presented to site supervisors. The aim here is to design out negative affective reactions to the images. Survey tools can capture pre-intervention antecedents of behaviour change. Action related and effectiveness knowledge (knowing ‘what’ to do and knowing the benefits of that action) are especially of interest as viewing thermal images with and without defects could enhance knowledge of what to do to minimise defects and also enhance understanding of the implications of those defects (see Figure 1). Other determinants such as goal setting, perceived self-efficacy and loci of responsibility can also be measured.

Intervention: Protocol of Defect Identification (at Mid-Build)

Site supervisors will identify defects without the thermal cameras (by eye) and document the findings. Then they will use thermal imaging cameras to identify & rectify defects before completion of the build, documenting findings. The number of defects identified without the thermal cameras, followed by those identified with the thermal cameras will be counted and evidenced. The number of defects remedied by the cohort of site supervisors will be counted. Defect identification will be validated by level 2 thermographers.

Post Intervention: Behaviour Change Assessment

A repeat survey tool for site supervisors can capture post intervention changes in antecedents of behaviour change. Semi structured interviews with site supervisors can further investigate their reaction to the intervention/thermal images and defect identification protocol. Follow on observations/interviews with site supervisors can track learnings, changed practices on site and any change towards a culture of near zero defects.

Discussion

From pre-intervention liaison with construction companies and from a combined technological, behavioural and quality systems approach, DeViz has some initial learnings.

Identifying defects which are visible via thermography, on site, mid-build has the potential to assist in the development of a catalogue of types of defects. Such a catalogue aligns with emerging quality approaches that aim to increase awareness towards thermal related defects. By identifying common mid-build, rectifiable defects, these can be communicated to site supervisors and be included in quality control procedures. Such a catalogue can be used as a learning tool to inform predefined procedures that aid the site operative in avoiding these defects occurring in the first place. In addition, a catalogue of defects can be used to form behavioural 'modelling' (Abrahamse, 2009) (i.e., using demonstrations, mock-ups) of the desired quality standard or behaviour on site. Knowing upfront what building elements will be checked and their quality acceptance criteria can potentially support behavioural change. Such an approach also aligns with traditional physical checklists and electronic checklists from emerging proprietary quality assessment systems such as 'Snagmaster' and 'Field View'. (Snagmaster ™ Viewpoint Field View are defect management applications for use on site). These provide detailed checks of build quality sometimes also providing photographic evidence of completed work, to a predefined quality standard. The process of recording specific quality outputs, via photography and thermal imaging, is also in line with the current consultations on the uplift of the Part L (Conservation of fuel and power) of the Building Regulations (England and Wales) and the new Future Homes Standard, focused on low-carbon heating systems and high levels of energy efficiency to be introduced in 2025 (Ministry of Housing, Communities and Local Government, 2021). The two proposed UK regulations suggest the use of time stamped and geotagged photographic evidence for quality compliance.

Earlier in this paper, it was noted that behaviours of individuals might be more likely to change if the behaviour is set within a supportive environment. In terms of the prevailing environment on site there may be potential practices which perversely act as barriers towards a defect identification and early rectification practice. If defects are rectified by a different team of operatives, at the end of the build, this can have the effect of defects being seen as an accepted part of the process, to be fixed by the team at the end. This mitigates against rectifying the defect earlier (with the subsequent advantages of them being more easily and cheaply accessed). In previous work using thermal images as a behavioural intervention, a tailored approach, using images personalised to the viewer has proved to be the most effective in attracting the attention of the viewer. Indeed images 'stand in for' messages/meanings and are subject to the individual interpretation of the viewer. The images are likely to be better understood and accepted if they relate to a known piece of work. In this sense the DeViz approach can involve the enabling of site supervisors to use thermal cameras themselves, in order to assess the building that they are involved in. This deeper involvement contrasts with current accepted use of thermal imaging which involves an approach where a separate team of thermographers take the images and report back, rather than an integration of locating and remediation.

Conclusion

In conclusion, as the DeViz Project embarks on its first phase of research (delayed by Covid-19), our early learnings suggest a protocol for using thermography mid-construction and on site. The protocol accesses the site mid-build and enables the required 10°C temperature difference. DeViz will pilot this protocol and track how defects are rectified following the imaging. Additionally, DeViz can establish a catalogue of defects which are visible via thermography, on site, providing an opportunity to develop a more systematic approach to preventing defects in the future. Such a catalogue has synergies with novel applications of quality assessment checklists and emerging quality management systems. Initial investigations also suggest synergies between a behavioural psychology approach and quality assessment systems. Taking a combined technological, behavioural and quality systems approach to visualising defects via thermography, DeViz investigates the progress towards reducing energy related defects in buildings by identifying defects thermally and rectifying them early.

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