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An innovative approach towards enhancing energy conservation in buildings via public engagement using DIY infrared thermography surveys

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ABSTRACT

Energy consumption in urban environment in the EU accounts for about 40% of the total energy consumption, and the majority of this energy is utilised for heating and air conditioning of buildings. Hence the process of insulating and retrofitting of relatively old buildings is essential to enhance the thermal performance and hence contribute to energy and carbon emission reduction. There is a need to enhance people's engagement and education in relation to such issues to inspire and encourage positive actions and investment from the public. This paper presents an approach of combining a novel training process using a low-cost infrared thermal camera with small scale building model to promote DIY (Do-It-Yourself) infrared survey for the public to evaluate the performance of their own homes in order to identify any issues related to insulation or air leaks from the building envelop to encourage them to take corrective actions. The work included the engagement of 50 people to survey their own homes to capture the technical findings as well as their personal reaction and feedback. The results show that 88% of participants have found the educational session helpful to understand the infrared thermography; and 92% have considered the infrared camera to be an effective tool to indicate location of heat losses. Additionally, 90% of participants trust that the thermal camera has helped them to identify insulation defects that cause heat losses in their homes. Moreover, 84% believe that the thermal imaging has convinced them to think more seriously about the heat losses of their homes and what they could do to improve that. The experimental thermography surveys have shown that many houses have limitations in terms of thermal insulation which have been identified by the participants. This DIY interaction has provided enhanced public engagement and energy awareness via the use of the technology. The financial issues are also found to be critical, as none of the participants would have done the survey if they had to pay for it. Hence, this paper provides a solution for households with limited budgets.

1. Introduction

There is a need for the improvement of public's awareness and engagement in relation to energy consumption in buildings towards more comfortable indoor temperature, energy conservation, reduction in carbon emission and improved sustainability. Thermal insulation is one of the most important factors that enhances the energy performance of buildings [1,2]. With improved insulation, new and renovated buildings will provide an acceptable level of energy conservation. According to the European Commission [1], in 2018 energy consumption in buildings in the EU accounts for about 40% of the total energy consumption and 75% of building stock is energy inefficient with 35% of EU's buildings are over 50 years old. It has been found that 36% of CO2 emissions in EU are produced by buildings. From the above it is clear that the building sector is the largest single consumer with high potential of efficiency improvements. The EU Directive 2018/844 had the goal of reducing energy consumption and carbon emissions by 20% by the year 2020 [2]. The directive also emphasises that all new buildings have to be nearly zero-energy buildings by the same period. Also the Energy Union and the Energy and Climate Policy Framework for 2030 establish ambitious commitments to reduce greenhouse gas emissions further by at least 40 % by 2030 in comparison with 1990 levels [3].

However, many countries in the EU and around the world have an old stock of houses that will still need improvement. To engage the public in this process, they need to understand the comfort, economic and environmental benefits of insulation and addressing any energy inefficiency issues with building envelop. At the same time, the householder needs to identify the nature and the size of the required improvement before any decisions are taken in this respect.

One of the actions which the UK government adopted to increase public energy awareness is the creation of Standard Assessment Proce-

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dure (SAP), which works as a calculation methodology for the energy performance of all new dwellings in UK. The first edition of SAP was published in 1993 and the present version is SAP 2012. RdSAP 2012 is the version, which is created for existing dwellings. The calculation is built on the energy balance in view of a range of aspects to promote energy efficiency [4]. At the end of October 2012 a new government policy launched in the UK by the Department of Energy and Climate Change. This policy is The Green Deal Home Improvement Fund, which permitted loans for energy saving measures for homes in England, Wales and Scotland [5]. According to a UK government report, at the end of December 2016 [6], there were 27.7 million homes in the United Kingdom, 19.1 million of which have cavity walls and 8.5 million have solid walls, 31% of the former had no cavity wall insulation and 92% of the latter had no solid wall insulation respectively. Additionally, 23.9 million homes had a loft, 34% of which were without loft insulation of at least 125mm. Hence, there is still significant potential for improvement of many homes to receive insulation, especially for those that have lofts and cavity walls [6]. Significant research has been done in exploring the benefits of improving the thermal performance of buildings envelop. For example, a methodology to analyse optimum insulation material for the building envelope and its thickness to achieve reduction in energy consumption is presented in [7]; where up to 40% in energy demand can be reduced. Reference [8] presents the results of a study on increasing energy efficiency in collective residential buildings using infrared thermography. As expected, the heating energy consumption is significantly reduced when external or internal insulation is applied. Al-Habaibeh et al. [9] presented a case study of an existing university building, where the insulation has been improved, mainly by adding an internal doubled glazing. The energy saving outcome of the refurbishments estimated to be about 6 °C in winter, which covers an area of 2172 m^2. The study compared between thermal images of the building from 2005 and 2010 before and after renovation respectively. The image comparison showed very clear improvement in the thermal insulation performance. Another study [10] has evaluated energy consumption, thermal properties and internal temperature of 14 dwellings as a result of a solid wall insulation retrofit. A decrease in heat transfer coefficient was calculated, indicating benefits of wall insulation. Friege [11] has investigated private homeowners' insulation activities in Germany, to evaluate the related new policy options. The survey included 275 homeowners, and the result integrated into an agent-based model (ABM). The study found that the regulation factor, in terms of obligating new homeowners to carry out wall insulation has a significant impact in increasing the total insulation rate in Germany by up to 40%, while factors such as economical means and information instruments have a very limited effect in this context. Johansson et al. [12] explored the performance of retrofitting of an old listed, brick and wood building in Germany by using vacuum insulation panels (VIP). A brick and homogenous wood wall selected to be insulated with VIP externally, and hygrothermal sensors were used for recording of measures. The results indicate an improvement of the thermal resistance of the retrofitted wall. Antonyová et al. [13] experimentally measured the thermal conductivity throughout the insulation material of a specific thickness. By using Peltier module, an outside environment temperature of −18°C has been generated on one side of a cuboid section of insulation material. Additionally, the approach allowed testing of the internal thermal behaviour of the material with respect to the thickness and material shape. The method has been applied on several selected insulation materials, and by using statistical methods, the results are particularly useful for determining the efficient thickness when selecting insulation material for building. Hilliaho et al. [14] have investigated the impact of added glazing on the indoor temperature of balconies in Finland's climate. The study involved temperature monitoring of 22 balconies (17 glazed) and their adjacent flats for circa 10 months' period. The results show that on average, the temperature of glazed balconies were 3.0 °C higher than the unglazed ones. The study stressed the effect of three main factors on the glazed balconies' temperature: firstly and the most critical one, is the structural air tightness; followed by solar radiation and finally the heat loss from adjacent building to balcony, which allows the balcony to store the heat loss of the building in mid-winter. According to Kylili et al. [15] infrared thermography is one of the most employed tools among the non-destructive testing (NDT) methods for building diagnostics and to assess thermal performance. A recent literature review paper by Kirimtat and Krejcar [16], has highlighted the importance and the effectiveness of infrared thermography to assess thermal performance. The visualisation of the heat loss from a building during winter nights, when the image is taken from outside, can be indicated normally by brighter areas which show where heat is escaping from. The areas of heat loss will be dark when the image is taken from inside which indicate cold points where heat is lost through the building envelop, e.g. through wall, window, door, roof, etc. Mauriello et al. [17] present an overview of increasing the role of thermal data collection techniques, and the future of thermography diagnostic as a kind of Human- Building Interaction (HBI). The reference presents a pilot study of the thermographic energy auditing, where the participants after a simple training offered to use a smartphone-based thermal camera to explore their environment. The study included three participants, who freely inspected different environment around them for 4 weeks' period. The study has a long-term vision to evaluate the opportunity of using thermography by volunteers as an interactive tool to scan and identify issues within building infrastructure.

1.1. Infrared thermography and behavioural theories

Sense infrared technology provides simple visualisation techniques, it has been recognised as a tool for public engagement and communication. According to a hypothesis of Boholm [18], the visuals may challenge a "positioning power" on the observer's mind, which may be resistant to observations that challenge the emotional state they crop. In comparison with the textual material, visual images significantly provide more feat, engagement and concern [19]. The most noticeable difference among the comparative impacts of text/verbal communications against visual messages comes to their emotional effect. It believes that visuals put people in an emotional position where the text/verbal material stay more logical, rational, and linear [20].

The Social Cognitive Theory by Bandura [21] views human as self-organizing, self-reflecting, proactive and self-regulating rather than as reactive creatures formed and driven by environmental factors or inner impulses. The model suggests a dynamic triadic interaction explanation for human functioning, which consist of personal, behavioural and environmental influences. Hence, energy users based on this theory, if they manage to understand the problem of their own house insulation, this 'self-regulating' culture could play an important role for engagement to improve their own homes. The Theory of Planned Behaviour (TPB) can also be used for prediction of intention and behaviour [22]. The TPB suggest that behaviour is dependent on individual's intention, which is, in its turn, depends on individual's attitude, subjective norm and perceived behavioural control. According to the theory, the central element is the individual's intention to perform a specified behaviour and it is expected to catch the motivational factors that influence people's behaviour. Generally, the stronger an intention to involve in a behaviour, the more possible must be its performance [23]. In this case, if occupants of buildings can be encouraged and motivated to take improving measures, this should lead to a better engagement.

The environmentally relevant behaviour model by Matthies [24] differentiates between two types of action: habitual behaviour and conscious decisions. The habitual behaviours are actions made regularly and are not reflected upon, and to these belongs most the energy consumption activities. However, based on this theory, to engage people, they will need to make conscious decisions, for a new norm should take place which is called by the theory 'norm activation'. This behaviour could be related to people's behaviour in buildings, but also could be related to accepting or rejecting the current performance of their buildings and the need to do something about it to improve the

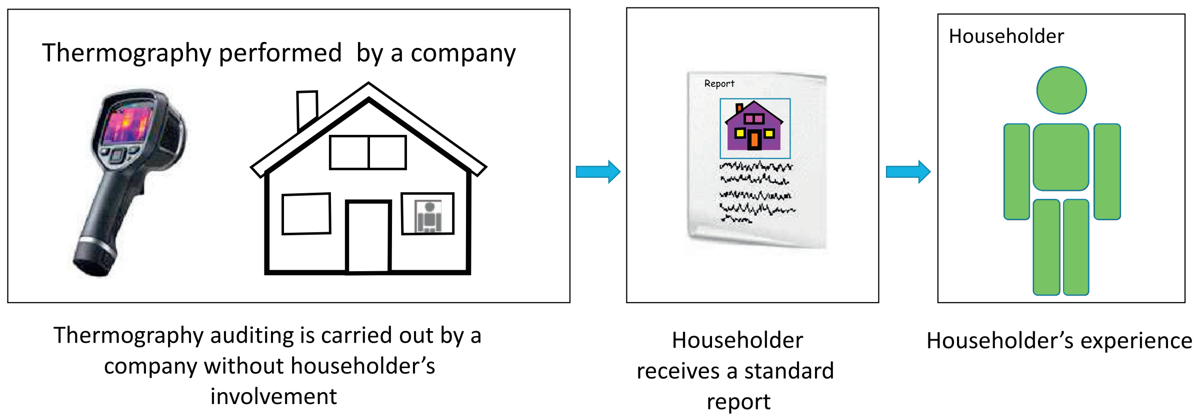

Fig. 1. Traditional thermography procedure.

conditions and reduce the monthly energy bills particularly during winter months. The process of 'norm activation' consists of three stages, including realising the existence of the problem, realising that behaviour (or the lack of action) is relevant to the problem and finally becoming conscious that there is possibility to influence the behaviour and its outcomes.

Hence some researchers have recognised this power of visualization and the influence of people's behaviour to enhance people's performance. For example, Goodhew et al. [25] has investigated the behavioural effect of visualisation of heat loss from residential homes and the consequences for energy saving using infrared technology. By providing thermal images, the study enabled householders to see how the heat escapes from their homes in order to study the eventual motivational impact on behavioural energy conservation. The research concentrates on a new examination of the behavioural effect, which is related to problem visualisation and the ability to encourage residential energy saving measures through such visualisations. The results show potential energy conservation by using the demonstrated visualisation technology. The reference recommends that future work will provide more dynamic visualizations of the heat flows, without identification of a methodology for that. However, the images were provided to participants and explained to them. Balvedi et al. [26] have articulated the effect of people's behaviour on energy consumption and have found that behaviour plays an important role in energy consumption. Pasini et al. [27] have showcased enhanced user engagement to practice energy savings using game approaches to enhance participation and engagement. The link between energy poverty and homes coldness has been addressed in [28]. Other research work also involved the effect of visualisation of infrared thermography on people's engagement [29,30] and results have shown significant effect on people's response.

In this paper, the lessons learnt from literature are combined to integrate infrared thermography with a game approach and behavioural theories to explore a new strategy for enhancing people's engagement to improve their building's performance or their related energy saving behaviour. The game approach is based on using the mobile based infrared camera to discover and identify defects within the insolation. The game approach should be driven by personal curiosity and provide excitement to the participants when using the technology.

2. Methodology

2.1. The new proposed strategy

When the current common practise of using infrared thermography is considered, it only uses the visualisation aspect to inform people about their own house. Fig. 1 presents the common practise of employing a professional person to capture the performance of the buildings via infrared thermography; and the points of concern to be reported and explained to the householder. It can be argued that limited engagement is expected due to the lack of participation; in addition to the expected cost of the professional's time. The report, which is normally done without the householder's involvement, include different calculation that might be difficult for the non-technical person to understand. As result of the process, the householder receives a report with explanation and suggestions for improvements. To address the limitations in the current culture, Fig. 2 presents the suggested methodology which is based on a higher level of engagement. It includes the integration of knowledge, training, game approach, behavioural theories and people performing their own infrared surveys. The argument is that when people do their own infrared surveys, they will feel empowered and motivated to improve the house they live in. Additionally, the impact of the game approach by utilizing the feeling of fun and the motivation to save energy will lead to identification of potential issues within the insulation. Also, if people have limited income and are not able to afford a professional, this approach forms a compromise to provide a reasonable evidence of information.

As shown in Fig. 2, the novel approach provides a thermography training for householders to be able to carry out their own thermography survey of their own house at a very limited or for free. The thermography training consists of a limited theoretical thermography session, followed by a practical training on a simple low cost and low resolution infrared camera (Flir-One) which is connected to a mobile phone. The practical training is applied on a simulation building model which is developed for this purpose [31,32]. The camera is the first version of mobile-based cameras that can be attached to an iPhone 5. To make it easier for participants, the infrared camera and the iPhone5 were lent as one unit to the participants. The camera had a sensitivity of 0.1 °C with blending technology of visual and infrared data. FLIR-ONE infrared images in this paper are displayed with visual edges of the objects to enhance the visualisation due to the low resolution of the original infrared image, which is named Thermal MSX (Multi Spectral Dynamic Imaging).

The training aims to increase the householders' awareness, understanding and motivation in relation to energy consumption in buildings. The thermography survey is an exercise for the householders to implement what they have learned in the educational session and to identify the areas of issues in the building simulator. The infrared measuring system is designed to improve the building energy awareness and engagement, particularly in relation to their respective own building. In addition, it is expected to observe some behavioural changes as a consequence of the visualised insulation issues. The simulation-building-model consists of two identical buildings, an insulated building and a non-insulated one, provided with control and temperature monitoring systems. For further details about the simulator, please refer to [31,32].

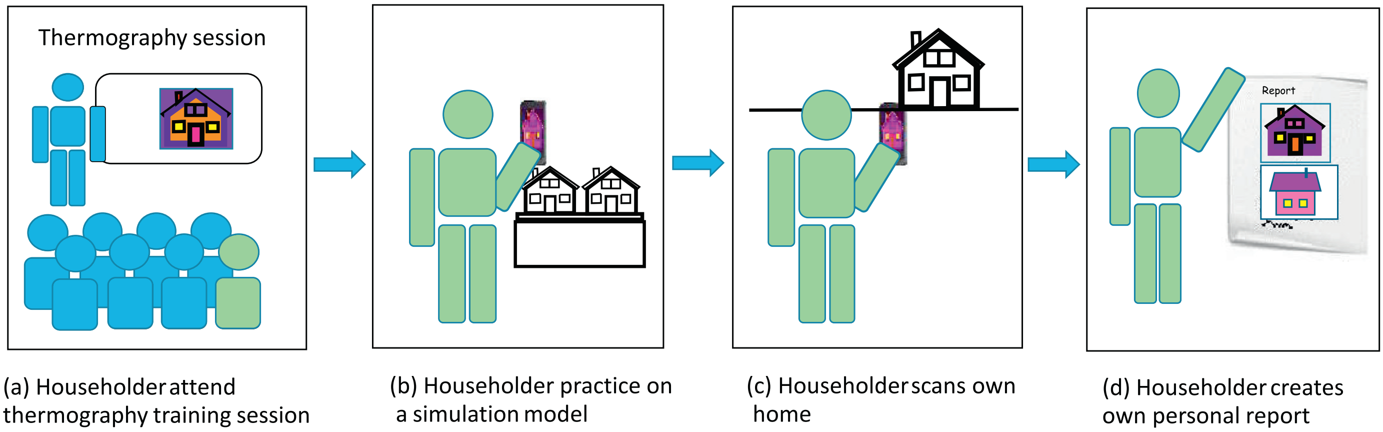

Fig. 2. Schematic diagram of a novel suggested methodology.

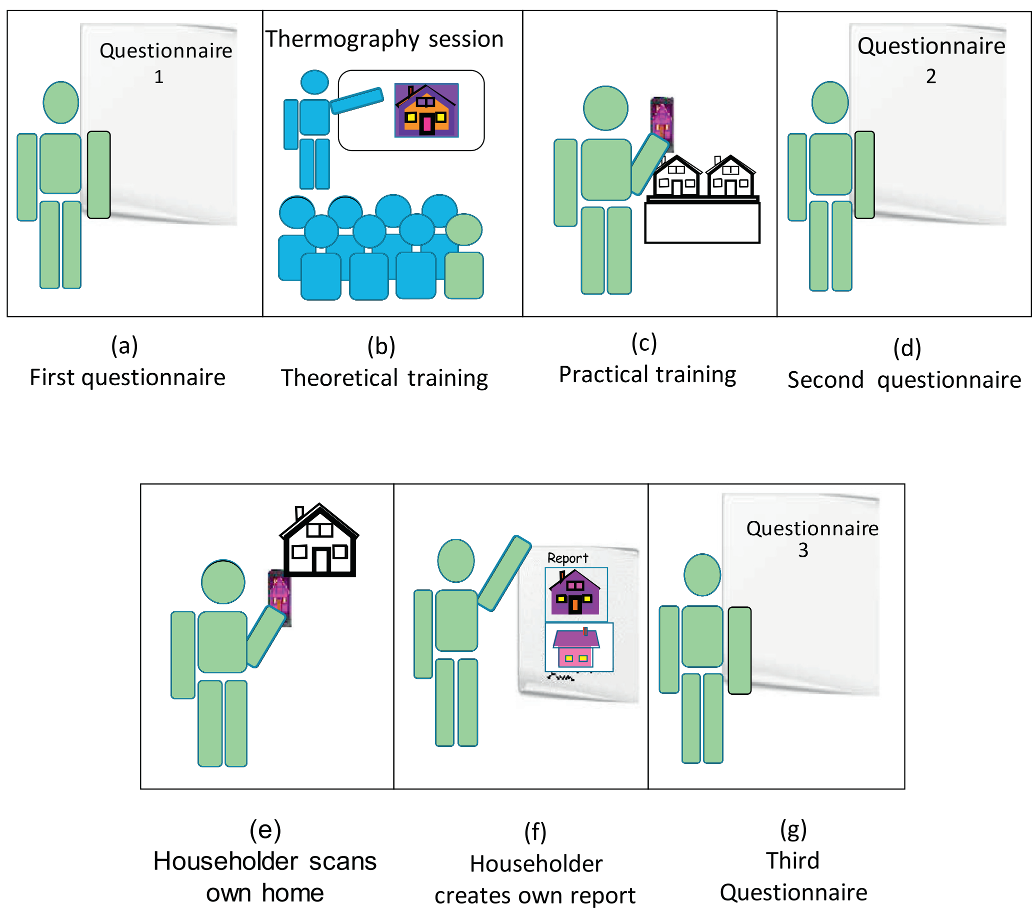

Fig. 3. A schematic diagram of the implemented methodology in this research work.

2.2. Experimental work

The study is designed to investigate the effect of enhancing people engagement in infrared thermography energy auditing by using a low cost thermal camera to scan their own buildings. To assess the value of people doing their own surveys, the study consists of three questionnaires that have been provided to participants between the stages of the process, as shown in Fig. 3.

Questionnaire 1 (pre-test), includes two parts of questions, sociodemographic characteristic part, which cover information about the participant and his/her household and the second part examine the participants' awareness regarding energy consumption and insulation issues related to their specific household. **Questionnaire** 2, covers the educational session, including participants evaluation of the session and what they have learned. **Questionnaire** 3 (post-test), consists of two parts, the first part is a repetition of the second part of the first questionnaire, to compare and assess their energy and insulation awareness related to their own buildings, before and after the thermographic survey. The second part of the questionnaire is related to their thermographic experience of their buildings, potential detected problems and the action may they plan to take to improve the performance of their buildings. The request for participation was advertised and the first 50 people who have responded were selected for this work. The participants have received the necessary instructions regarding health and

Fig. 4. Educational session for participants.

safety before they collected the infrared camera and the associated kit. The health and safety instruction included necessary information about participants' safety while they carry out the thermography auditing of their building. Only thermal images of their own building from outside were required, and indoor images were optional. The instruction included also technical recommendations regarding the optimal conditions for thermography, particularly the minimum temperature difference between the inside and the outside of the building and the most suitable times for thermography. This includes to conduct the survey at night when the temperature difference between the indoor and outdoor is at least 10°C.

The educational session, see Fig. 4, was limited to general information regarding energy consumption in buildings and a training about how to use the infrared camera and carry out the simple thermography survey. Each training session lasted for about 60 minutes only including the experimental training.

The thermal measurement system, see Fig. 5, consists of a low-cost smartphone-based thermal camera (FLIR-ONE) connected to a smartphone (iPhone 5). Two identical thermal systems were available to use in this study. Additionally, the auditing kit included a thermometer for monitoring of internal and external temperatures, a reflective vest, a health and safety instruction on how to carry out thermography survey and instruction on how to use the infrared camera. The training was done on the small model rather than an actual building, because the training in this case could be done in a safe and relaxed environment during the day time regardless of the outside temperature and weather conditions. Moreover, participants could attend at the same time and the insulated and poorly insulated building could be seen using the same image at the same time for comparison (Fig. 5-b).

Fig. 5 shows the simulation model of two buildings, one is insulated and the other is poorly insulated. The simulation model help in two ways: (1) to train people on using the infrared camera; and (2) train on detecting issues with building insulation. Each model a base of 20 cm x 15 cm with a maximum highest of 18.5 cm. Wall thickness is modular depending on the insulation used. For full details about the model, please refer to [31,32].

The participates collected the thermal system during daytime and returned it back on the next day, to be able to carry out the thermography during the night time. After the thermography survey, the participants completed the third questionnaire. The thermography survey was carried out between February and March in the city of Nottingham in UK in 2016. The average highest and lowest temperatures were 9 °C and 1 °C respectively. Following the thermography survey, the researchers went through the images together with the participant and discussed quality of the images, the survey experience and the possible actions which may take place to improve the efficiency of the building.

2.3. Houses characteristics

In total 50 householders (n=50), have participated in the data collection, see Appendix 1. The analysis is conducted quantitatively via questionnaires and qualitatively via the response of the participants and comments via the case studies the infrared images they have captured. For a sample of (n = 50) for an infinity population this indicates a margin of error in the sampling process to be ± 12% with confidence interval of higher than 90%. Confidence interval is the probability that the sample accurately reflects the attitude of the population while margin of error is the range in percentage that the population's response may deviate from the response of the sample. Appendix 1 shows the building demographic data of the buildings included in this study, where 42% of the households are owners respective 58% tenants. The biggest group of the properties are semi-detached houses (36%), followed by detached houses (22%). The age of the buildings varies between new buildings 16% (0-20 years old) and old buildings 24% (over 80 years old). Most of the buildings have double glazed windows (80%) and the rest are single glazed. At least 50% of the roofs are insulated, while 28% of householders are unsure if their roof is insulated or not. Appendix 2 illustrates a summary of a sociodemographic characteristic data of the participants and their households, which only include the relevant cases for discussion. Each participant is given a reference number (e.g. P1 for participant number 1) and the results will be anonymously presented in this paper based on the reference number.

3. Results

For the presentation of results, the response of questioner 2 will be initially discussed to identify the feedback about the training session. The results of questionnaires 1 and 3 (pre and post testing) will be discussed using the same graphs. Followed by the quantitative results of the participant's comments and case studies.

3.1. The effectiveness of the infrared thermography training session

When participants are asked about the value of the conducted training session, 88% of participants agree or strongly agree that the educational session helped them to understand the infrared thermography of buildings, see Fig. 6. The results of other questions show that the infrared camera is found to be comfortable tool to use to scan the building simulator (94%), a very effective tool to reveal the heat losses (92%) and is very easy to use (96%) respectively. The results show that 82% of participants indicate an improvement in their awareness of the way in which energy is lost from buildings using the small-scale building simulator such as walls, windows, doors, frames and roof. In total, 88% of participants confirm that the educational session has helped them to understand the infrared thermography, and 84% have indicated that it has encouraged them to inspect the insulation of their own homes.

Many comments expressing increasing of energy awareness after the session are communicated:

> "Teaching session was quite informative." (P20); "Learning how much energy certain types of heaters use and how that translates into actual cost on bills" (P42); " I found the comparison between efficient and non-efficient technology very helpful and effective in understanding energy consumption (P06); "The session made me also more aware of ways to prevent heat lost" (P18); and "The teaching session gave some very good and simple (almost shocking!) examples of efficient use of electricity, I was surprised how much heat is lost through house walls" (P17); "I think the teaching course was good. I already have a background on thermal cameras but it is the first time to use the one attached to iPhone, it is brilliant idea" (P02);

(a) Thermography training on the simulation model.

(b) Using the infrared camera on the simulation model.

Fig. 5. Training the householders on the developed simulation building model, the use of FLIR-ONE camera is shown in figures.

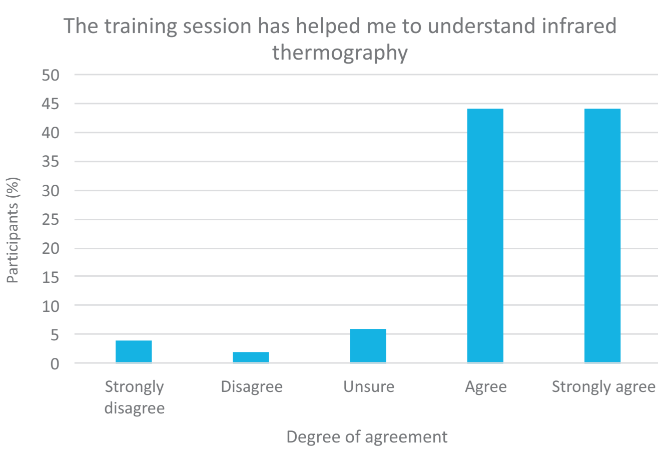

Fig. 6. How helpful the educational session has been in understanding the infrared thermography.

"The session made me very *curious about the heat lost in my house and I was really intrigued by the infrared camera".* (P18) and "[The training session] *made me realise how much we ignore the importance of energy efficiency" (P14).*

Both qualitative comments and quantitative analysis indicate that the majority of participants have found the teaching session of the infrared camera and the building model informative.

3.2. Pre and post testing response

The participants' reaction before training and after the survey is captured in several questions. When they are asked about their awareness of the major energy-loss issues in their own homes, a clear improvement has been identified after they carried out the thermography survey, see Fig. 7. A comparison between the responses from the first questionnaire (pre-test) and the third questionnaire (post-test) shows once again a clear improvement of people's awareness concerning the insulation measures which make the biggest saving effect in their homes, see Fig. 8.

Providing such attractive modern device (FLIR-One) to be used on a smart phone to allow people to inspect their own homes and identify the areas of issues in insulation may increase their motivation to be engaged towards doing home insulation improvement and more sustainable energy consumption. Many of the comments show a significant interest to the thermal camera and the thermal images:

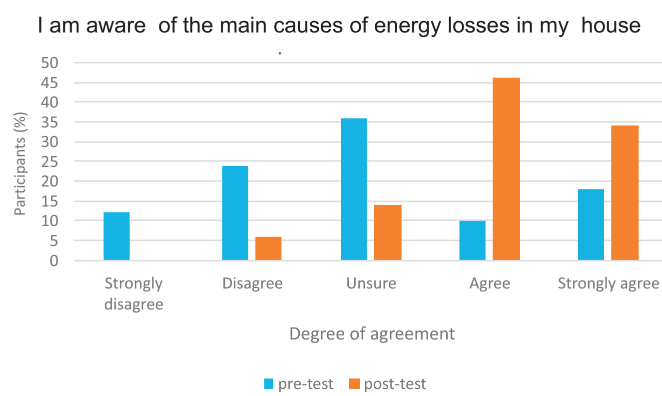

Fig. 7. The pre- and post-test of participants' response regarding the identification of the causes of heat losses.

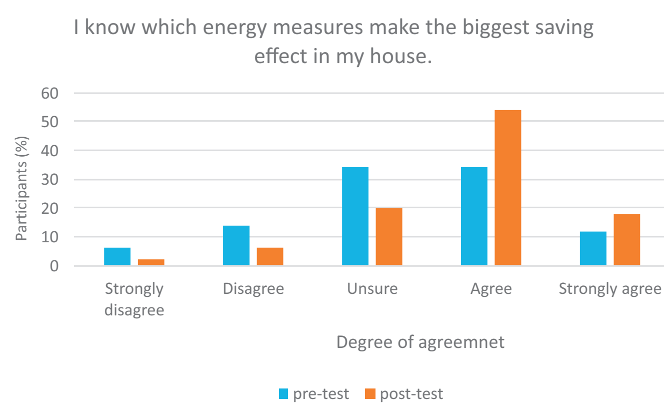

Fig. 8. The pre- and post-test of participants' response concerning the energy measures, which make the biggest saving effect in their homes.

"*This device is quite interesting and amazing because it tells me how and where heat is going out from my room. Now I know how to minimize room-heat loss*" (P12); *"Thermal images revealed that from where the most of the heat is escaping from the house*" (P20); and "*I was very surprised to find that there appears to be more heat lost through the walls than through the roof. I was also very interested to see the improvement*

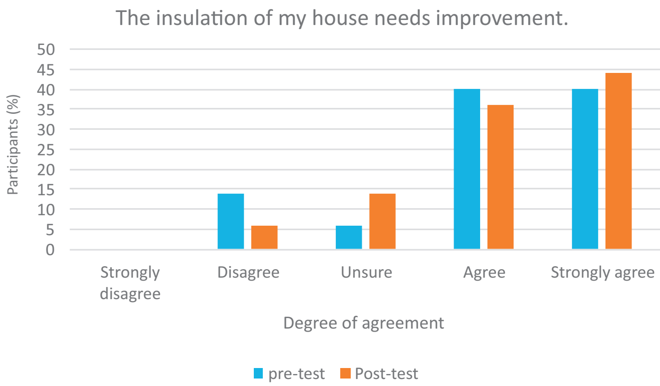

Fig. 9. The pre- and post-test of participants' response regarding the need of improvement in their respective house.

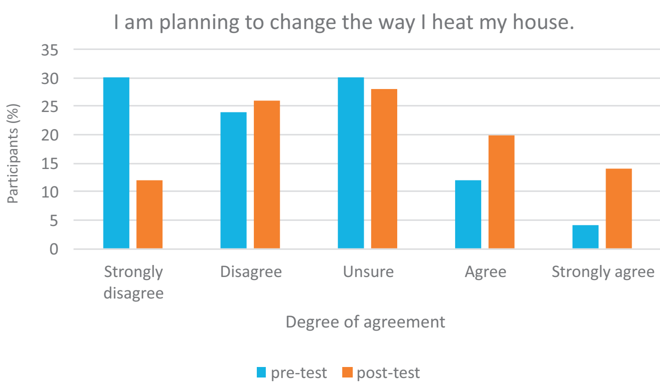

Fig. 10. The pre- and post-test of participants' response regarding their plan to change the way they heat their houses.

in the amount of heat lost through those parts of the walls that I know to be better insulated than other parts" (P48);

In total, 90% of the participants believe that the thermal camera has helped them to identify insulation defects causing heat losses in their own homes; 84% consider that the thermal camera helped them to identify changes they can make to improve the energy efficiency of their homes and 80% of participants agree or strongly agree that their respective house needs improvement, see Fig. 9.

About 84% of participants consider that the thermal images have convinced them that the heat is escaping from their homes. 94% agree or strongly agree that the thermal images helped them to see how much heat was lost from their homes. 84% believe that the thermal imaging has made them think more seriously about the heat losses from their homes. A number of participants are planning to change the way they heat their houses, see Fig. 10, for example reducing the radiators' temperature in some locations.

The householders are found to be impressed with the thermal camera and how it helped them to identify the areas of defect in their insulation in a very easy way (P30, P43 and P47), and measures taken as a result can help in increasing the energy efficiency of the home and saving of money (P32 and P47).

"Using the thermal camera enabled me to detect the areas where the heat escapes, and consequently do something about it to make the house more efficient and ultimately save money." (P47)

According to the participants' comments, along with the educational session the thermography survey they have done promoted the increase in their building energy awareness, particularly in relation to the participants own buildings (P22, P46, P12, P17, P43, etc.).

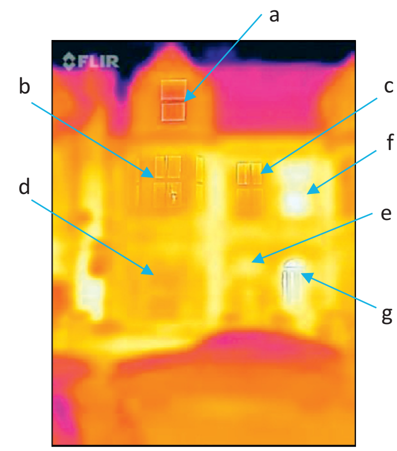

Fig. 11. IR image with visual edges of a building taken by participant P49.

"…the study has created more awareness about the use of energy in the house." (P22)

Different behavioural changes are also observed followed the thermography inspection, for example many of the participants mentioned the use of curtains during the night (e.g. P17, P22 and P46):

"I am trying to use curtains during the night to minimize the heat loss from the window." (P12).

As a result of increasing of awareness and undertaking the thermography survey the householders became more oriented on the way in which they operate the heating of different part of their home.

"I am planning to lower the volume of my e-heater so as to warm my room in an energy efficient way" (P12);

"… will change the sitting of the heater in the corridor to lower temp to decrease the loosed energy, because the place is not well insulated." (P43).

Some householders plan to take necessary actions in order to reduce the lost energy:

"…. installing plastic secondary glazing to more windows and putting up more curtains. " (P17) ; *"… and purchase some door mats to keep the heat in."* (P34); and *"Will look into future upgrades as and when required repairing."* (P33).

Another tenant householder have chosen to move from an inefficient house, and this can be an important message for the landlords to improve their rented properties, which in general use to be less efficient than the owned properties [11].

"I am planning to move out form this house, because I saw a lot of loss energy through the insulation." (P25).

The study has also inspired a participant to raise his ambition regarding his future super-efficient home.

"Participating in this project has even further boosted my desire to design and build my own super-efficient home!" (P17).

In order to match the householders' specific comments with the right images and provide high standard of research quality, the authors have arranged a meeting to discuss with the participants the captured thermal images in detail, and the following comment is one of these examples, where the householder has been satisfied with the efficiency of his house windows and doors. It also shows how the householder got confirmation about the benefit of the secondary door in saving energy, especially when he compares it with his neighbour's, see Fig. 11.

In relation to Fig. 11, the participant stated: "The thermal images reassured me that my three-year-old double *glazing (a, b, c and d) is*

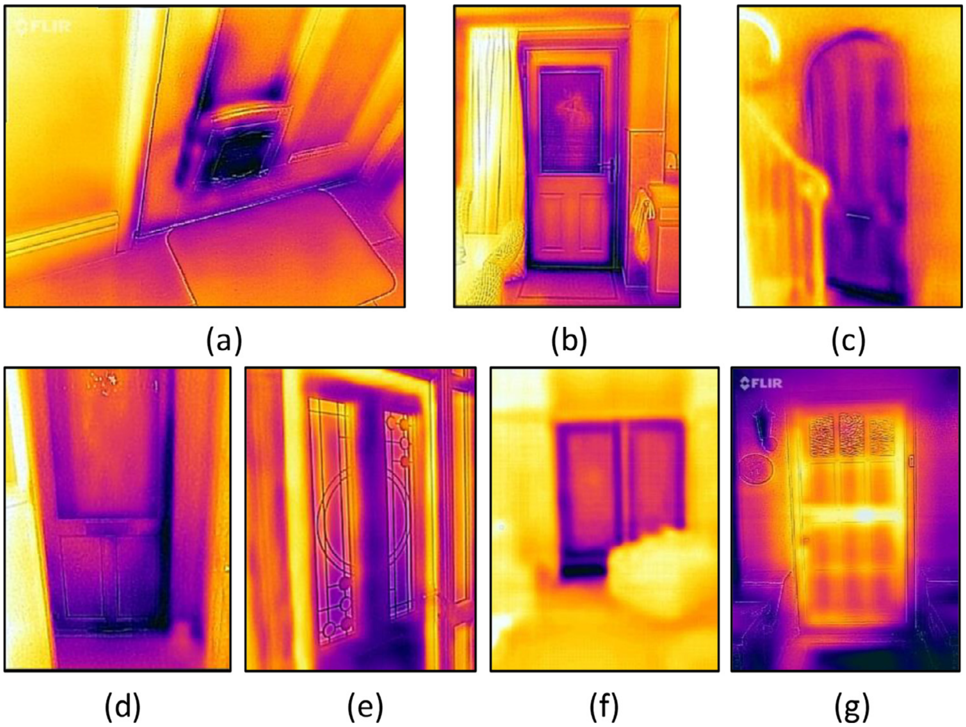

Fig. 12. IR images with visual edges of doors taken by participants, a)P06, b)P13, c)P17, d)P42, e)P45, f) p48 and g)P50.

working well. All the windows were replaced at the same time. At this time of year, the heating is on constantly. [My neighbour] His windows (f) were single glazed. (f) is the 19th Century main door but there is a second single glazed porch door in front of it. My neighbour's door (g) is identical but he has no porch door in front of it" (P49).

3.3. The thermography survey and identification of insulation issues

The results of the thermography survey are divided into five different categories respectively: Doors, windows, walls, roofs and floors. In this section, only the most typical cases are discussed which constitutes only part of the participants in this study (see Appendix 2). The thermal images of the buildings are taken by the householders (participants) and are linked to their own comments.

The comments show that the thermography survey has enhanced the participants' building energy awareness in general and particularly more awareness increasing is observed concerning the individual's own building and its thermal performance.

> *"Using the camera has helped prove some of my previous ideas about heat loss from my house, and also highlighted things that I was unaware of. For example, heat coming through the walls from my neighbours house; effects from heating with an open fire; the effectiveness of simply drawing curtains/blinds."* (P17)

The next sections are categorised based on the basic components of the building envelope which the participants were inspecting in the thermography survey, including doors, windows, walls, roofs and floors; thermal bridges or the slab-facade union issues are discussed within those sections as suitable.

3.3.1. Thermal insulation of doors

Doors and door frames together represents an important part of a building and is inspected widely by the participants in this study.

Fig. 12 (a, b, c, e and f) shows some typical cases of door issues. Gaps around doors is generally a very common problem, even in this study, which mainly depends on the age of the doors in the old homes. In most of the cases, the participants tried to implement various measures to reduce the heat loss through these gaps, e.g. by adding draught seals around the doors or filling the gaps.

> *"In the short term, I am planning to cover door openings, such as the cat flap and any other small openings around the doors, in order to avoid the heat loss noticed through the thermal camera."* (P06); *"I intend to insulate… also draft excluders around the doors.* "(P13); *"… I am filling gaps around doors, adding draught strip around doors."*(P17); *"I am losing heat from around the front door frame, which I plan to reduce by fitting foam insulation strip."* (P45); and *"I may try and improve the draft proofing to the doors .."* (P48).

Some of old, external doors cannot be closed properly, which means loss of heat through these openings between the door and the frame (Fig. 12-d).

> *"Seeing how even small openings/cracks can leech heat and the importance of properly sealing up things like windows and doors. Our external conservatory door struggles to close and it was very obvious from the images the effect that was having."* (P42)

There are even participants, who plan to make drastic improvement of their external doors, by replacing them with new ones (Fig. 12-g):

> *"The external doors will be replaced with double glazed plastic doors in due course and funds allow."* (P50).

3.3.2. Thermal insulation of windows

Fig. 13 presents examples of poorly insulated windows. Old windows, both single and double glazed, and even some low quality new double glazed are a cause for losing energy in buildings, but by using curtains at night times the heat loss through the windows can be reduced, and the participants are aware about that now as a good practice.

> *"As the thermal imaging let me know that most of the heat are escaping from my window (3 pieces' windows), I am trying to use curtains during the night to minimize the heat loss from the window.* " (P12)

Old double and single glazed windows installed before 2002, can need draught proofing. The potential draught in buildings can account

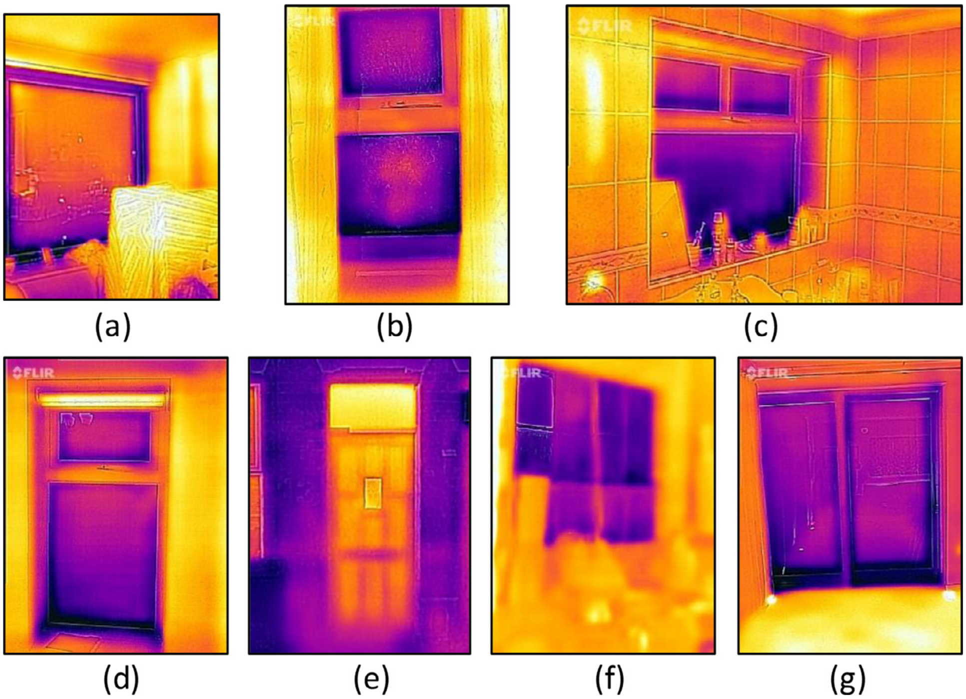

Fig. 13. IR images with visual edges of windows taken by participants; a) P12, b) P23, c) and d) P38, e) P44, f) P46 and g) P48.

for massive amounts of energy loss, therefore draught proofing can make significant energy saving:

> *"adding draught strip around doors and windows that do not have draught strip, or where old draught strip is worn, installing plastic secondary glazing to more windows and putting up more curtains."* (P17).

Again, some participants feel the power of the visual image, which convinces them to plan to replace an inefficient window with a new one, which evaluates as a better solution in term of energy saving:

> *"The thermal imaging showed that heat was being lost through the windows … It may be time to think about replacing my double glazed windows…"* (P23); *"We were thinking about insulating the bay window in the front bedroom which we will definitely do now. … and think about changing the other windows for better quality ones."* (P38); "… *change the single glazed window above the front door to a double glazed one."* (P44); and *"Will upgrade windows"* (P46).

Some of air leaking around the doors and windows can be more complicated, and the household has difficult to deal with.

> *"… the cold spots around doors and windows I think are to do with design faults which would require fairly major renewal work to remedy.* "(P48).

3.3.3. Thermal insulation of walls

Figs. 14 and 15 represent examples of the infrared images captured and the participant's reference number. Some participants are convinced regarding the benefit of insulating their homes, particularly when the energy loss is significant and it feels cold.

> *"I intend to have the bungalow fully insulated from exterior wall insulation, this is where most of the heat was lost in my property*." (P13).

Fig. 14-a in relation to householder P13, shows a bright image of the house is specific locations, which indicate significant heat loss through windows, doors and walls. Fig. 14-b demonstrates indoor image of two completely dark external walls, which means cold areas. Fig. 14-c clearly illustrates that the walls at the right side of the window and the hallway below the window are completely dark, which is again an indication of cold areas.

Most of the homes that built before 1919 probably have solid external walls and they lose twice as much heat as cavity ones do. Insulation of solid walls therefore have significant potential to save energy.

> *"I plan on having the walls insulated as there are no cavity walls thus lots of heat escaping.* " (P14).

Fig. 14-d also represent an inefficient house. Below the window in Fig. 14-e the wall is completely dark, which is absolutely cold non-insulated area. Fig. 14-f shows a completely dark cold external wall, in clear contrast to a bright internal wall and ceiling.

Some participants are surprised over the potential amount of heat, which is lost from their house, and thinking about the potential of improving it.

> *"I saw how much heat is being lost through the exterior walls and how much difference it would make to insulate walls. However, this would be financially not viable.* " (P18).

As image (b) in Fig. 15 illustrates, the external wall is completely dark from inside, non-insulated wall, in contrast to the internal bright warm wall. Some participants were able to discover some defect/damage in their wall, which they did not suspect previously, and immediately they try to investigate and solve the issue in a professional way.

> *"I'm going to contact a builder/expert to look into the heat loss in our back bedroom - there was a lot of heat loss at the top of the side wall (all the way across) where the guttering is externally*." (P34).

Image (d) in Fig. 15 represents a dark path at the top side of the window, which is seen as it spreads upwardly, while the thermal image (Fig. 15-c) of the mentioned window from outside did not show any wall defects. Also, another participant will investigate a potential defect/damage that indicated during the thermography:

> *"We will also look at the small front bedroom above the window -there was a lot of heat loss there too."* (P38)

Fig. 15-e illustrates another dark path above the window, which spreads down.

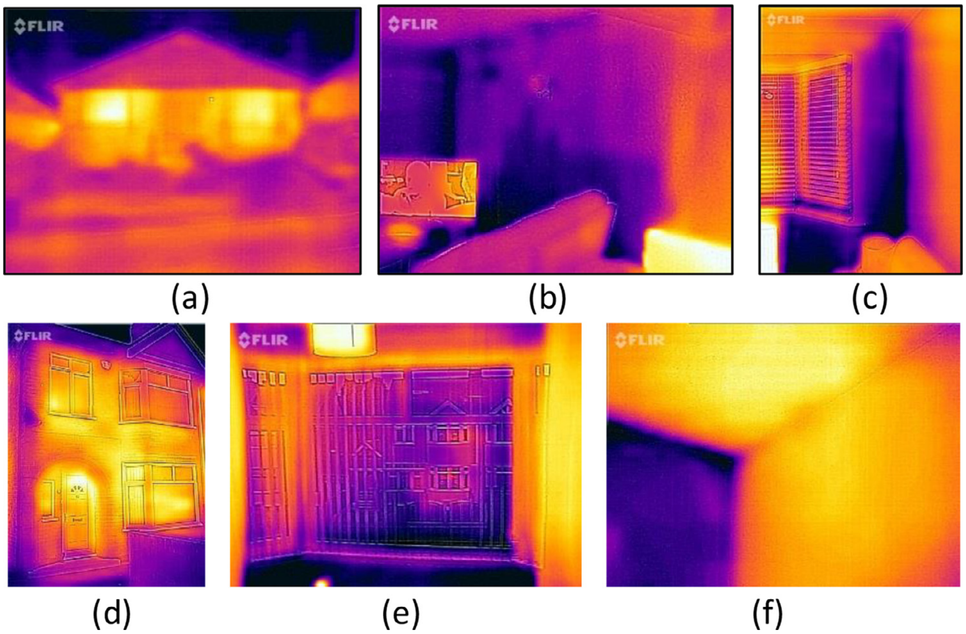

Fig. 14. IR images with visual edges of walls taken by participants; a), b) and c) P13, d), e) and f) P14.

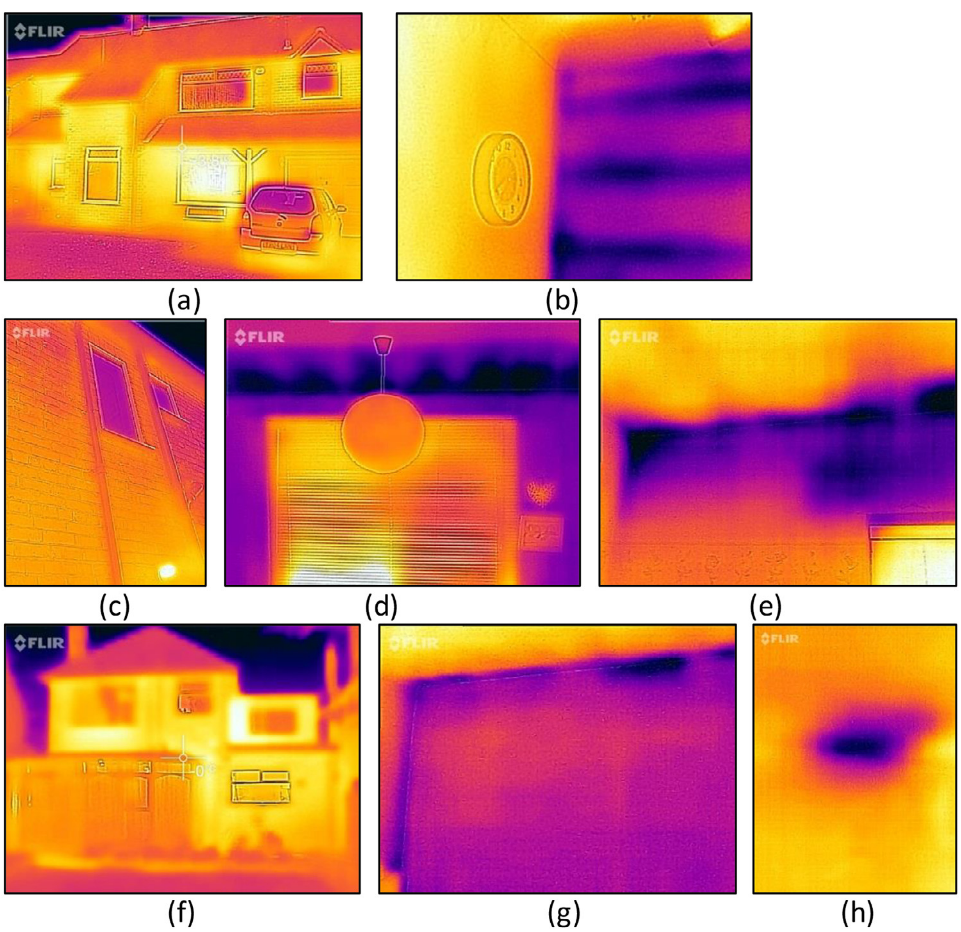

Fig. 15. IR images with visual edges of walls taken by participants; a) and b)P18, c) and d) P34, e) P38, f), g) and h) P42.

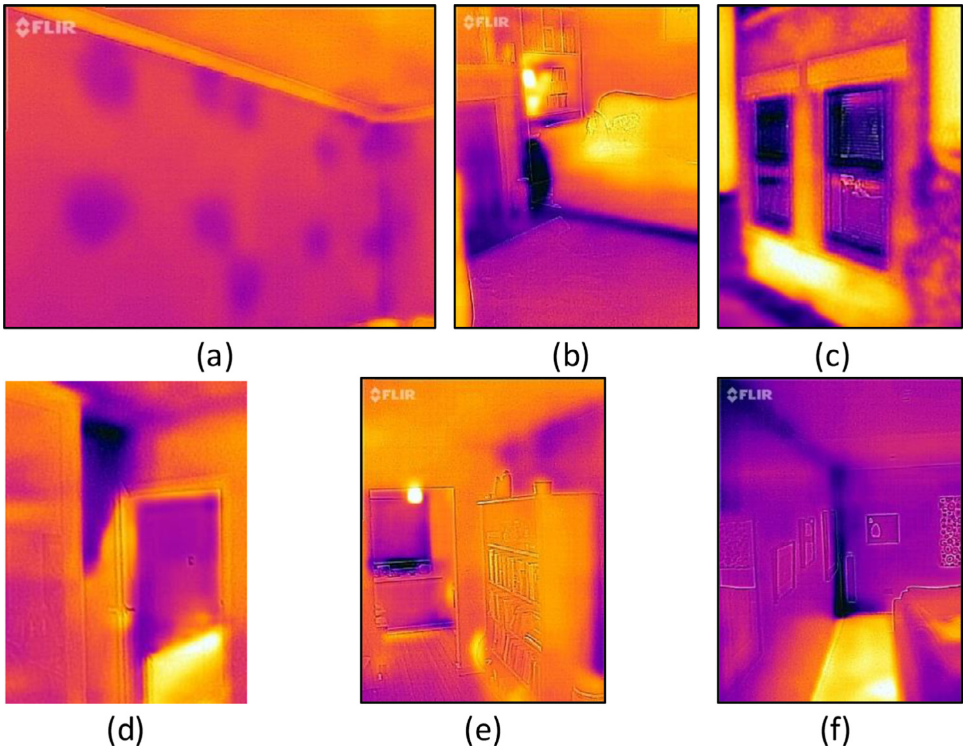

Fig. 16. IR images with visual edges of walls taken by participants; a) P43, b), c) and d) P45 and e) and f) P48.

To be able to see cold spots on the wall by the necked eye, especially at the upper parts, is not easy; and when the thermal image revealed that, the householder became more convinced regarding the source of coldness, and further the extent of energy loss in the building.

> *"Seeing darker, cold patches in the corner of a few walls made me realise just how much heat can be lost that way.* " (P42).

Fig. 15-g shows a dark hallway wall, which is a big source for coldness, while Fig. 15-h reveals a cold dark sport on the wall very clearly.

Some participants, by revealing cold spots in their walls have got an explanation for why his house is cold and inefficient, for example:

> *"… there is cold spots in many places which make the house cold and inefficient.* " (P43)

Fig. 16-a shows many dark cold spots on the wall that are very difficult to identify and quantify by the necked eye. Do-it-yourself (DIY) thermography is a good opportunity to inspect the efficiency of installed insulations, to see if everything is done properly. A participant found an unexpected big dark spot in the lounge (Fig. 16-b) and a bright area below the window (Fig. 16-c).

> "There is a very cold spot near my sofa in the lounge, which I Need to find the cause of and rectify. I have had cavity wall insulation but there are areas of heat loss through the walls, particularly from the radiator below the window in the lounge, where *the photo taken outside shows heat loss right through the wall. Unfortunately, there is nowhere else suitable to site the radiator. The insulation needs improving, and there are cold spots on internal walls that need investigating.*" (P45).

Fig. 16-b and c demonstrate a big dark area on the wall, close to the sofa and a bright area below the window respectively. Both cases represent poor quality insulation or a post-installation damage. Such defects are difficult for the householder to discover by herself. These issues may need to be investigated by a professional builder/thermographer.

The thermography survey reveals the missing area of insulation, and the heat visualisation does not leave much space for speculations. The householder discovered easily that the insulation renovation was not done properly (Fig. 16-f).

> *"It was revealing that in my new extension, which was built 8 years ago, there was a very cold area down one corner where two walls meet which must mean that the builders failed to take the cavity wall insulation right into the corners.* " (P48).

An improper renovation work always leads to later confusion and dissatisfaction for the householder, when the costly investment unable to be offering an improvement and the householder cannot afford an additional investment for improvement (Fig. 16-e and f).

> *"Whilst the thermal imaging has educated me about the weak spots in the insulation of my home I am unsure whether I will take any action as it would require fairly invasive work to the walls. I have already got cavity wall insulation and I think the only way of improving on this would be to line all the walls internally with insulated board."* (P48).

The householder goes further and suggests thermography training for builders to give them a new perspective and a new tool to improve the accuracy of their work.

> *"Thermal imaging would be a useful education tool to demonstrate to builders the impact of their failure to make sure every part of the building is properly insulated. It is easy during the building process for builders to lose sight of the reason why it is important to take care with insulation. If something is not visible when the building is finished builders can be tempted to miss that thing out!* "(P48).

3.3.4. Thermal insulation of roofs

Fig. 17 presents examples of case studies for roofs and loft hatches. Loft hatch is an area within the building where lots of heat can be lost through, therefore it is necessary to make sure that the loft hatch fits snugly and draught proof strips are being fitted around the edges. This issue is shown clearly in the householders' thermal images (Fig. 17-a, d, f and g). Some of the householders had identified the loss of heat from their roof during the thermography, and now they became more aware about the need of improvement.

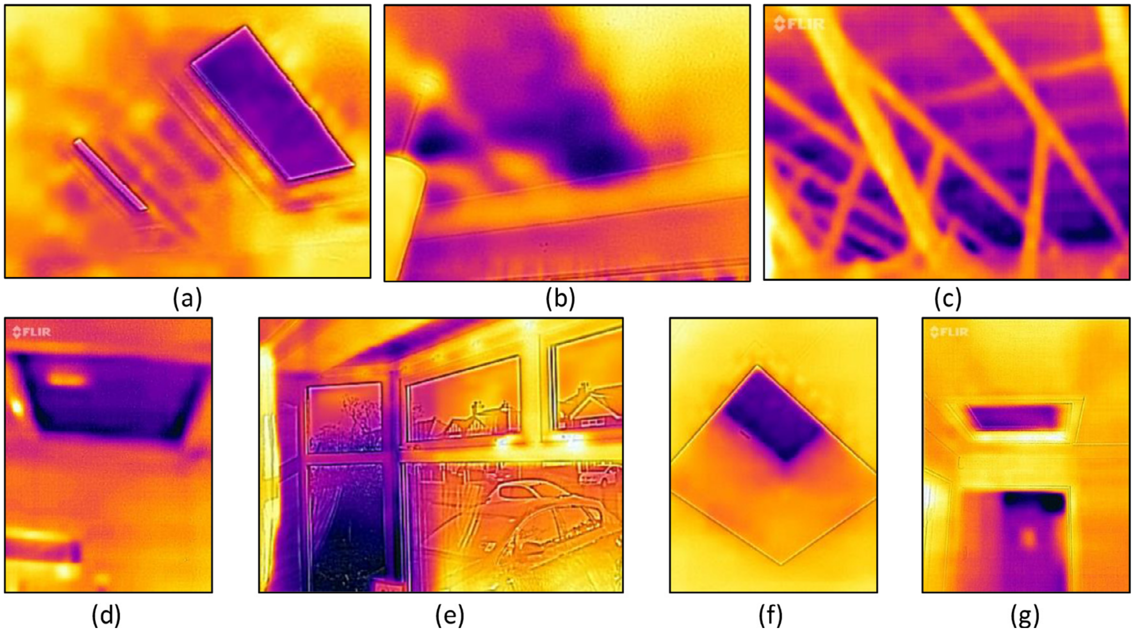

Fig. 17. IR images with visual edges of roofs taken by householders; (a) P17, (b) P18, (c, d) P23, (e) 34, (f) P37 and (g) 38.

"I identified a few places in the attic that were losing lots of heat. It is clear that insulation *needs improving in those places."* (P18).

While other householders want to take action and solve the defects observed by the thermal images, which is again show the power of the visual image to effect on the change of behaviour.

"The thermal imaging showed that heat was being lost through the windows and especially through the hatch door to the roof space. … I shall certainly see to insulating the roof space hatch door." (P23); *"I'm also going to have our loft insulated."* (P34); *"We will replace the loft hatch and insulate it* "(P38).

Some letting householders try to inform their landlords about the insulation issues and ask them to take action to improve it.

"I will be asking the owner of the house to consider insulating the attic ceiling/roof." (P17); and *"Might inform letting agency about my concerns to the roof and walls insulation, how it affects my bills*." (P37).

In contrast to the above cases, there are other householders who are happy with the result of their roof inspection.

"I'm renting the house, therefore I will not change any insulation, but I will let landlord know that the new loft insulation is made well." (P43); and *"It would appear that the roof is already adequately insulated."* (P48).

3.3.5. Thermal insulation of floors

Floor contributes to heat loss from the building, even if the amount is less that the other mentioned areas within the building. Some of the householders captured these heat losses during their thermography surveys (Fig. 18-a and b), as it can be seen in the both thermal images the floor has a dark colour which indicate the coldest areas in the respective image.

"… assess the potential thermal bridge in the kitchen floor" (P32); and *"My kitchen floor is clearly not insulated; when I replace the kitchen I will address this"* (P45).

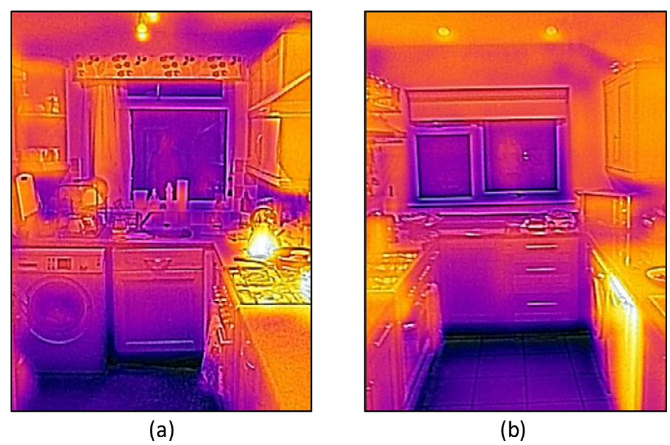

Fig. 18. IR images with visual edges of floor, taken by householders, (a) P32 and (b) P45.

4. Discussion

From the results it is evident that the participants have been engaged in the process to do their own infrared surveys; and they were curious and enthusiastic in using the infrared mobile phone technology. This could be due to the 'achievement' component of the DIY survey and the 'empowerment' they have felt by doing the survey themselves. Also there is a 'social' component when the participants attended the training sessions in groups. Sense of accomplishment seems to be reflected in the feedback and the comments they have provided.

The results of this paper suggest that providing visible, real time, vivid, dynamic energy related information can promote energy saving behaviour changes and increase awareness and engagements. The drive to participate could also be related to people attraction to gadgets and the game approach, or interactive decision theory [33]. In this case, the individual who is doing the infrared survey is trying to utilize the fun of the game and seeking a 'reward' which occurs by identifying potential issues within the insulation. As a consequence of eventually discovered insulation issues, people may take actions to solve these issues. This interaction between the person and his home by applying a game approach can lead to increasing individual's engagement and awareness about its own building, which in its turn can lead to improvement of buildings performance. Fig. 19 summarised the suggested model of this paper and theories behand it.

Unlike annual energy savings, infrared thermography provides immediate response which can evaluate the current situation and the ef-

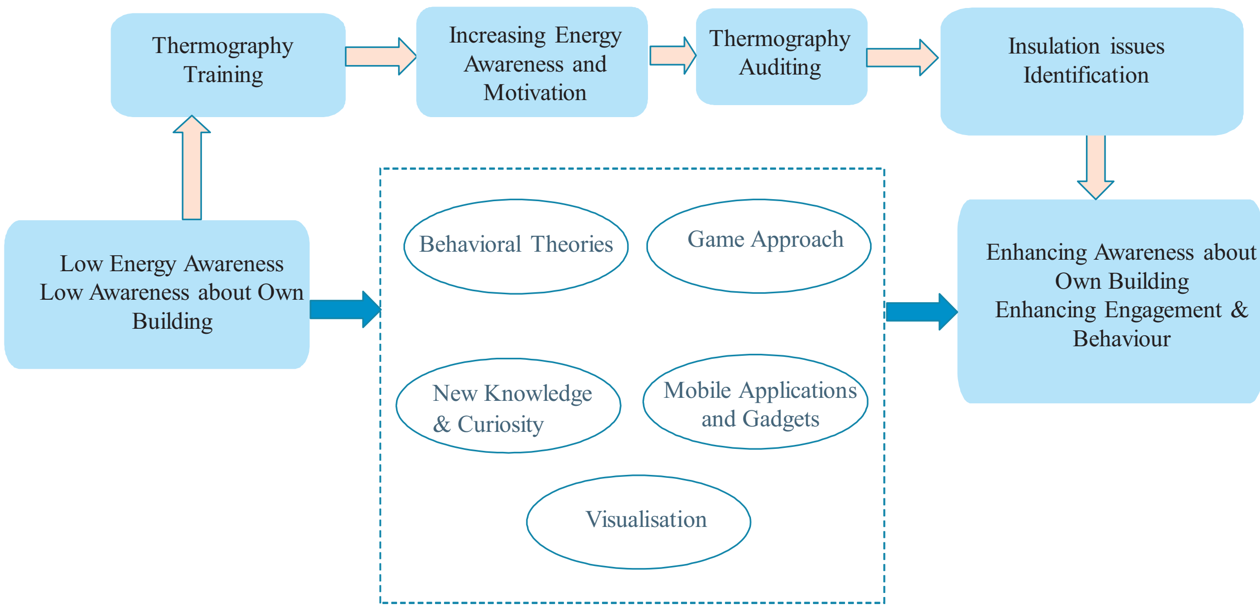

Fig. 19. The applied model of enhancing people engagement in energy conservation and background theories.

fectiveness when doing any thermal improvements such as using the curtains at night as an additional layer of insulation on windows. This instant feedback creates the drive of 'action' and 'observe' approach. Another drive for the participants is to maximise their financial savings and reduce energy use. This unexpected output of the survey or the result of the modification, creates an inner motivation.

In support to Matthies [24], 'conscious' decisions are supported by the self-conducted infrared survey; and in line with Boholm's opinion [18], visual images have provided a strong influence to demonstrate issues which are far away from our daily experience and show them subjectively vivid, this impact of the visual image is clearly shown in the comments. With the DIY approach, which also normally gives people the satisfaction of achievement, the involvement of people has been significantly high. This psychological drive to participants, when integrated with the visual presentation of the infrared thermography, the training and knowledge gains, seems to create a motive to be involved and achieve positive outcome to change the performance of the house.

From the qualitative and quantitative data, it is evident that participants have enjoyed using the smart-phone based infrared technology and the training on the small-scale building simulator. The building simulator has the advantage of the ability to be used in-doors for training at any time and at any external temperature. Unlike training on real buildings, the simulator has achieved a similar outcome at much lower cost and without leaving the training room.

According to [23], the stronger an intention to involve in a behaviour, the more possible must be its performance; and this DIY infrared surveys have enforced such intention. The participants' energy awareness and motivation have been improved after they have attended the educational session. The participants' awareness concerning the condition of their own buildings' insulation have also been improved after they have carried out the thermography survey and identified the insulation issues. The process, particularly the thermography survey, have promoted voluntary retrofit future plan engagement and change of behaviour related to daily use towards more sustainable operation of their respective building.

5. Conclusions

This paper has suggested a novel approach for enhancing and encouraging people's engagement by training and educating them to do their own DIY homes' infrared thermography surveys to identify main issues that would require improvement. Majority of people may not have a budget to spend on a professional infrared thermography survey; however, low cost infrared cameras with some basic training could play a vital role in DIY surveys, when people do their own inspection of their houses. During this research work, participants were very keen to take part. This could be associated to the fun-related aspects of using the technology, combined with people's love to gadgets and the curiosity from what they will find when doing the work, which could be explained by the excitement of the game approach and behavioural theories of taking conscious decisions to enhance their homes energy performance, following the work that they have conducted themselves.

The survey and equipment used in his case may not be at the same level as of professional surveys, but it has been found to provide some information and knowledge to house owners. The feedback from the 50 volunteers in the quantitative and qualitative analysis indicates a positive response and high level of engagement.

For example, the results show that 88% of participants have found the educational session helpful to understand the infrared thermography; and 92% have considered the infrared camera to be an effective tool to indicate location of heat losses. Also, 90% of participants trust that the thermal camera has helped them to identify insulation defects that cause heat losses in their homes. In total, 84% believe that the infrared survey has convinced them to think more seriously about the heat losses of their homes and what they could do to improve that. The suggested DIY approach of using infrared thermography utilises the modern trend of people's attraction to mobile phone applications and their interest to use smart phone gadgets. People have identified a wide range of main causes of heat losses such as solid walls, poor quality windows and poorly insulated roofs and floors. Future work is planned which will include a wider number of participants in several countries to be able to quantify the benefits of the approach.

Declaration of Competing Interest

The authors also declare that there is no other conflict of interest including any financial, personal or other relationships with other people or organizations within three years of beginning the submitted work that could inappropriately influence, or be perceived to influence, their work.

Appendix 1: Building demographic data.

Characteristics	Frequency	Percentage
Ownership		
Owner	21	42
Tenant	29	58
Total	**50**	**100%**
Property type		
A terraced house	5	10
Detached house	11	22
Semi-detached house	18	36
A flat/ground floor	3	6
A flat/middle floor	5	10
A flat/top floor	8	16
Total	**50**	**100%**
Age of the property (Years)		
0-20	8	16
21-40	10	20
41-60	9	18
61-80	6	12
81 or above	12	24
Do not know	5	10
Total	**50**	**100%**
Type of windows		
Single glazed	8	16
Double glazed	42	84
Triple glazed	0	0
Total	**50**	**100%**
Condition of the loft/attic		
Insulated	25	50
Non-insulated	6	12
Unsure	14	28
Not applicable	5	10
Total	**50**	**100%**

Appendix 2: Summary of the sociodemographic data

ID	Participant's age group	Educational level	Ownership	Type of property	Age of property (years)	Type of windows	No. of rooms	No. of occupants
P02	45-54	Post Graduate	Owner	Semi-detached	41-60	Double glazed	**3**	**5 or More**
P06	25-34	Post Graduate	Owner	Terraced	81 or above	Double glazed	4	2
P12	25-34	Post Graduate	Rental	Middle floor flat	Do not know	Single Glazed	2	1
P13	55-64	Secondary or lower	Owner	Detached	41-60	Double glazed	5 or more	2
P14	45-54	Further Education	Owner	Semi-detached	61-80	Double glazed	5 or more	2
P17	35-44	BSc or BA	Rental	Semi-detached	81 or above	Single Glazed	5 or more	1
P18	25-34	Post Graduate	Owner	Detached	41-60	Doble glazed	5 or more	4
P20	25-34	Post Graduate	Rental	Semi-detached	81 or above	Doble glazed	5 or more	4
P22	35-44	Post Graduate	Rental	Semi-detached	0-20	Single Glazed	2	4
P23	45-54	BSc or BA	Owner	Detached	21-40	Doble glazed	5 or more	4
P25	25-34	Post Graduate	Rental	Middle floor flat	21-40	Doble glazed	5 or more	5 or more
P28	25-34	Post Graduate	Rental	Top floor flat	Do not know	Doble glazed	3	4
P30	35-44	Post Graduate	Rental	Top floor flat	21-40	Doble glazed	2	1
P33	35-44	BSc or BA	Rental	Semi-detached	41-60	Doble glazed	5 or more	3
P34	25-34	Post Graduate	Owner	Semi-detached	81 or above	Doble glazed	4	3
P37	25-34	BSc or BA	Rental	Top floor flat	0-20	Doble glazed	2	2
P38	25-34	BSc or BA	Owner	Semi-detached	61-80	Doble glazed	5 or more	2
P42	25-34	Secondary or lower	Rental	Detached	Do not know	Doble glazed	5 or more	4
P43	25-34	Post Graduate	Rental	Top floor flat	61-80	Doble glazed	3	4
P44	25-34	BSc or BA	Owner	Terraced	81 or above	Doble glazed	5 or more	2
P45	55-64	Further Education	Owner	Semi-detached	61-80	Doble glazed	5 or more	1
P46	45-54	BSc or BA	Owner	Semi-detached	81 or above	Doble glazed	5 or more	5 or more
P47	25-34	BSc or BA	Rental	Top floor flat	Do not know	Doble glazed	3	1
P48	55-64	BSc or BA	Owner	Detached	41-60	Doble glazed	5 or more	3
P49	45-54	BSc or BA	Owner	Semi-detached	81 or above	Doble glazed	5 or more	4
P50	55-64	Secondary or lower	Owner	Detached	81 or above	Doble glazed	5 or more	2

* Throughout this paper, this unique code has been applied to mark questions drawn from the questionnaire.

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