AUTOMATED COST ANALYSIS OF ENERGY LOSS IN EXISTING BUILDINGS THROUGH THERMOGRAPHIC INSPECTIONS AND CFD ANALYSIS

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ABSTRACT

Understanding energy performance of existing buildings is vital to increasing their efficiency and reducing the overall energy consumptions. This entails facility managers to systematically monitor building energy performance and reliably identify and analyze potential problems. Currently, infrared thermography is widely used as a primary diagnostic tool for the detection of building performance problems. Nonetheless, applications of thermal images for building inspection are mainly restricted to manual and labor-intensive identification and qualitative assessment of heating or cooling loss. Automated identification of potential problems and reliable cost analysis of the associated energy loss can help homeowners to minimize financial risk of retrofits and maximize energy savings. To that end, this paper presents a new automated method for calculating the cost of energy loss for building diagnostics. In the proposed method, first, using a hand-held thermal camera, the auditors collect digital and thermal imagery from the buildings under inspection. Then, using a recently proposed method for Energy Performance Augmented Reality (EPAR) modeling, an actual 3D spatio-thermal model is generated and superimposed with a computational fluid dynamics (CFD)-based expected energy performance model. The resulting EPAR model is placed into the method proposed in this paper for cost analysis of the energy loss. Through a new 3D thermal mesh modeling using *k-d* tree structure and nearest neighborhood searching, performance deviations between these models are automatically calculated. Using a temperature threshold, the areas associated with potential performance problems are detected in the EPAR model and are visualized using a metaphor based on traffic light colors. Then, the actual R-values of the detected areas are measured at the level of 3D points. Based on the measured R-values and the estimated air change rate for the detected air leaks, (1) the heat loss or gain caused either by poor insulation or air infiltration/exfiltration and (2) the associated energy costs are automatically calculated. The proposed method is validated on several locations of existing residential buildings. The preliminary results show the potential of the proposed method for minimizing the inspection time as well as the risk associated with the cost analysis of retrofitting potential building performance problems.

KEYWORDS

Building Retrofit, Thermography, Image-based 3D Reconstruction, Computational Fluid Dynamics (CFD), R-value

INTRODUCTION

Improving building efficiency is a key to cutting energy consumptions. One primary source of energy loss is poor insulation in building envelopes. To minimize these losses, the U.S. Department of Energy (DOE) has recently placed new standards for insulation of building envelopes. These standards vary based on the climate conditions and the locations of the buildings. Many state or local building codes also require minimum insulation requirements for existing buildings. Accordingly, practitioners are now selecting the building materials that have higher R-values for their projects. R-value is an indicator of the ability of the material to resist the heat flow. Higher R-values in building materials indicates better insulations and has a greater potential for building energy savings.

Despite such efforts, buildings still waste a great deal of energy. According to a recent U.S. DOE report (U.S. DOE, 2010), around 35% of input energy in the building sector is currently being wasted. The energy inefficiency related to building performance problems accounts for over $80 billion per year in the

U.S. During the operation phase in the building life-cycle, the building's ability to resist the heat flow typically decreases due to the deterioration such as degradation of old insulation and missing insulation. Thus, the actual R-values of building areas containing performance problems become lower than the notional value declared by the manufactures. Decreasing the resistance of heat transfer through building materials indicates the increase in energy required for heating or cooling. Thus, in addition to the importance of selecting and using building materials with R-value, it is also important to monitor the actual R-value of materials during the building operation phase.

Recently, infrared thermography has been considered as a robust diagnostic method for sensing building thermal performance. Infrared thermography helps with detection and measurement of surface temperature variations. Despite the benefit, current building thermographic inspections have the following challenges: (1) *manual and subjective analysis*: collecting and analyzing a large number of thermal images for the purpose of whole building diagnostics requires significant time and effort. Moreover, the quality of these inspections is directly affected by the knowledge and experience of the auditors; (2) *qualitative interpretation*: current thermographic inspections are typically focused on visual detection of abnormal regions. Without quantitative interpretation of thermal images, cost analysis of the energy loss associated with the observed problems is difficult. If the cost associated with the detected performance problems is unknown, homeowners may be reluctant to invest their money for retrofitting.

In order to overcome the challenges associated with manual and inconsistent interpretations of large numbers of unordered thermal imagery for the purpose of holistic building diagnostics, the authors recently presented a new Energy Performance Augmented Reality (EPAR) modeling method (Ham & Golparvar-Fard, 2013). These models have the capability of jointly modeling and visualizing actual and expected temperature values for the entirety of building at the level of 3D points. In order to overcome the challenges associated with qualitative analysis, this paper presents a new method for calculating the cost of heating and cooling loss based on 1) EPAR models and 2) estimations for actual R-values. The proposed method can quantify the energy and monetary losses associated with potential performance problems in buildings, and in turn help owners to systematically analyze the Return on Investment (ROI) for retrofitting their facilities. Ultimately, renovating building performance problems for high thermal resistance and air tightness help building occupants to achieve optimal thermal comfort as well as reduce the energy consumptions for heating and cooling. In the following sections, first the related works are briefly overviewed. Next, the research objective, the underlying algorithms and assumptions for calculating the heat loss and the associated energy costs are presented in detail. Finally, we discuss our preliminary results, the potential benefits, and the limitations of the proposed method.

BACKGROUND

Recently, a few studies in the building diagnostics research community have focused on analyzing thermal images to understand the actual conditions of the heat transfer within building environments. Madding (Madding, 2008) is one of the first studies that propose a method for analyzing thermal images to estimate the R-value of building environments. As part of the proposed methods, this work also calculated the potential savings associated with various insulation retrofit options. To automate the quantitative analysis of thermal imagery, R-value calculator and energy saving estimator was developed in an Excel spreadsheet. Fokaides and Kalogirou (Fokaides & Kalogirou, 2011) evaluated the applicability of thermography for the determination of the overall heat transfer coefficient of building envelopes, which is U-value (reciprocal of R-value). For validation purposes, the results of the measurements were compared with the corresponding notional values, and an acceptable level of accuracy was reported. These works present promising results and show the applicability of thermal imagery for reliable quantification of the actual heat transfer conditions within building environments. However, considering the large number of 2D thermal images to be manually analyzed, these methods may require significant time and efforts for the purpose of assessing the actual heat transfer conditions of the entirety of a building. Moreover, these studies used a single temperature data point from the designated area in 2D thermal imagery to assess the actual R-value. Thus, they assumed that all spots in the designated area for inspection have the same R-value. However, the actual R-values in building environments typically vary at the level of 3D points depending on the different level of building deterioration. A 2D patch-based method may not accurately represent the dynamic variations of the actual R-value at the level of 3D point. Finally, the state-of-the-art method do not consider the energy loss associated with air infiltration/exfiltration which can account for 25~50% of the total building heat loss (Stein, 1997). There is a need for more robust methods using thermal cameras that can rapidly and reliably explore actual heat transfer conditions associated with potential performance problems in buildings.

AUTOMATED COST ANALYSIS OF THE ENERGY LOSS ASSOCIATED WITH POTENTIAL BUILDING PERFORMANCE PROBLEMS

Using EPAR models - which contain actual and simulated building thermal performance data in 3D - our goal is to create and validate a new algorithm that automatically calculates the cost associated with total energy loss caused by potential energy performance problems. Figure 1 shows an overview of the data and process in our proposed method. Our method mainly consists of four steps: 1) automated identification and calculation of the area associated with potential performance problems; 2) measuring the actual R-values of the inspected building environments at the level of 3D points; 3) automated calculation of the heat loss/gain due to poor insulation and air leaks; and finally 4) automated cost analysis of the energy loss for the buildings under inspection.

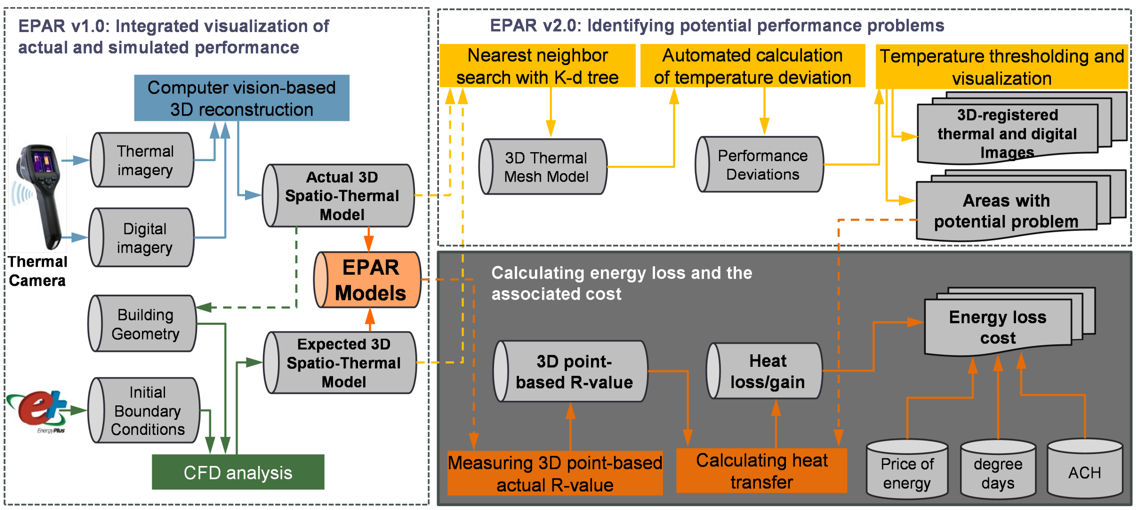

Figure 1 – Overview of data and process in the proposed method

Automated Identification of Potential Areas for Building Retrofits

To automatically analyze the cost associated with energy loss in buildings, we first need to identify the sources of heat loss and gain. To identify the building areas with energy performance problems, the proposed method in this paper builds on the recently prototyped EPAR modeling method (Ham & Golparvar-Fard, 2013). For EPAR modeling, an auditor collects a large number of digital and thermal imagery from the building under inspection. These images will be captured using a single thermal camera which has both thermal and digital lenses. First, by using the collected digital images, a dense 3D geometrical point cloud model of the building is generated. Here, an image-based 3D reconstruction method is used, which consists of Structure-from-Motion (SfM) and Multi-View Stereo (MVS) algorithms. Then, for 3D thermal modeling, the collected thermal images are placed into a 3D thermal point cloud modeling pipeline which consists of two steps: 1) thermal camera calibration; and 2) estimation of the relative pose between digital and thermal lenses. Next, the expected thermal performance of the building is simulated through the CFD analysis. For this purpose, the initial environmental and geometrical boundary conditions are respectively acquired from EnergyPlus and building geometrical point cloud model. Finally, the actual and simulated thermal performance models are automatically integrated in a 3D virtual environment, resulting in the EPAR model. Figure 2 shows the EPAR modeling process for indoor building environments. From left to right, each figure shows: (a) unordered digital and thermal imagery, (b)

3D building geometrical and (c) thermal point cloud models, and (d) the results of CFD analysis (The figure is best seen in color).

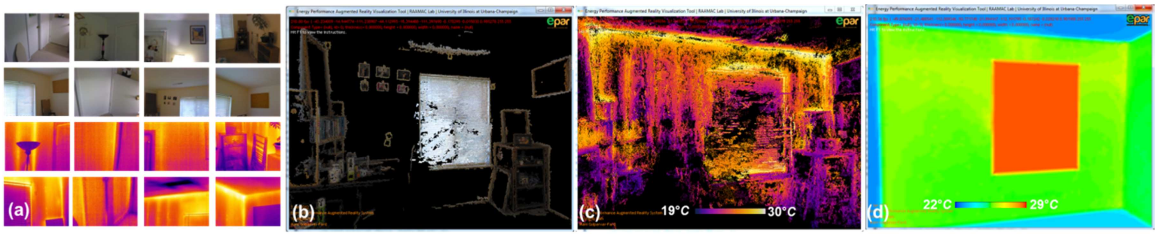

Figure 2 – The EPAR modeling process

To improve the completeness of the point cloud models, a new 3D thermal mesh modeling method was proposed using *k-d* tree structure and nearest neighborhood searching algorithm. Comparing the actual measurements and simulated results of building energy performances in form of 3D mesh-based EPAR models, performance deviations were systematically explored. Here, a single temperature threshold was used to identify potential performance problems. Finally, the detected potential performance problems are interactively visualized within the EPAR models using a metaphor based on traffic light colors. For more details in the process for identifying potential performance problems in the EPAR models, the readers are recommended to look into (Golparvar-Fard & Ham, 2013).

Automated Calculation of the Areas Associated with Potential Performance Problems

Based on the resulting EPAR models, we calculate the building areas containing potential performance problems. To do that, the surface area of the generated 3D thermal mesh is computed. For this, we first find those faces from the triangle mesh which are associated with the potential performance problems (color-coded in red). Then, we measure the total area by finding the coordinates of the three vertices from each face, calculating the areas using the cross product of two corresponding vectors, and aggregating them. Figure 3 summarizes the proposed algorithm.

Input: Three vertices which form faces in triangle thermal mesh

$$Q_1 = \{P_1^i | \forall i \in (1,2,\dots,m), P_1^i = < X_1^i, RGB_1^i >\}$$
$$Q_2 = \{P_2^i | \forall i \in (1,2,\dots,m), P_2^i = < X_2^i, RGB_2^i >\}$$
$$Q_3 = \{P_3^i | \forall i \in (1,2,\dots,m), P_3^i = < X_3^i, RGB_3^i >\}$$

Output: Total area with potential performance problems (A_P)

for *i*=1:*m*
    if RGB_1^i & RGB_2^i & RGB_3^i = (255, 0, 0)
        return X_1^i, X_2^i, X_3^i
    end if

$$A_P^i = \frac{|X_2^i X_3^i - X_3^i X_2^i, X_3^i X_1^i - X_1^i X_3^i, X_1^i X_2^i - X_2^i X_1^i|}{2}$$

end for
return $\sum A_P^i$

Figure 3 – Algorithm for calculating building areas associated with potential performance problems using the EPAR mesh models

Measuring the Actual R-Values of Building Environments at the Level of 3D Points

In order to calculate the heat loss/gain, the actual heat transfer conditions of the associated building areas need to be measured. In quasi-steady-state heat transfer conditions, the overall heat transfer rate through a building surface (A) with ΔT temperature difference between inside and outside can be described using the following equation:

$$\frac{dQ}{dt} = \frac{1}{R} \times A \times \Delta T \tag{1}$$

Thus, for calculating the amount of heat transfer (Q) through the detected building surface with performance problems (A_P) in 3D EPAR models, we measure the actual thermal resistance (R-value) of building environments at the level of 3D points. Our work for measuring the actual R-value is based on the environmental assumption that the main heat transfer in indoor building environments is due to the thermal convection and radiation which can be given by the following equations:

$$Q_{Con} = \alpha_{con} \times Area \times (T_{inside,air} - T_{inside,wall}) \tag{2}$$

$$Q_{Rad} = \varepsilon \times \sigma \times Area \times (T^4_{inside,wall} - T^4_{inside,refleted}) \tag{3}$$

Where α_{con} is the convective heat transfer coefficient, ε is thermal emissivity, σ is Stefan-Boltzmann constant ($5.67 \times 10^{-8}\ \mathrm{W(m^2K^4)^{-1}}$). Within the EPAR models, $T_{inside,wall}$ can be queried at the level of 3D points. α_{con} is influenced by airflow types (e.g., laminar or turbulent) and temperature deviations between the air and building surface. In this paper, we adopted the convective heat transfer coefficient from (ISO 6946:2007).

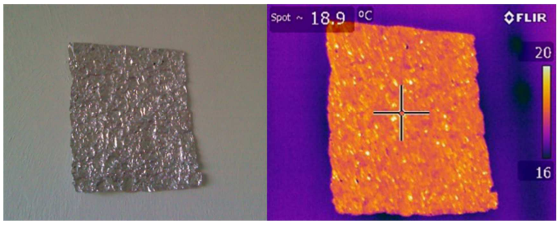

Figure 4 – Measuring the reflected apparent temperature with the crumbled foil

$T_{inside,reflected}$ is the inner surface temperature of building environments which is theoretically well known *apparent reflected temperature*. To measure the apparent reflected temperature, we used a small crumbled aluminum foil located on the inspection areas (Figure 4) (FLIR system, 2010). Since the aluminum foil has low emissivity and high reflectivity and even diffuses the reflected heat, we can robustly measure the temperature of the inner walls from the surface of the crumbled foil. We assume that the apparent reflected temperatures of all building surfaces are constant during indoor survey (Fokaides & Kalogirou, 2011). By combining Eqs. 1, 2, and 3, actual R-value at the level of 3D points in the EPAR models can be calculated using the following formula:

$$\mathrm{R} = \frac{T_{inside,air} - T_{outside,air}}{\alpha_{con} \times (T_{inside,air} - T_{inside,wall}) + \varepsilon \times \sigma \times (T^4_{inside,wall} - T^4_{inside,refleted})} \tag{4}$$

Automated Calculation of Heat Loss & Gain and the Associated Energy Cost

Here, we measure energy loss through 1) surfaces containing degradation of old insulation or missing insulation; and 2) air leaks.

Energy Loss for Poor Insulation

Increasing the heat transfer through walls indicates the energy loss needed for heating or cooling. Based on Eq. 5, the heat loss/gain associated with poor insulations is calculated using the following three values: 1) measured 3D point-based actual R-values (R_{Actual}); 2) detected building areas with potential performance problems in the EPAR models (A_P); and finally 3) '*degree days*' which is the combination of the time (t) and temperature difference between the average outdoor and a predefined baseline (ΔT) (The National Oceanic and Atmospheric Administration (NOAA), 2013)

$$Q_{Ins} = \frac{1}{R_{Actual}} \times A_P \times \Delta T \times t \quad (5)$$

Energy Loss for Air Infiltration and Exfiltration

Air leaks also lead to energy loss through cold air infiltration in winter and exfiltration in summer. The heat loss/gain associated with air infiltration/exfiltration is calculated using Eq. 6. To do that, the following four values are used: 1) the heat capacity 1205.8 which is derived by multiplying the density of air (1.2 Kg/m^3) by its specific heat (1004.83 J/Kg); 2) the volume of the closed building space under inspection (*V*); 3) the number of total air change per hour (*ACH*) based on the tightness of construction; and finally 4) '*degree days*' ($\Delta T \times t$).

$$Q_{Air} = 1205.8 \times V \times ACH \times \Delta T \times t \quad (6)$$

Energy Loss Costs

The final step of the process is to estimate the energy loss cost associated with the detected heat loss/gain due to poor insulations and air infiltration/exfiltration. The total energy loss cost can be estimated using the following Eq. 7 based on the retail price of energy such as electricity or gas.

$$Energy\ Loss\ Cost = (Q_{Ins} + Q_{Air}) \times Retail\ Price\ of\ Energy \quad (7)$$

EXPERIMENTAL RESULTS

Experimental Setup

In order to validate the proposed method for automated cost analysis of the energy loss associated with potential building performance problems, several experiments were conducted on interior locations of an existing residential building. For the EPAR modeling, digital and thermal images (2048×1536 and 320×240 pixels respectively) were collected using a FLIR E60 thermal camera. Gambit 2.2.30 and Fluent 6.2.16 were used for geometrical modeling and CFD analysis respectively. For turbulence modeling, the renormalization group (RNG) $k - \varepsilon$ model is used in this paper. The RNG $k - \varepsilon$ model has been experimentally demonstrated as a robust turbulent model that can provide the most reliable results for modeling building indoor environment (Chen, 1995). Since CFD analysis are typically implemented in a quasi-steady-state, the heating and cooling airflows from the HVAC system are assumed to be uniformly distributed with a constant property (e.g., temperature and velocity) on the entire supply openings.

Results and Discussions

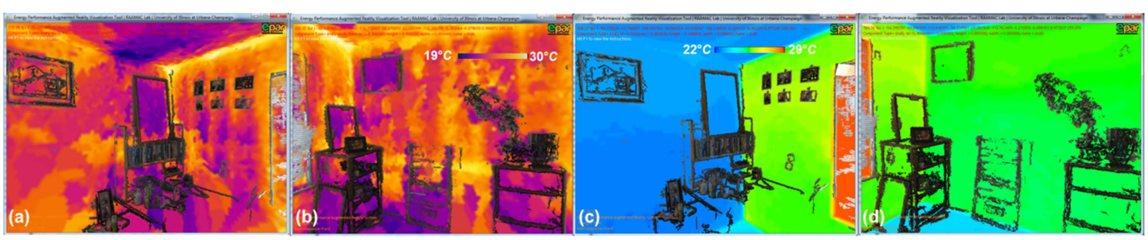

Figure 5 – 3D mesh based actual and simulated thermal performance along with the 3D building geometrical point cloud in EPAR models

Figure 5(a) and (b) present the 3D thermal mesh model, and figure 5(c) and (d) show the VRML-based CFD model from the same viewpoint in EPAR model. As we observed the difference between Figure 5(a) and (b) and 4(c), 3D thermal mesh modeling can overcome the limitation of the areas that are sparsely reconstructed in the point cloud model. Figure 6(a) and (b) show examples of the detected building areas containing potential performance problems in the EPAR models. The areas highlighted with red color are identified as the potential problems based on the deviations between the actual measurement from thermal camera (Figure 5a and b) and simulation results from CFD analysis (Figure 5c and d). In this paper, our analysis is based on the assumption that thermal deviations above the 2˚C threshold are considered as potential performance problems. This assumption is based on 1) the measurement accuracy of the FLIR E60 camera we used for data collection; and 2) the recommended typical accuracy of the CFD simulations for indoor building environments (Fan & Ito, 2012; Vera, Fazio, & Rao, 2010). Here, the detected areas indicate the typical performance problems (6a): between a side wall and a ceiling around the HVAC system; and (6b): between a side wall and a floor adjacent to exterior. Considering the age of this residential building which was built in the beginning of the 1980s, these deviations may be caused by construction defects or insulation voids. Such thermal deviations above the predefined threshold provide building auditors with feedbacks on what areas are needed for additional detailed diagnostics. Figure 6(c) and (d) show 3D-registered thermal and digital imagery where the performance problems were observed. By interpreting thermal performances (the 3D-registered thermal imagery) with the corresponding building semantics (the 3D-registered digital imagery), the localization of potential performance problems in buildings can be facilitated for rapid remedial decision-makings. The figure is best seen in color.

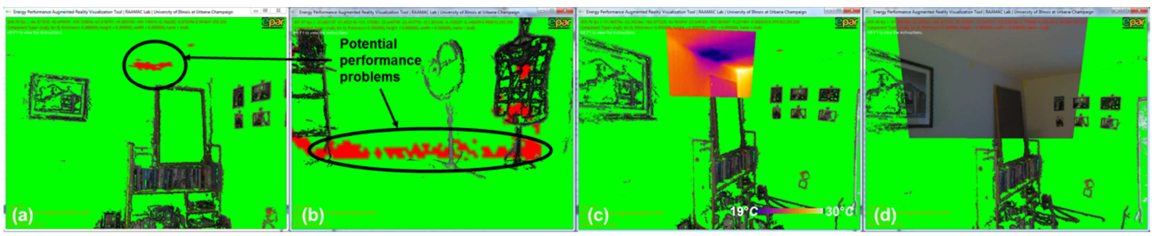

Figure 6 – Examples of the detected potential performance problems along with the 3D building geometrical point cloud and 3D-registered images within the EPAR models

Table 1 represents the results of our experiments on calculating building areas with potential performance problems, the amount of heat loss and gain, as well as the associated energy cost. The most accurate way to determine Air Change per Hour (*ACH*) is to use a blower door test. As a proof of concept, we assumed that *ACH* is 1 in this paper, which indicates the average of moderate and leaky condition (Van der Meer, 2001). For calculating energy loss cost associated with annual heating and cooling loss, we used 'heating and cooling degree days' data (The National Oceanic and Atmospheric Administration (NOAA), 2013). As a result, we calculated the cost of the annual energy loss for this room to be $75.33 per year. By converting the temperature data sensed from building surfaces into the cost of energy loss, building auditors can reduce the time and effort required for analyzing large numbers of building thermal images and overcome the challenges associated with qualitative and visual interpretation of building thermal imagery. Rather they can spend their time on the more important tasks of retrofit decision-making.

Table 1 – Heat loss and gain as well as the associated cost

Areas with potential problems (m^2)	Heat loss/gain (poor insulation) (*J/s*)	Heat loss/gain (air leaks) (*J/s*)	Degree days[+]	Price of electricity[++] (*cents/kWh*)	The cost of Energy loss (*$*)
0.94	2.82	4.07	4867	9.36	75.33

[+] Cooling & heating degree days (The National Oceanic and Atmospheric Administration (NOAA), 2013)
[++] (U.S. Energy Information Administration, 2012)

CONCLUSIONS

Current thermographic inspections for building diagnostics are mainly based on the auditors' knowledge and focus on qualitative interpretations of a large number of unordered 2D thermal images. Consequently, building owners may be reluctant to invest their money in retrofitting their buildings due to the lack of quantitative analysis associated with the value of their investment in retrofit. To quantify the energy loss and monetary impacts associated with potential building performance problems detected from 2D thermal images, we present a new automated method for calculating the heating loss/gain and the associated energy cost by measuring the actual R-value of the building environments within the EPAR models at the level of 3D points. This can further motivate homeowners to retrofit their buildings by helping them better understand the cost-benefit ratio for various retrofit investments. Future works include eliminating false positives from the detected performance problems and estimating *ACH* caused by air leaks through a blower door test. There is also a need for classifying the types of energy performance problems within the EPAR models for more accurate cost analysis of the energy loss. The results of our ongoing research efforts will be presented in a near future.

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