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BIM and Thermographic Sensing: Reflecting the As-is Building Condition in Energy Analysis

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Abstract: ***This paper presents an automated computer vision-based system to update BIM data by leveraging multi-modal visual data collected from existing buildings under inspection. Currently, visual inspections are conducted for building envelopes or mechanical systems, and auditors analyze energy-related contextual information to examine if their performance is maintained as expected by the design. By translating 3D surface thermal profiles into energy performance metrics such as actual R-values at point-level and by mapping such properties to the associated BIM elements using XML Document Object Model (DOM), the proposed method shortens the energy performance modeling gap between the architectural information in the as-designed BIM and the as-is building condition, which improve the reliability of building energy analysis. Several case studies were conducted to experimentally evaluate their impact on BIM-based energy analysis to calculate energy load. The experimental results on existing buildings show that (1) the point-level thermography-based thermal resistance measurement can be automatically matched with the associated BIM elements; and (2) their corresponding thermal properties are automatically updated in gbXML schema. This paper provides practitioners with insight to uncover the fundamentals of how multi-modal visual data can be used to improve the accuracy of building energy modeling for retrofit analysis. Open research challenges and lessons learned from real-world case studies are discussed in detail.***

Keywords: Multi-modal Visual Sensing and Analytics; Building Energy Modeling and Analysis; Thermographic Sensing; Building Information Modeling (BIM)

I. INTRODUCTION

Today, practitioners in building energy domain widely use publicly available energy modeling and analysis tools such as EnergyPlus to model the building energy performance and simulate the energy consumption during a given time period. Especially, these tools are mainly used to evaluate the impact of different building design or operation decisions on energy consumption. Despite their benefits, a lot of building characterization for energy modeling involves manually inputting parameters to describe the physical layout and building material properties with regard to their impact on the heat flow. To address such challenges in modeling, transferring building information in BIM into energy analysis tools is currently gaining the popularity to streamline several steps in the traditional modeling process of building energy performance [1].

BIM-based energy modeling can provide easy and rich access to building information in BIM (e.g., building geometry, construction types, and the associated material properties) for running energy simulation engines. Here, one significant parameter used in thermal analysis is the overall heat transfer coefficient of building envelopes. Thermal conditioning of indoor air is basically related to heat transfer between inside and outside of buildings since unnecessary and excessive heat transfer through envelopes makes occupants uncomfortable and power use inefficient for space conditioning that accounts for up to 20% of the total energy consumption in the U.S. [2]. Thus, inputting the accurate heat transfer coefficients in energy model can improve the accuracy of thermal analysis as wells as provide more reliable information about overall energy use in buildings [3].

In the current BIM-based energy modeling process, it is assumed that each building element has a constant surface-wide thermal property that is typically obtained from industry standard databases available in BIM-authoring tools. However, such modeling assumption is not always applicable for existing buildings since the as-designed building condition is not always maintained due to deteriorations over the whole life cycle of the buildings. This issue is exacerbated especially for wood-frame residential buildings as about 87% of residential buildings in the U.S. were built before the year 2000 when the current rigorous energy standards were not established [2]. Moreover, for a majority of old building elements such as historic building façades, the associated thermal property information are not typically available, which make it difficult to characterize building performance for energy modeling. Thus, without sensing the as-is building conditions and reflecting them in the energy modeling process, energy analysis of existing buildings is more likely to be skewed, especially overestimated based on the as-designed building information. Very recently, the problems of the impact of such energy performance modeling gap on the accuracy of energy analysis have

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received attentions [4, 5]. Despite their benefits, to address the fundamental challenges in BIM-based energy modeling assumptions & simplifications documented in the U.S. GSA's BIM Guide for Energy Performance [1], several technical challenges still remain open as follows:

(1) Limited characterization of the as-is building condition: A single measurement of the as-is thermal property for each building assembly using a Heat Flux Meter (HFM) or a thermography would not accurately capture the as-is condition of large building areas that contain significant thermal resistance non-uniformity.

(2) Manual identification of BIM elements associated with the sensed as-is building condition: This technical challenge makes 'updating BIM data' time-consuming and labor-intensive. This issue is further exacerbated for large quantities of BIM elements which need to be updated.

For rapid and reliable BIM-based energy modeling and analysis, given multi-modal visual data collected from existing buildings and the as-designed BIM, this paper presents an automated method for updating BIM in terms of thermal properties of building assemblies and experimentally explore the impact on BIM-based energy load calculation. The goal of this paper is to answer the following three research questions:

(1) How can we automatically associate multi-modal visual data collected from building environments with BIM elements?
(2) How can we automatically update the thermal properties of BIM elements to reduce the gap between the architectural information in the as-designed BIM and the as-is building conditions?
(3) How much can the proposed vision-based framework impact on BIM-based energy analysis?

In the following sections, the underlying method is presented in detail, and the experimental results, perceived benefits, and open research challenges are discussed.

II. Automated Vision-based Method for Updating BIM For Accurate Energy Analysis

Building upon [3], Figure 1 summarizes the components of the proposed automated vision-based method for reflecting the as-is building conditions in BIM-based energy modeling to improve the reliability of energy analysis. The following sections describe each step in detail.

A. 3D Spatio-Thermal Modeling of Built Environments in the BIM coordinate system

1) Computer Vision-based 3D Spatio-Thermal Modeling of Built Environments: The computer vision-based method for producing 3D spatio-thermal point cloud models wherein surface thermal profiles of building environments are characterized in 3D builds upon our recently developed prototype [6]. First, using a hand-held single thermal camera equipped with a built-in digital camera, practitioners collect digital and thermal images from the buildings under inspection. Typically, thermal images have low spatial resolutions and lack distinct visual features. These characteristics of thermal imagery impede the direct application of Structure-from-Motion (SfM) which is the most dominant pipeline for image-based 3D reconstruction in computer vision domain. Instead, we leverage (1) a thermal camera calibration; and (2) the estimation of the relative pose of the thermal camera lens with respect to the built-in digital camera lens. Finally, by using the calculated thermal camera parameters and the undistorted thermal images, 3D thermal point cloud is generated using Multi-View Stereo (MVS) algorithm.

2) Generating the Meshed BIM and Mapping the Point Cloud Data to Vertices in a Mesh: The challenge in leveraging the resulting image-based 3D point cloud models is that the model would be incomplete or noisy for flat surfaces that do not have enough visual features such as surfaces on drywalls. To improve the model completeness, mesh modeling is conducted. First, boundary points of BIM elements surfaces are extracted from the gbXML schema by querying the content of the

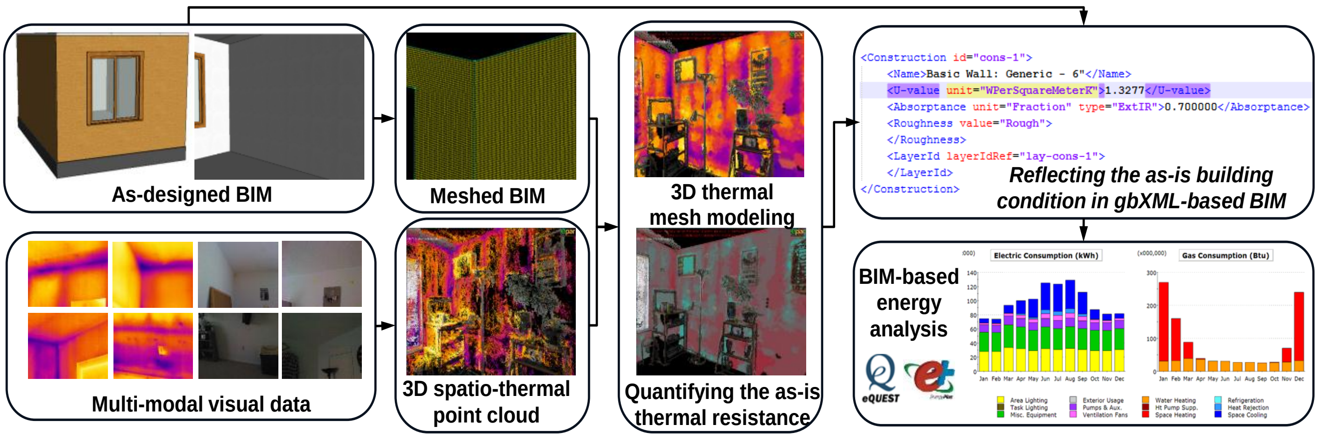

FIGURE I.
Overview of The Proposed Method for Updating BIM

sub-element ‘Coordinate’ of the queried gbXML-element ‘PlanarGeometry’. Next, by discretizing the surfaces into a set of faces, ‘Meshed BIM’ is created. Then, in the ‘Meshed BIM’, the centroid points of each mesh face are derived as the basis of the geometrical transformation. Finally, thermal profiles in form of 3D point cloud are mapped to the centroid of each mesh face in the ‘Meshed BIM’ based on the nearest neighborhood searching algorithm in the *k-d* tree structure. By mapping 3D point cloud data to the meshed BIM, the as-is thermal profiles can be automatically matched with the corresponding geometrical information in the BIM coordinate system, as opposed to manually matching each measurement to the relevant BIM elements in prior works.

B. Converting 3D Thermal Profiles into the As-is Thermal Resistances of Building Assemblies at Point-level

The thermal resistance of building elements (i.e., R-value) can be defined as a reciprocal of the heat transmission through a unit surface with temperature differences between inside and outside of buildings (Eq. 1).

$$R = \frac{\text{Area} \times \Delta T}{dQ/dt} \quad (1)$$

In this paper, measuring the as-is thermal resistances is based on the environmental assumption that the indoor heat transfer is attributed to thermal convection and radiation in a quasi-steady-state heat transfer conditions [7, 8]. By substituting the amount of overall heat transfer with the combination of thermal convection (Eq. 2) and radiation (Eq. 3), the as-is thermal resistance can be calculated.

$$Q_{\text{Convective}} = \alpha_{\text{convective}} \times \text{Area} \times \left|T_{\text{inside,air}} - T_{\text{inside,wall}}\right| \quad (2)$$

$$Q_{\text{Radiation}} = \varepsilon \times \sigma \times \text{Area} \times \left|T^4_{\text{inside,wall}} - T^4_{\text{inside,refleted}}\right| \quad (3)$$

Where $\alpha_{convective}$ is the convective heat transfer coefficient, ε is thermal emissivity, and σ is Stefan-Boltzmann constant. Here, because the point-level thermal profiles can be extracted from vertices in the meshed BIM ($T_{\text{inside,wall}}$), the as-is thermal resistance also can be calculated at point-level in 3D. When considering small-scale energy problems that are typically prevalent in real-world building environments, this helps better characterize the as-is building conditions for large areas of building envelopes that contain thermal resistance non-uniformity.

C. Automated Updating BIM Data by Reflecting the As-is Building Conditions in the Associated BIM Elements

1) Deriving Weighted-average of Point-level Thermal Resistance Measurements: Despite the benefits of the proposed point-level measurements, current energy simulation engines typically require a single thermal property to be input for each building element. To convert point-level measurements into a single value for each building assembly, the weighted average is calculated based on the contribution of each point-level measurement to the associated surface area (Eq. 4 and 5).

$$\frac{1}{R_{total}} \times A_{total} \times (\Delta T \times t) = \left(\frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_k}\right) \times \left(\frac{1}{k} \times A_{total}\right) \times (\Delta T \times t) \quad (4)$$

$$R_{total} = \frac{k}{\sum_{n=1}^{k} \frac{1}{R_n}} \quad (5)$$

2) Updating Thermal Properties of BIM Elements in gbXML Schema: Based on the derived thermal resistance for each building assembly, the material property of the associated BIM elements is automatically updated in their corresponding gbXML entry. The XML Document Object Model (DOM) is leveraged to enable dynamic access and update of thermal properties in gbXML schema. Finally, the updated gbXML-based BIM is used as an input of BIM-based energy analysis tools.

III. Experimental Results and Discussions

A. Experimental Setups & Performance Evaluation Measures

In this paper, as a proof of concept, the scope of updating BIM is limited on exterior wall assemblies. The two case studies were in the corner of the building layout and thus performed the measurements for two wall assemblies in each building space. The residential building under inspection was built in early 1980’s. Digital (2048×1536 pixels) and thermal (320×240 pixels) images were collected by using a FLIR E60 thermal camera with a built-in digital camera.

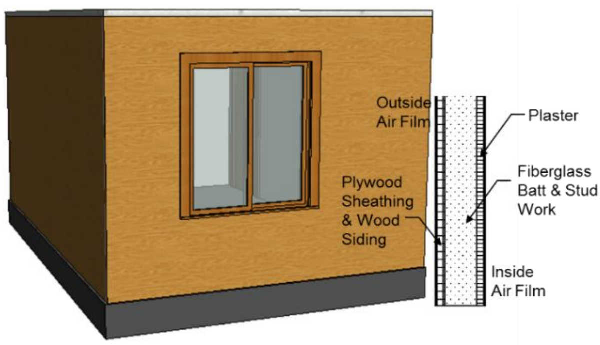

FIGURE II
A Part of As-designed BIM and Building Material Layer Sets of Exterior Wall Assemblies (Case #1)

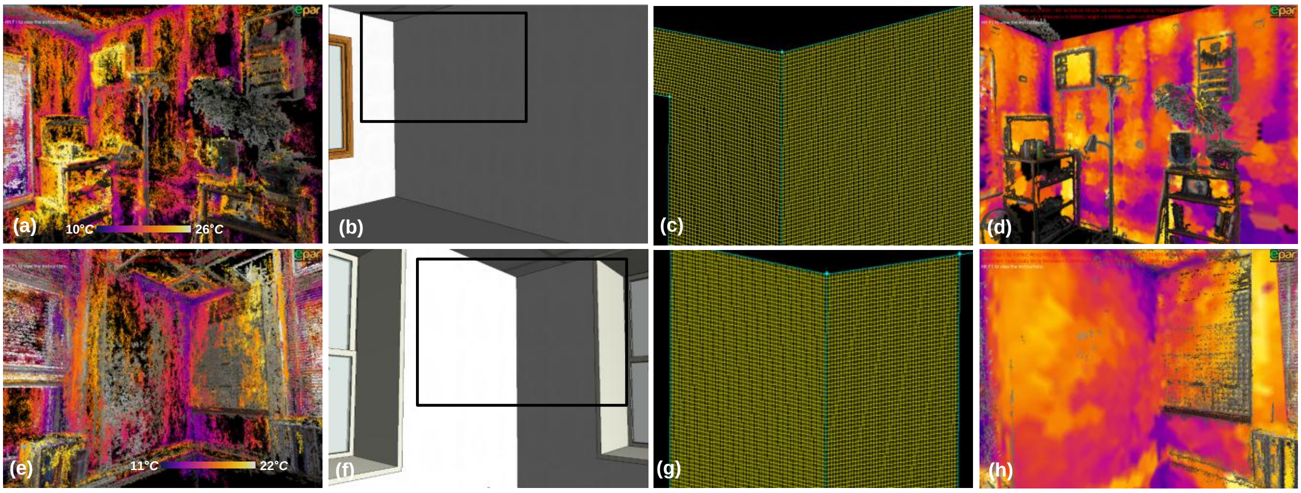

FIGURE 3.
Left to Right: 3D SPATIO-THERMAL POINT CLOUD; BIM FROM THE SAME VIEWPOINT; MESHED BIM; AND 3D THERMAL MESH MODELING

For validation, the following two performance evaluation metrics are used. First, we studied how accurately the as-is thermal resistances are measured. To do that, the deviations between the thermography-based measurements and the notional values declared by manufactures were calculated. In this paper, the validation experiments were conducted for window components since windows are mostly standardized and their thermal properties are more likely to be consistent over time. Second, we studied how precisely the as-is thermal resistance values at point level in 3D are mapped to each nearest vertex in the meshed BIM. This value is calculated by minimizing the sum of squared residual errors of Euclidian transformation for control points between 3D point cloud models and the BIM models.

B. Experimental Results on Mapping Actual Thermo-physical Properties to associated BIM Element

Figure 3 illustrates 3D spatio-thermal point cloud, mesh models, and BIM from the same viewpoints. Figure 4 presents the distribution of the thermography-based thermal resistance measurements for an exterior wall and their 3D visualization.

Table 1 describes the detailed experimental results. As can be seen in the table, the deviations between our measurement and notional values were 13.33% and 10%. Since it is not easy to maintain a perfect steady-state condition during thermogaphic inspections, more research needs to be conducted on how the measurement errors caused by non-steady-state conditions can be minimized in real-world buildings. In addition, although reasonable practical range of registration errors (≃10mm) were reported, there is still room for improvement by leveraging dedicated visual sensors such as a RGB-D sensor to improve the model completeness of 3D thermal model.

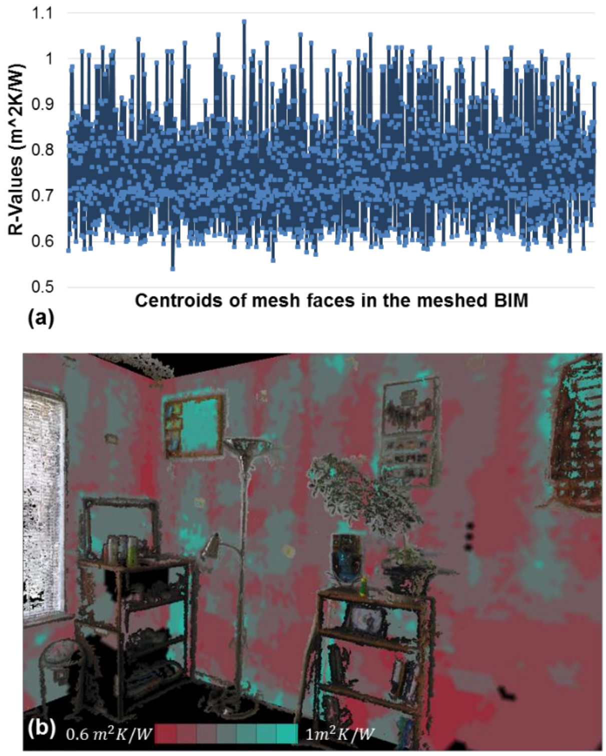

FIGURE IV.
DISTRIBUTION OF THERMOGRAPHY-BASED THERMAL RESISTANCE MEASUREMENTS AND THEIR 3D VISUALIZATION (CASE #1)

TABLE 1. EXPERIMENTAL RESULTS OF TWO CASE STUDIES

Items	Case #1	Case #2
# of thermal images	446	429
Point cloud density (# of 3D points)	3,042,350	2,838,478
Computational time for 3D modeling	2.5hr	2.3hr
Registration error (coordinate system transformation) (mm)	10.70	11.09
Weighted-averaged thermography-based thermal resistance measurements of walls (m^2K/W)	0.75	0.83
Thermography-based thermal resistance measurements (m^2K/W) for validation	0.26	0.27
Notional value (m^2K/W) for validation	0.30	0.30

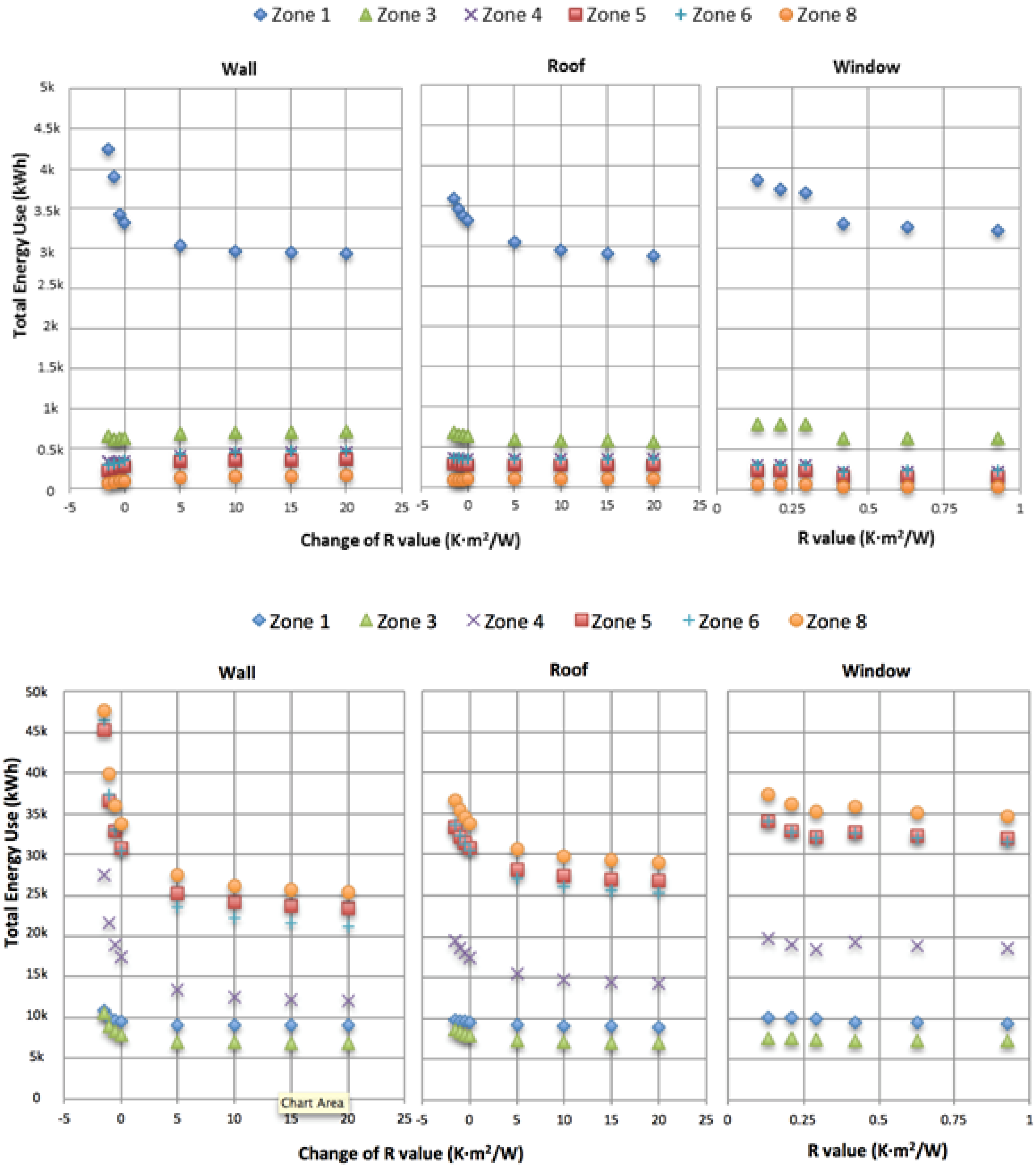

FIGURE V
IMPACT ANALYSIS OF VARIATIONS OF THERMO-PHYSICAL PROPERTIES TO ENERGY LOAD ESTIMATION UNDER THE SIX DIFFERENT CLIMATIC ZONES IN THE U.S. (TOP: COOLING LOAD, BOTTOM: HEATING LOAD)

By using the proposed method, the thermography-based building diagnostic results are automatically associated with their corresponding BIM elements and update the material properties in gbXML-based BIM models.

C. Impact Analysis of Reflecting the As-is Thermo-physical Properties of Building Envelopes in BIM-based Energy Analysis

In this paper, the impact of reflecting the as-is thermo-physical properties of different building envelopes (i.e., walls, roofs and windows) on BIM-based energy analysis under the six different climatic zones in the U.S (Miami (Zone 1), San Diego (Zone 3), Seattle (Zone 4), Chicago (Zone 5), Burlington (Zone 6), and Bethel (Zone 8)) was explored. Figure 5 shows the results of impact analysis in terms of the variations of energy load calculation with respect to the change in the thermo-physical property of each building element. As a proof of concept, the linear regression analysis was used to infer the impact coefficient for each case. Figure 6 illustrates the impact coefficient of each case. Here, the impact coefficient refers to how much

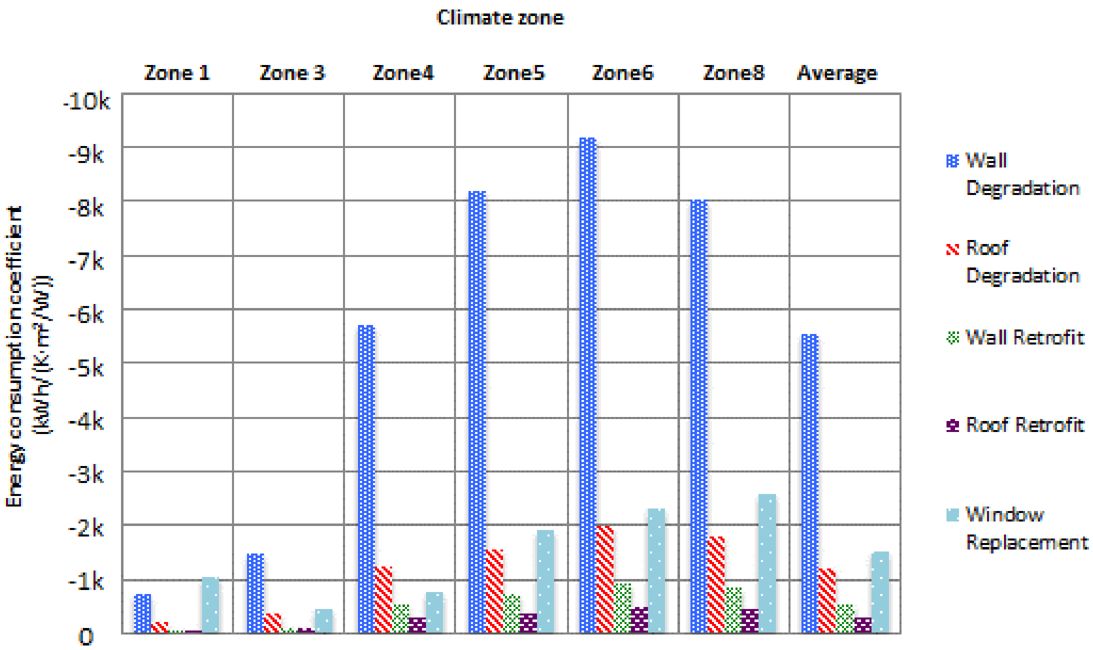

FIGURE VI
IMPACT COEFFICIENT OF DIFFERENT BUILDING ENVELOPES UNDER THE SIX DIFFERENT CLIMATIC ZONES IN THE U.S.

building energy consumption is likely to be sensitive as thermal resistances of building envelopes are changed. As can be seen in Figure 6, it is observed that the cases of decreasing in thermal resistances have relatively higher impact on energy load calculation than increasing thermal resistances. For example, the impact coefficients of walls under degradation were 10.27 times higher than that under retrofit scenarios. In addition, it is observed that walls have the highest impact coefficient among others. When it comes to the impact of different climate, it is observed that the impact coefficient in the cold region (Zone 5, 6 and 8) are higher than those in the warm region (Zone 1, 3, and 4). These experimental results show significant potentials of reflecting the as-is building conditions from thermographic inspection (i.e., the as-is thermal resistances calculated in the proposed vision-based method) in BIM-based energy modeling to improve the accuracy of energy analysis, especially for buildings with wall degradations in the cold region. Identifying such sources of energy inefficiency and taking proper actions for retrofitting the problems by building practitioners will deliver substantial energy saving benefits during building operations.

IV. CONCLUSIONS

A. *Summary and Contributions*

This paper presents an automated method for reflecting the as-is building conditions in the BIM-based building energy modeling process to improve the reliability of building energy analysis. By leveraging collections of digital and thermal images, 3D spatio-thermal models are first generated, and then the as-is thermal resistances of building assemblies are derived at point level in 3D. By mapping the resulting 3D point cloud data to the nearest vertices in the meshed BIM, the as-is thermal resistance values are automatically matched with the corresponding geometrical information in the BIM coordinate system. Finally, by using XML Document Object Model (DOM), thermal properties of BIM elements are automatically updated in gbXML schema. Experimental results in existing buildings show how the proposed method can automatically associate the as-is thermal property of building assemblies with the relevant BIM elements and semantically update the as-designed BIM data. In addition, the structured survey results with domain experts with 2 to 10 years of experiences in building energy auditing validated the practical significance of this research.

By using the updated gbXML-based BIM (i.e., as-is building condition) as an input of energy simulation engines as opposed to using the notional value declared in the industry standard databases (i.e., as-designed BIM), the proposed method reduces the gap between architectural information in the as-designed BIM and the actual data needed for energy performance simulation of existing buildings. This will complement current BIM-based energy analysis tools such as AUTODESK Green Building Studio by better characterizing the as-is building condition in the modeling process. In addition, in the case of historic building façades that used building materials that are not available in today’s standard material databases, this research helps robustly define the associated thermal property information as opposed to using substitutions in existing literatures. Such accurate modeling further enables practitioners to conduct more reliable energy analysis by understanding the impact of the as-is building conditions on building energy consumptions. In addition, this will improve the decision-making for choosing the most appropriate retrofit alternatives when evaluating the impact of different retrofit decisions on energy consumption for retro-commissioning and continuous commissioning.

B. Gap-in-Knowledge and Opportunities for Future Research

Although several scientific contributions and practical significances of the proposed method were documented as above, critical and prevalent research challenges still remain as follows. First, in the experiments conducted in this paper, it is assumed that BIMs are already developed by modelers. Nonetheless, the major challenge in building energy analyses is that only a few existing buildings have a complete record of the as-built information or BIMs that are used as inputs for building energy analysis. In this sense, there is a need for deriving the underlying mechanism for automated BIM generation from images as well as its semantic updates for energy analysis. Second, in addition to focusing on building envelops, there is a need for exploring how to reflect the as-is conditions of building systems (e.g., HVAC systems) in BIMs and study their impact on energy simulation. Finally, for scaling-up the proposed method to the building level, more research need to be conducted for investigating how separated 3D thermal models for each building space can be integrated to understand and model the as-is energy performance at building scale. By using multi-modal visual data collected from building environments, these works are currently being explored as part of our ongoing research.

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