Updating R-values of BIM Elements using 3D Thermography for Accurate Building Energy Performance Simulation

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ABSTRACT

Over the past few years, anecdotal evidence and controlled studies on predicting the actual energy performance of existing buildings have raised concerns about the accuracy of energy performance simulations using Building Information Models (BIM). Among numerous sources of modeling inaccuracy, the wrong thermal properties of solid assemblies can significantly impact the reliability of the BIM-based energy analysis. Without considering the diminishing thermal resistance (i.e., R-value) of building materials caused by their deteriorations and updating such material properties in BIM, BIM-based energy simulation of existing buildings could be unreliable for retrofit decision-making purposes. This paper proposes an automated method for updating the R-value of building elements in BIM. By exploring 3D spatio-thermal models reconstructed from 2D thermal images, the actual R-values are calculated at the level of 3D points. The calculated actual R-values are used to automatically update the thermal properties of the corresponding gbXML-based BIM elements. For validation, several experiments on measuring and updating the R-value of BIM elements are conducted in an existing residential building. Using the proposed method, BIM-based energy analysis tools can more accurately model the as-is conditions of existing buildings and estimate their actual energy performances.

INTRODUCTION

Today, energy performance simulation tools such as EnergyPlus widely use Building Information Models (BIM) for supporting building retrofit decision-makings (GSA 2012). BIMs can provide easy and rich access to building information such as building geometry and material properties, allowing energy modelers to minimize the time and efforts needed to construct energy models for simulating the impact of different retrofit alternatives on energy consumption. Accordingly, the Green Building XML (gbXML) schema has been developed to facilitate transfer of building information stored in BIM to energy simulation tools. As such, several companies such as Autodesk and Graphisoft are adopting the gbXML to build on the potentials of BIM for rapid building energy performance simulation purposes (gbXML 2013).

Despite their benefits, predictions obtained from the BIM-based energy simulation tools typically deviate from actual measurements (Yudelson 2010). These deviations are mainly due to many assumptions and simplifications that are typically made during the modeling process. Accordingly, several studies such as (Azar and Menassa 2012) have focused on addressing the challenges of modeling dynamic patterns of building occupancy during building energy simulation process. In addition to occupancy patterns, another major factor in the accuracy of building energy analysis is the accurate modeling of thermal properties for solid assemblies such as exterior walls (Ham and Golparvar-Fard 2013). During the operational phase of a building, the ability of building materials to resist heat flow (i.e., R-value) typically decreases due to their degradations or faulty constructions. Depending on the level of the deteriorations, the actual R-values are thus lower than the notional values declared in the industry standard database in the BIM-authoring tools. Without accounting for diminishing thermal resistance of building elements in BIM, BIM-based energy simulation for existing buildings would yield deviated predictions, which causes high degree of uncertainty in simulation and adversely affects retrofit decisions. Our hypothesis is that if thermal properties of BIM elements are reliably measured and updated, the BIM-based energy simulation is likely to produce more accurate predictions in building energy performance.

Building on our prior work on 3D spatio-thermal modeling of built environments using 2D infrared images (Ham and Golparvar-Fard 2013), this paper presents a new automated method for updating R-values of BIM elements. To that end, the actual heat transfer conditions of building assemblies are calculated at the level of 3D points in meshed BIM, and associated with the corresponding gbXML-based BIM elements. The resulting updated gbXML-based BIM represents the as-is condition of the existing buildings more precisely, which helps improve the accuracy of BIM-based energy performance simulation. In the following sections, we first review the related works, and their limitations are discussed. Next, the underlying assumptions and algorithms for our method are presented in detail. Finally, the experimental results, perceived benefits, and open research challenges are discussed.

BACKGROUND AND RELATED WORKS

Measuring actual thermal resistance of building assemblies using thermography. During the design phase of a building, R-value of building assemblies can be easily calculated by aggregating notional R-values of all layers in a building element. In contrary, during the operational phase of a building, the application of the destructive method for verifying presence of insulation in building elements and measuring their actual R-values is less practical. Instead, the actual thermal resistance of building assemblies can be non-destructively calculated by measuring the heat-flux between interior and exterior of a building. By exploiting indoor surface temperature obtained from thermography and assuming a steady-state condition in building interiors, several researchers (Fokaides and Kalogirou 2011; Madding 2008) measured the actual R-values of building elements by calculating the heat-flux and reported accuracies of around 10-20%. Nonetheless, there are still limitations associated with the direct applications of these prior works for updating R-value of BIM elements for as-is building energy performance modeling. First, in terms of sensing, a large number of thermal images (e.g., ~300-400 images for a 4×5m^2 room) still need to be examined manually. This requires significant time and efforts for analyzing the whole building environment. More importantly, in terms of energy analysis, by using a single or at most a few temperature data extracted from the designated area, the prior works conducted a single measurement of the actual heat transfer condition for building elements. Due to the non-uniform deterioration across the geometrical forms of building elements, the actual R-value may vary over very small scales in building assemblies. Thus, there is need for a more robust method that can rapidly and reliably model the actual heat transfer condition of building environments.

Relating the measured thermal property to BIM element. A few studies have focused on associating BIM with the measured thermal property. Lagüela et al. (Lagüela et al. 2013) presented a method for visually mapping thermal texture onto the BIM element. Their recent work (Lagüela et al. 2014) proposed a method for changing the thermal property in gbXML-based BIM. This work measured the actual heat transfer condition by using a surface temperature data obtained from a thermal image, and linked a single measurement of R-value to the corresponding building element in gbXML schema. Despite their benefits, this may not accurately model the actual thermal properties of building elements since they conducted a single measurement of the actual R-value for the entire areas of building elements. More importantly, this should manually find the building element corresponding to the measurement. Considering large numbers of building elements and thermal images in built environments, it is not trivial to manually match each measurement with each building element, which makes the process time-consuming and error-prone. Thus, there is a need for an automated method for matching the measurement with the corresponding BIM element for rapid building energy performance modeling.

OVERVIEW OF THE PROPOSED METHOD

This paper aims to create and validate a new automated method for updating R-value of BIM elements for accurate BIM-based building energy performance modeling and simulation. To that end, we propose a thermography-based method for measuring actual R-value at 3D points in a non-destructive manner and associating actual thermal property measurements with BIM elements in gbXML schema.

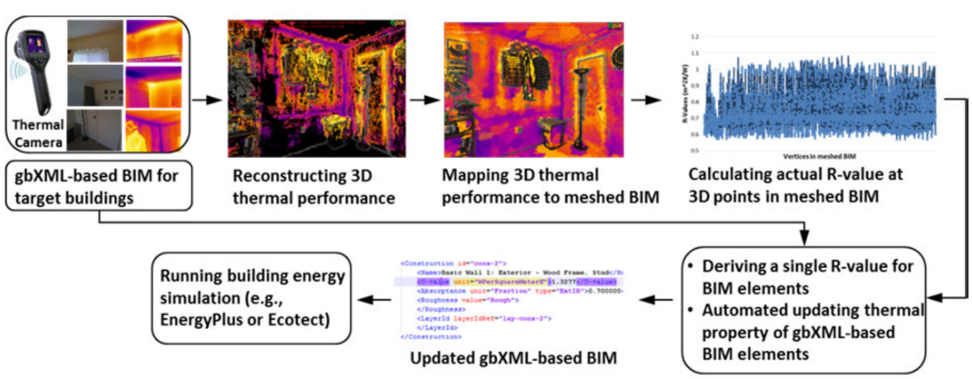

Figure 1. Overview of data and process in the automated method for updating thermal properties of gbXML-based BIM elements using thermography.

In the proposed method (Figure 1), an image-based 3D spatio-thermal modeling method is used to query 3D thermal performance information from building environments. We assume the gbXML-based BIM of the target existing buildings is already developed by modelers. In this BIM, the thermal properties of building elements are solely obtained from generic construction material data available in BIM-authoring tools or specifications. We first map the 3D thermal information queried from 3D spatio-thermal model to the meshed BIM. Next, we calculate actual thermal resistance of building assemblies at the level of 3D points in the meshed BIM, and then the actual R-values of building assemblies are converted into a single value for each building element. Finally, thermal properties of the corresponding BIM elements in the gbXML schema are automatically updated based on the calculated R-value, which generate the as-built gbXML-based BIM for accurate building energy performance modeling. The following sections describe each step in detail.

Reconstructing 3D thermal performance using 2D thermography. Our method for calculating actual heat transfer condition of building assemblies at the level of 3D points builds on the recently prototyped image-based 3D spatio-thermal modeling method. The building practitioners first collect digital and thermal images from the buildings under inspection. We leverage the unordered collection of digital and thermal images captured using a single hand-held thermal camera with a built-in digital camera. Through a thermal camera calibration, a relative pose estimation of the thermal camera with respect to the digital camera, and the Multi-View Stereo algorithm, these images enable the actual thermal performance of the building under inspection to be modeled in form of 3D spatio-thermal point cloud. The readers are encouraged to look into (Ham and Golparvar-Fard 2013) for more details on the automated image-based 3D spatio-thermal modeling process.

Mapping 3D thermal performance to meshed BIM. The resulting 3D thermal point clouds are typically incomplete and include large numbers of points that do not belong to the building geometry itself. To improve the model completeness and the reliability of the assessments, we map the 3D spatio-thermal point cloud to BIM by using *k-d* tree structure and the nearest neighborhood searching algorithm. In this process, we use the meshed BIM as the basis for the transformation. Here, the boundary points were obtained from the content of the sub-element 'Coordinate' of the element 'Surface' in gbXML schema. Then, the planar geometry is divided into a set of identical areas to form the baseline mesh model. Each vertex in the meshed BIM is associated with a temperature reading averaged from all thermal images that observed the vertex during thermographic inspection.

Calculating actual R-value at the level of 3D points in meshed BIM. Our work for measuring R-value is based on the following environmental assumptions: 1) the indoor building environment has a quasi-steady state condition of heat transfer during thermographic inspection; 2) the overall heat transfer (Q) of building environments is attributed to thermal convection and radiation (Fokaides and Kalogirou 2011; Madding 2008). Under the steady-state condition of heat transfer with the temperature difference between inside and outside (ΔT), the overall heat transfer (Q) rate through building surface with the area of (A) having a thermal resistance (R) can be described using the following equation:

$$\frac{dQ}{dt} = \frac{1}{R} \times A \times \Delta T \qquad (1)$$

The amount of heat transfers (Q) caused by thermal convection and radiation between the indoor surface of building environments and the surrounding air are calculated using the following equations respectively:

$$Q_{Convection} = \alpha \times Area \times \left|T_{inside,air} - T_{inside,wall}\right| \qquad (2)$$

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

Where α is the convective heat transfer coefficient affected by airflow types, ε is thermal emissivity, σ is Stefan-Boltzmann constant. $T_{inside,air}$ and $T_{outside,air}$ are measured using a thermometer. $T_{inside,reflected}$ is measured by using a small crumpled aluminum foil located on the inspection areas. Due to the low emissivity and high reflectivity of the foil, reflected temperature of building environments can be robustly measured from the crumpled foil (Ham and Golparvar-Fard 2013). Finally, by combining equation (1), (2), and (3), the thermal resistance (R) is calculated using the following equation:

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

Within the meshed BIM, $T_{inside,wall}$ can be queried at the level of 3D point. Thus, by using the equation (4) with the queried 3D thermal performance from meshed BIM, actual R-value are calculated at the level of 3D point in meshed BIM.

Deriving a single R-value for BIM elements and Automated updating R-value of gbXML-based BIM elements. Since current building energy performance simulation tools require a single thermal property for each building element, we need to translate the calculated point-level actual R-values into a single R-value for the corresponding BIM elements. In the meshed BIM, the sum of the amount of heat transfer through each mesh face of a building element is the same as the amount of heat transfer through the whole area of the building element (Equation 5). Based on this, the single R-value for building elements can be calculated with the equation 6:

$$\frac{1}{R_{total}} \times A_{total} \times (\Delta T \times t) = \left(\frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_k}\right) \times (\frac{1}{k} \times A_{total}) \times (\Delta T \times t) \qquad (5)$$

$$R_{total} = \frac{k}{\sum_{n=1}^{k} \frac{1}{R_n}} \qquad (6)$$

Here, k is the number of mesh faces on each building element in the meshed BIM. Once the single actual R-value for each BIM element is calculated, by matching the attribute "id" on the element 'Construction' with the attribute "constructionIdRef" on the element 'Surface', the content of the sub-element 'U-value' under the element 'Construction' in the gbXML schema is changed to the reciprocal of the R-value. Ultimately, the gbXML file converted from a pre-existing BIM is automatically updated in terms of thermal condition of as-is building environments.

EXPERIMENTAL RESULTS

To validate the proposed method, as a proof of concept, we conducted a case study on a bedroom in an existing residential building. The residential apartment under inspection was built in early 1980's. For the 3D spatio-thermal modeling, digital (2048×1536 pixels) and thermal (320×240 pixels) images were captured by using a FLIR E60 thermal camera which has a built-in digital camera. For calculating heat transfers caused by thermal convection, we adopted the convective heat transfer coefficient (α) from (ISO 6946:2007).

Results and discussion.

Figure 2(a) illustrates a 3D thermal point cloud, and figure 2(b) and (c) represent views of the 3D thermal mesh model and Building Information Model (BIM) of the same building environment under inspection.

Figure 2. (a) 3D thermal point cloud and (b) mesh models jointly visualized with the building geometry, and (c) BIM of the same building environments.

Figure 3(a) and (b) present the distribution of the measured thermal resistances for exterior walls and the visualization using different color gradients in 3D. As observed, 3D visualization allows quick understanding of the distribution of the actual R-value for building assemblies. After the actual R-values are calculated at the level of 3D vertexes, we derive a single R-value for the corresponding BIM elements that is in form of an input of current building energy simulation tools. Figure 4 shows the relevant part of the automatically updated gbXML file through the proposed method. By using the updated gbXML-based BIM as an input of BIM-based energy performance simulation, practitioners are more likely to reliably analyze thermal loads and the associated energy consumption, which benefits retrofit decision-makings for different retrofit alternatives.

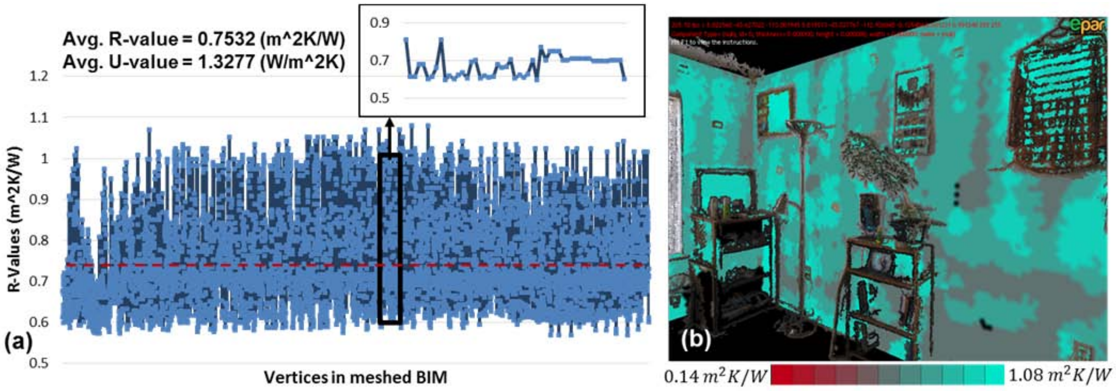

Figure 3. Vertex-level actual R-value distribution of the wood frame wall (left) and 3D visualization along with the building geometry (right).

```xml
<Construction id="cons-2">
    <Name>Basic Wall 1: Exterior - Wood Frame. Stud</Name>
    <U-value unit="WPerSquareMeterK">1.3277</U-value>
    <Absorptance unit="Fraction" type="ExtIR">0.700000</Absorptance>
    <Roughness value="Rough">
    </Roughness>
    <LayerId layerIdRef="lay-cons-2">
    </LayerId>
</Construction>
```

Figure 4. The relevant part of the element 'Construction' in the updated gbXML-based BIM for the case study.

RESEARCH CHALLENGES AND OPEN PROBLEMS

Although the proposed method enables to automatically update R-value of BIM elements by using thermography, there are several open problems which still require further investigation: 1) currently, the data types that can be incorporated into the gbXML schema only include geometrical information for 3D planar polygon and 2D rectangular polygon. How to model and update thermal properties of non-planar building elements remains uninvestigated; and 2) during thermographic inspection, it is difficult to measure the actual thermal properties of the building areas occluded by objects. Due to space limitations in most existing buildings, it is not trivial to remove all objects that block the line of sight to building elements. How to extrapolate R-value for occluded areas also remain as an open problem.

CONCLUSIONS

For BIM-based energy analysis of existing buildings, transferring BIM information into energy simulation tools would yield deviated results since it does not account for as-is building conditions. In this paper, we present a new automated method for updating thermal properties of gbXML-based BIM elements through reliable assessment of 3D building condition using thermography. We demonstrate that the proposed method can minimize the need for manual processes for associating actual thermal property measurements with the corresponding BIM elements in gbXML schema. This can shorten the gap between architectural information in BIM and the as-is building conditions in terms of thermal performance, and ultimately has potential for improving the accuracy of the BIM-based energy simulation. Our future works involve performing extensive experiments and quantifying the impact of the accurate modeling of building material property on energy performance simulation. These are currently being explored as part of our ongoing research.

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