Building Envelope Thermal Performance Analysis using BIM-Based 4D Thermal Information Visualization

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Abstract:

This paper focuses on the performance of the building envelope of existing buildings by creating 4D models of thermal data to identify areas that require modifications. The proposed method is based on the integration of a digitally captured thermal data of the building envelope and sensors' data inside the building with the BIM model. For that, thermographic images are captured and values of air temperature and relative humidity inside the building are collected by a data logger different times. The collected data are then imported into existing BIM model of the building. Hence, the BIM model is enriched by spatio-temporal surface and air temperature information. Consequently, the thermal information of the building can be visualized in 3D or 4D to help analyzing heat energy performance and thermal comfort level such as heat diffusion through building facades and thermal comfort-index. The results of the case study showed that the time coded temperature distribution data captured by thermal cameras can be visualized in the BIM application and can be used to provide users with crucial information to help identifying performance shortcomings.

Keywords: 4D thermal mapping, Thermal performance, Building Information Modelling, Energy efficiency improvement

1. INTRODUCTION

Building Information Modeling (BIM) is becoming a tool for supporting energy efficiency analysis through three-dimensional analytical models which can be a shared resource of building information such as physical properties, functional characteristics, costs, and construction time via various file formats (Lagüela et al., 2012a). A four-dimensional model enables project technicians to analyze the progression of construction activities through visualizing series of events on timeline schedules.

In order to analyze the thermal performance of a building, thermal cameras can be used. They commonly provide quantitative and qualitative data through thermographic images (Lagüela et al., 2012b). The use of thermal cameras is mainly for visualizing temperature information of building surfaces and can be used for detection of thermal bridges, heat infiltration, location area of heat loss, location of heat source, and assessing the performance of an insulation (Young et al., 2014). It has proved to be an adequate technique for diagnosing and monitoring heat radiation from buildings (Grinzato et al., 1998). However, 2D thermal imaging lacks complementary information, such as geometry, volume of space, and actual site location of the building. For this reason, integration of 3D geometry with thermal data results in having an accurate and geometrically referenced thermal distribution data, which enables quantitative estimations, such as heat diffusion and heat radiation of building surfaces (Vidas et al., 2013).

It is insufficient to provide only a real-time thermal distribution information to help decision makers taking better options for energy efficiency retrofit for an existing building. The thermographic and geometric data and visualizations generated from a 4D thermographic model provide useful quantitative and qualitative information for supporting building energy diagnosis. Motamedi et al. (2014) investigated detection of root-causes of problems in a building through a BIM-based visual analytics tool, which uses color coding of components and visualizes them in 3D and 4D models to help experts with problem-solving. Similarly, thermographic 4D modeling in BIM has the potential to be used as a new tool for the performance analysis and energy efficiency improvement of building envelopes of existing buildings. It allows users analyzing the spatial distribution of surface temperatures over time, with respect to building geometry and setup, in a holistic manner.

The paper presents a methodology for the integration of 3D geometry and time-coded thermal data in order to create 4D thermographic model that visualizes changes of thermal information of building surfaces. It uses time-coded thermographic images that are acquired by thermal cameras and are integrated with a BIM model. In addition, data loggers and sensors are used for collecting room temperature and humidity information. Tools such as Autodesk Revit, Naviswork, Rhinoceros and its plug-in Grasshopper were used in our experiments. The main contribution of this paper is to create a new method and a tool for the analysis of thermal performance and thermal comfort level in the building for energy performance evaluation using a BIM-based 4D thermographic model. The method proposes visualizing patterns of surface temperature changes together with sensor data values, which are all geometrically referenced within the building model. The applicability of the method is verified in a real-world case study.

2. LITERATURES REVIEW

Several environmental factors affect the thermal comfort. ASHREA standard 55 defines the thermal comfort as a state of mind which expresses satisfaction with the thermal environment (Paliaga et al., 2013). Thermal comfort measurable influential factors can be divided into physical, physiological, and psychological factors (Huizenga et al., 2006). Main factors are air temperature (ºC), relative humidity (%), mean radiant temperature (ºC) (the average temperature of surfaces), air velocity (m/s), metabolic rates (met), and clothing insulation (clo). There are three different methods for describing thermal comfort including; Predicted Mean Vote (PMV), Predicted Percentage of Dissatisfied (PPD), and Adaptive Method Model (Fangeret al., 1970). The adaptive method concept is applicable to naturally ventilated buildings with no mechanical cooling, and heating system installed (Hoyt et al., 2013). This method is based on the fact that such buildings achieve thermal comfort across a wider range of indoor temperature because of increased level of personal control over operable windows (de Dear et al., 2013). Room temperature is affected by the air temperature and generated radiation from building surfaces. The temperature difference between human skin and surroundings directly influences on the amount of transmitted heat. It is one of significant factors on the comfort level in the adaptive method. Controlling radiant heat is necessary to maintain comfort by techniques such as installing insulation to control heat transfer for building envelopes. Mean Radiant Temperature (MRT) is calculated based on the temperature of surfaces surrounding an enclosed space by considering conical angles of those surfaces with respect to the human body (Bradshaw et al., 2006). Based on available literature, the evaluation of thermal comfort with the correlation of surface temperature and air temperature can be performed using two difference tools; adaptive method chart (Hoyt et al., 2013) and the correlation of indoor air temperature and surface temperature chart (Sedlbauer et al., 2005; Gut et al.,1993).

Recently, thermal camera is commonly used as a tool to detect surface temperatures. Thermal imaging is a method for diagnosing the condition of buildings, detecting the exact areas of heat sources in the building, and measuring heat emissivity by transforming hidden characteristic to visible images (Eads et al., 2000). The color pattern in thermal images shows different temperature ranges of building surfaces. Thermal imaging can provide data to support thermal comfort analysis. Additionally, it helps identifying the potential problem areas that need to be improved (Grinzato et al., 1998).

The crucial concept of the BIM process is to provide interoperability between two or more platforms for exchanging information and facilitating collaboration between stakeholders (Macii et al., 2011). BIM data exchange is currently done by the Industry Foundation Class (IFC) and Green Building XML (gbXML) (Dong et al., 2007). IFC and Green Building XML standards are used for sharing physical and functional characteristics of a building between stakeholders in different phases of the life cycle. One of various applications of BIM is to monitor energy consumption (Klein et al., 2012). A BIM model that is used for energy analysis requires specific information of material (e.g., U-values, R-values, and Solar Heat Gain Coefficient (SHGC) of components) to perform the energy analysis (Volk et al., 2014). These indices were found to have maximum impact on the energy saving potential (Sinha et al., 2013).

A number of previous research studies have proposed methods for 3D thermal modeling (e.g., Schreyer et al. 2009; Lépine et al., 2012; Lagüela et al., 2012; Ham et al., 2012; Ham et al., 2014; Demisse et al., 2013). Techniques for creating 3D thermal models for measuring surface temperature of existing buildings can be divided into three categories. The first category is to map infrared images to a 3D model, the second category is to fuse infrared and digital images to visualize thermal data, and the third category is to map infrared images to 3D point clouds (Wang et al., 2013). However, it is insufficient to only provide spatial heat distribution model. Methods for finding the correlation between time and the changes of heat distribution patterns, integration of spatio-temporal thermal data in the BIM model for real-time thermal visualization, and providing adequate measurement techniques for identifying temporal correlation between surface temperature values and thermal comfort level, have not been fully proposed yet and these topics still remained as research gaps. Therefore, this paper investigates a new method for integrating 3D geometry, and time-coded thermal data for creating 4D thermographic models and aims to address some of the above-mentioned gaps.

3. PROPOSED METHODOLOGY

The proposed method consists of four main steps (shown in Figure 1). The first step is BIM modeling and data collection. Thermographic data such as surface temperature readings (i.e., thermographic images) together with sensors' reading (such as air temperature and humidity values) are collected from an existing building. A 3D BIM model of the building, which includes geometry information as well as material and properties is also created (Figure 1(a)). The second step is to map thermographic images to the BIM and integrate sensor data with the BIM model. For that, software applications such as Navisworks, Rhinoceros and Grasshopper can be used. The integrated thermal data provide not only information for visual analysis but also inputs for tools such as thermal evaluation applications (Figure 1(b)). The third step is to create appropriate outputs from the BIM to be used for thermal performance analysis and thermal comfort evaluation. In this step, target outputs such as 3D (spatial) and 4D (spatio-temporal) visualizations can be obtained (Figure 1(c)). In the fourth step, using visualizations and statistics provided in the third step, experts can identify root-causes of problems and inefficiencies and suggest improvement scenarios (Figure 1(d)).

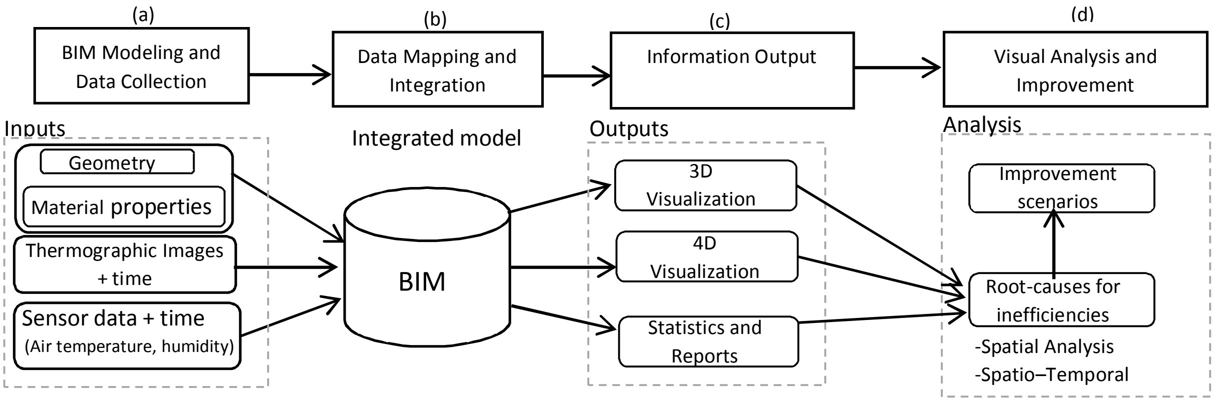


Figure 1. Overview of the proposed method

3.1 THERMAL DATA COLLECTION AND INTEGRATION

After creating an as-built 3D BIM model of the building and assigning materials and thermal properties, collected thermal data are imported to the BIM. Thermal data include thermal images and sensor readings. The integration process to add thermal information to the BIM is shown in Figure 2.

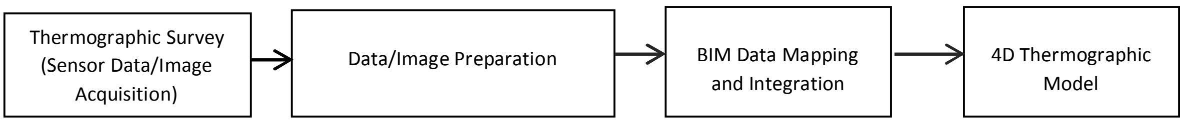
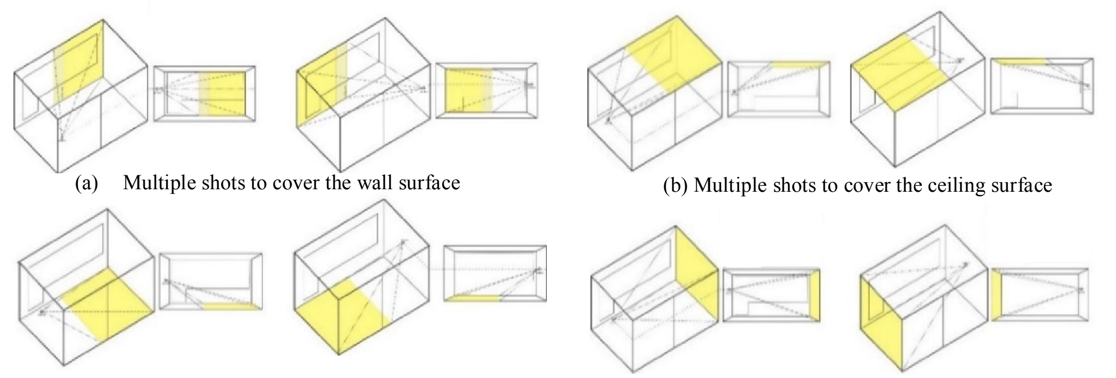


Figure 2. Workflow for integrating thermographic data and BIM

Thermographic Image and Sensor Data Acquisition

In order to acquire thermographic images, thermal cameras are used. The images should be taken in a clear weather condition (rain causes water and humidity on the building envelope which affects the results). In order to perform a thermographic survey for the interior of a typical rectangular-shape room, the following general guidelines are advised; 1) if a building surface cannot be covered in a single shot, multiple shots should be taken to cover the surface (Figure 3 (a,b,c)). However, the perspective distortion should be corrected in a later stage. Additionally, thermal images need to have at least 30% overlap with each other while covering the entire surface; 2) if building surfaces can be covered in a single shot, the photo should be taken with a straight view of the surface and focusing on the center point of the surface (Figure 3 (d)); 3) a fixed coordinate system should be used for identifying locations of the thermal camera when capturing thermal images. Additionally, obstacles and assets that are blocking the target surface should be cleared.



(a) Multiple shots to cover the wall surface

(b) Multiple shots to cover the ceiling surface

(c) Multiple shots to cover the floor surface

(d) A single shot with a straight view of the surface

Figure 3. Illustrations general guideline for the acquisition of thermographic images

Air temperature and relative humidity data are collected using sensors. Measurement points inside the building are recommended to be set at the desk height and away from walls by at least one meter. The number of sensors and distance of each sensor depends on the area size. In our case study (Section 4), five temperature and humidity sensors are used for the room with the area of $24m^2$, one sensor for outdoor temperature and four sensors for indoor air temperature measurement (Figure 4).

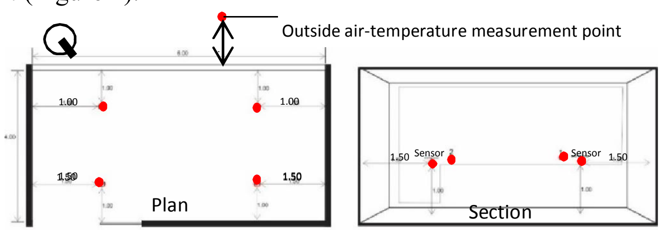


Figure 4. Placement of sensors for the case study

Image Preparation

If 2D thermographic images are not taken with a straight view of the surface, a step to remove the perspective distortion is required. Additionally, after fixing the perspective distortion, if multiple images of one surface are acquired, they need to be adjusted and stitched together to create a seamless image (Figure 5). These changes are done using raster graphics editors (such as Adobe Photoshop). In this step, considering dimensions of the surface is important as the size of combined images should correspond to that of the surface. The combined images of each surface is then mapped into the BIM model.

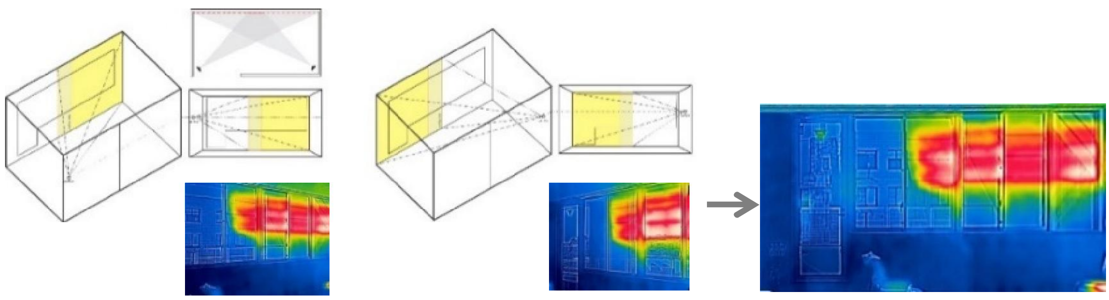


Figure 5. Adjusting the perspective distortion and stitching multiple thermographic images

Automatic integration of thermographic images and temperature data with 3D BIM

In this step, adjusted thermographic images that are taken at various times, are processed for automatic mapping in a 3D BIM to create 4D visualizations. Having color coded images added as textures in the 3D BIM model helps users analyzing thermal performance using the walk-through capability of BIM tools. In addition to attaching textures, thermal data values (such as sensor readings and surface temperatures) are captured and imported to the BIM model. For that, temperature values are extracted from images using color codes and imported to the BIM with their coordinates references and timestamps. In order to acquire the numerical temperature data from thermographic images, the relationship between R, G, B and thermal values are needed (as shown in table 1). In our study, a set of interoperable tools for BIM modeling and 4D visualizations were used. Autodesk Revit was used for creating BIM model and Navisworks was used for 4D modeling. Rhinoceros with its plugin Grasshopper were used to extract thermal values from images and to simulate the changes over time. Figure 6 show the Grasshopper definition for extracting RGB values from the thermal images. Details of the case study is presented in Section 5.

Table 1. The relationship between temperature and R, G, B values

Temperature range ^{o}C	Color legend	R	G	B
35.5 - 38		255	255	255
33 - 35.5		255	127.5	0
30.5 - 33		255	255	0
28-30.5		127.5	255	0
25.5-28		0	255	0
23-25.5		0	255	127.5
20.5-23		0	0	255
18-20.5		0	0	127.5
16		0	0	0

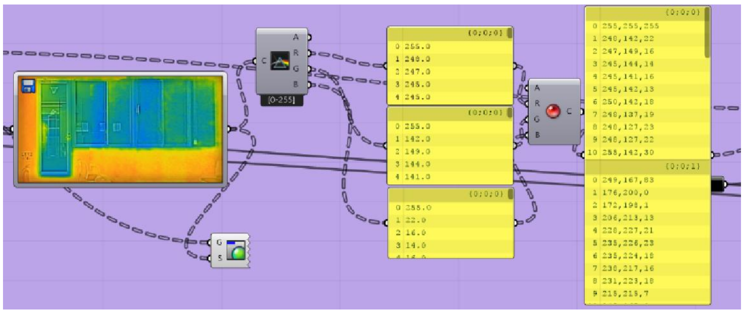


Figure 6. Grasshopper definition for extracting thermal data as RGB value

The sensor data (i.e., temperature and humidity) should also be recorded in the BIM. Existing IFC resources are proposed to be used for storing such data. Using IFC standard facilitates sharing data between numerous BIM-compatible software applications. Various IFC resources are used to capture required information. Definitions and the geometry of the room space are described by *IfcSpace* resource. *IfcSpace* represents an area or volume bounded that provide certain functions within a building. Temperature and humidity sensors are described as types of *IfcSensor* and their properties are captured using resources such as *Pset_SensorTypeTempearureSensor*. The absolute geometric placement of the space and sensors is defined by *IfcLocalPlacement*. *IfcThermodynamicTemperatureMeasure* is a resource to keep temperature values. *IfcTimeSeries* describes a set of time series with a time-stamped data entries. It allows collecting data over intervals of time (buildingSMART International, 2015). As indoor air temperature and humidity are recorded over a period of time, such resources can be used to host logged data in a standard BIM.

3.2 INFORMATION OUTPUT AND ANALYSIS

After integrating timestamped thermographic images, temperature, and humidity data in the BIM model, various outputs can be generated. An example of such outputs is a detailed surface temperature map extracted from RGB values of 2D thermographic images that are saved in the BIM model. Additionally, 3D representations of building envelope with added thermal images as textures, are another possible output. The user can use the walk-through feature of BIM applications to view the textures. 4D visualizations are another type of outputs that show the changes of thermal values over time. Sample 4D visualization is shown in Figure 6. Additionally, sensor data that are stored in the BIM can be exported for thermal performance and thermal comfort analysis.

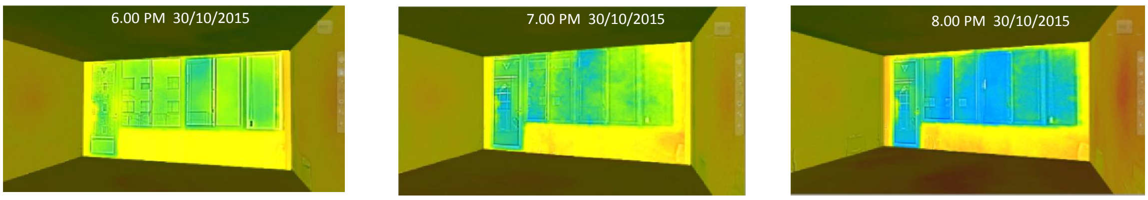
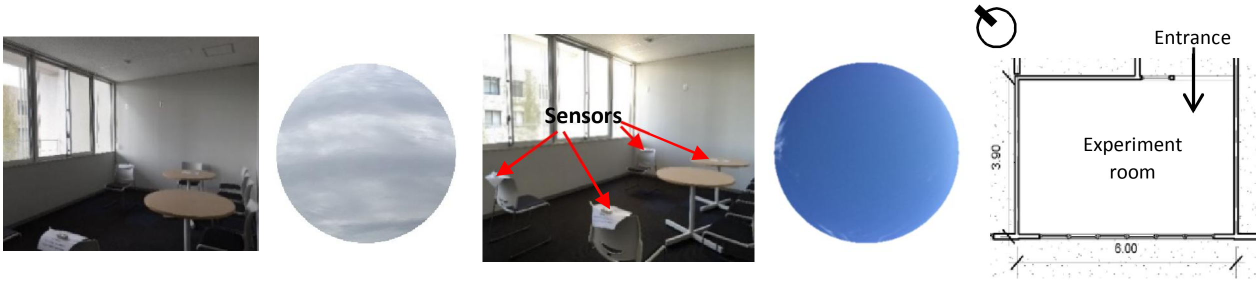


Figure 7. Example of 4D visualization

The thermographic 3D model that is enriched by temperature data of surfaces can visualize potential problem areas by showing locations of heat leakages on the building envelope, as well as to help evaluating thermal performance and comfort level. It increases the ability of users to monitor building envelope and immediately detect the exact locations of heat sources. Moreover, due to the fact that the proposed thermographic 3D model contains geometry and assets' information, the spatial relationships between elements can be visually analyzed. Additionally, thermographic textures on a 3D model support assessing the amount of emission from surfaces using color coding. 4D visualizations allow users to view the changes of thermal information over time and can be a basis for spatio-temporal analysis. Each part of the captured thermal scene assists estimating the temperature distribution as well as estimating thermal comfort in different times of a day.

4. CASE STUDY

The thermographic survey was performed at the end of September and the beginning of October 2015, in both cloudy and clear weather conditions from 9.00 a.m. to 8.00 p.m. The 4th floor dining lounge of the M3 building at Osaka University, Japan was chosen an experimentation area. The experimentation room was a typical rectangular shape room shown in Figure 8 (c). The average indoor air temperature in the cloudy day was 25.69 ºC with 38.90% of relative humidity (RH). The average indoor air temperature of the day with clear sky was 25.04 ºC with 47.22 % relative humidity. Figure 8(a) and 8(b) show pictures of the room in cloudy and sunny weather conditions, respectively.



(a) Experiment room in cloudy sky (b) Experiment room in clear sky (c) Room's Plan

Figure 8. Experimentation room condition

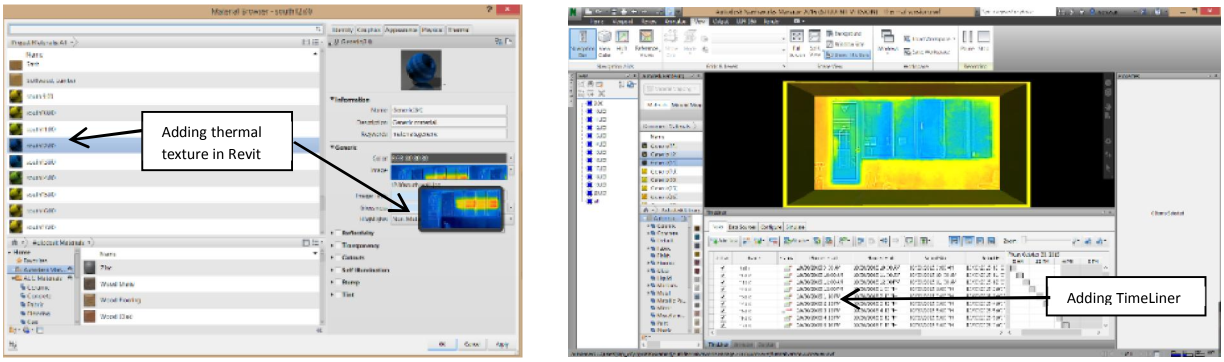
4.1 THERMOGRAPHIC DATA ACQUISITION AND BIM MODELING

2D thermographic images were captured using a low-cost thermographic camera (i.e, FLIR C2), with infrared sensor 80×60 (4,800 measurement pixels). Temperature range of the camera is -10ºC to +150ºC, with ±2°C accuracy. The field of view of the thermal camera is 41º×30º. The interior thermographic survey allowed the acquisition of thermal imaging for the entire surfaces of the experimentation area with up to eight pictures following our proposed guideline (explained in Section 3) (Figure 3). Air temperature and relative humidity data were collected using data loggers (i.e., HOBO UX100). Four measurement points for collecting inside air temperature and RH measurement were chosen at the working level of 1.0 meter above the floor, with 1.0 and 1.5 meter distances from their adjacent walls (Figure 4). For outside temperature measurement, one data collection point was chosen, which was 1.5 meters away from the South-West wall. Sensors were set to collect real-time temperature and humidity measurements at time intervals of 15 minutes.

4.2 DATA PREPARATION AND INTEGRATION WITH BIM

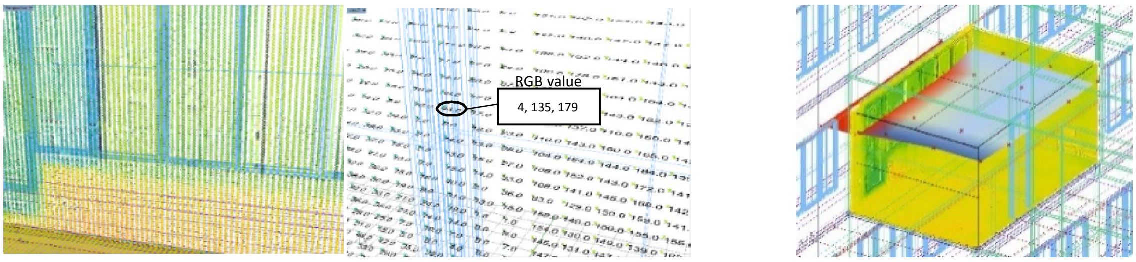
Acquired thermographic images were adjusted for removing perspective distortions (especially for the South West wall, ceiling and floor in Figure 4 due to large angles). The images were combined to a seamless thermographic image with a straight view that covers the entire wall considering the dimensions of the respective wall. Adobe Photoshop CS4 was used in this step. Autodesk Revit 2015 was used for modeling the experimentation room. In order to present 4D thermographic models, first, multiple thermographic images were added as textures for the material of the building envelope using *Appearance Asset* interface which is one of general information of the material panel in Revit (Figure 9 (a)). After adding thermographic images as textures in the model, Revit can be used for creating the walkthrough in the thermal 3D model. Tools such as Navisworks and Rhinoceros were chosen for mapping time-coded thermographic images and temperature data in the BIM. The model was exported from Revit to Navisworks using NWC file format. *TimeLiner* component was required to simulate the 4D dynamics of the model over a period of time in Navisworks (Figure 9 (b)). The model was also exported to Rhinoceros via IFC file format. Rhinoceros with its plugin Grasshopper were used to extract thermal values from thermographic images (Figure 9 (a)), which can simulate the changes of thermal information over time. Color map is needed to interpret temperature values. In order to complete mapping series of thermographic images on a BIM model in Rhinoceros, an additional IFC surface object should be created. Each thermographic image was then projected on its respective parallel wall. The numeric temperature data acquired by data loggers were imported to Rhinoceros using HOBO

Ware and Excel for showing the spatial distribution of air temperature values. (Figure 10 (b)). Automatic mapping of thermographic images was performed in Naviswork and Rhinoceros according to the description explained in section 3.



(a) Creating new material in Revit (b) Adding TimeLiner component in Navisworks

Figure 9 Mapping series of thermographic images on a BIM model



(a) Thermal information and RGB colors value (b) Example of 3D spatial air temperature data

Figure 10 Visualization of thermal information

4.3 THERMAL PERFORMANCE AND COMFORT ANALYSIS

After completing the experiment using the proposed methodology, 4D thermal visualizations and data were created by integrating thermographic images, geometric information, and time stamps. In order to analyze thermal performance of the building envelope, the relationship between surface temperatures, mean radiant temperature, and air temperature, were focused in the case study. Figure 11 shows an example of the visualization output. An engineer can visually observe the surface temperature of different areas using a color map and identify patterns of inefficiency or sources of problems. For example, to detect areas with excessive heat loss or heat generation in the building. As shown in Figure 11, the changes of locations of high temperature areas in different time can be visualized through the 4D thermographic model, which is useful to plan for improvement. The period of time that should be considered to protect heat is from 12.00 to 2.00 p.m. on the South West wall. The highest surface temperature was reached approximately 37 ^{o}C on window glasses area. Additionally, as the average of surface temperature is an integral part of MRT calculation, this information can be used to evaluate thermal comfort using the adaptive method. The details of visual analytics method and a thorough analysis for this case study is the future work of this research.

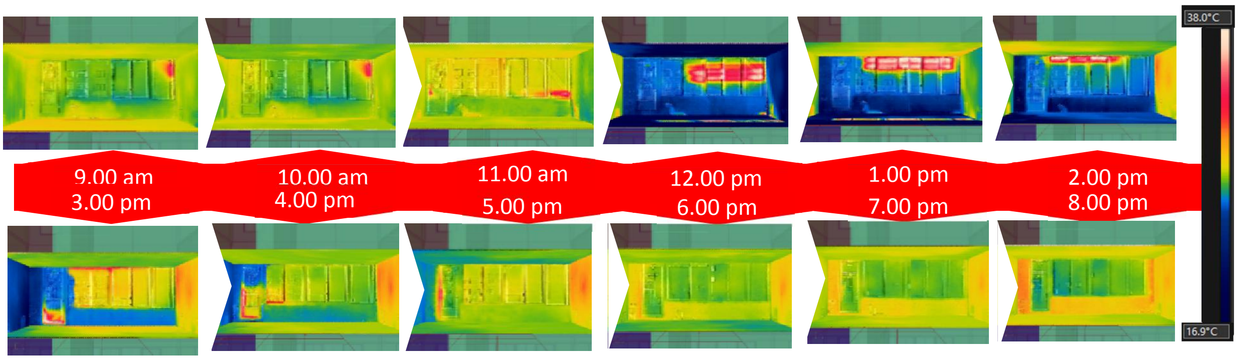


Figure 11. An example of thermographic 4D information visualization

5. CONCLUSION

This paper investigated a method for creating BIM-based 4D thermographic visualizations for thermal performance analysis and thermal comfort evaluation of an existing building. The resulting 4D thermographic model has a potential of serving as a tool for visualization and diagnosis of building conditions. The proposed method has been verified in a case study in a campus building. Images taken by a thermal camera and sensors reading were mapped into the BIM using tools such as Navisworks and Rhinoceros. Thermographic information as well as sensors' data provided surface temperature distribution in a target space. Our initial results showed that the data can be successfully integrated and 3D/4D outputs can be used for thermal performance analysis and thermal comfort evaluation. More detailed analysis of acquired results will be presented in future reports and publications. In order to acquire thermal data, a high-resolution camera should be used. However, fixing perspective distribution of acquired images at post-processing can lower the quality of data. Exporting thermal information to IFC file using proposed IFC resources, developing a method for thermal comfort analysis using 4D thermal model, combining CFD tools with the thermal model for analyzing the effect will be future work of this study.

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