A Framework for Constructing Semantic As-is Building Energy Models (BEMs) for Existing Buildings Using Digital Images

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Abstract –

Retrofits of existing buildings have great potential to reduce global energy consumption and greenhouse gas emissions. Energy modeling of existing buildings, which is commonly conducted to prioritize retrofit strategies, relies on as-is building energy models (BEMs) that represent actual conditions of buildings. Recent efforts have focused on leveraging sensing technologies such as laser scanning and photogrammetry to capture as-is conditions of buildings and developing automatic methods for creating BEMs using the captured data. However, the majority of these efforts are limited to reconstructing 3D facade geometries with poor semantic information for rough BEM use. To this end, this paper presents a framework for an image-based approach to construct complete and semantic as-is BEM geometry models for existing buildings. The framework consists of four modules: 1) the data capture module that collects digital images of building facades and interior spaces and relevant "placement" information for geometry definition; 2) the building surface geometry reconstruction module that recognizes main building components required by BEM and reconstructs their 3D surface geometries from captured images; 3) the semantic enrichment module that adds the required geometry-related semantic relationships among the reconstructed building elements and interior spaces; and 4) the BEM creation module that stores the semantic geometry model in IDF data model. This framework is expected to extend existing research by creating complete (i.e. include not only building facades but also interior spaces) and semantic-rich as-is BEM geometry models.

Keywords –

Building energy model (BEM); building surface geometry; image-based 3D reconstruction; semantic enrichment; existing buildings; IDF

1 Introduction

The building sector accounts for almost 35%-40% of the total energy end-use worldwide [1, 2]. In this sector, most energy consumption is contributed by the operation of existing buildings [3]. Retrofits of existing buildings towards energy efficiency improvement have been well recognized as an important role in reducing global energy consumption and greenhouse gas emissions. Building energy simulation is a powerful and computerized approach for assessing building energy performance [4]. In building retrofit decision-making processes, this approach is commonly used to prioritize various retrofit strategies by quantifying their potential energy performance improvements and associated cost savings. To implement such simulations reliably, as-is building energy models (BEMs), which represent the actual conditions of existing buildings, need to be created first.

The creation of a BEM for an existing building requires large amounts of inputs, which typically include building geometry, constructions, HVAC systems, space loads, local weather data, operating schedules and other relevant parameters [5]. In the current practice, these inputs are primarily manually prepared by energy modelers using design documents (e.g., 2D CAD drawings and specifications) and/or actual photos [4]. This manual process is usually labor-intensive, costly, and error-prone, and inevitably arbitrary due to the human interpretation of the design documents [6]. Furthermore, the resulting BEMs may only exhibit the as-design rather than the as-is conditions of buildings [7]. This is because buildings tend to be deteriorated in performance and usually undergo various renovations over their service lives. In addition, design documents for many old buildings are even not available.

To address these issues, some recent efforts have focused on leveraging sensing technologies such as laser scanning and photogrammetry to capture as-is conditions of buildings and developing approaches that can use the captured data to automatically create as-is BEMs or as-is

BIMs for energy analysis purposes [8, 9, 10, 11]. According to the type of input data, these approaches can be roughly categorized into two groups: point cloud-based approaches and image-based approaches.

Point cloud-based approaches extract 3D semantic models from the point clouds of buildings that are usually collected from a laser scanner. Wang et al. [9] developed a methodology for automatically reconstructing 3D surface geometries of building envelopes using point cloud data. In their method, five types of building components required by BEM (i.e., walls, doors, windows, floors and roofs) can be recognized and reconstructed. Dı´az-Vilarin˜o et al. [8] developed a 3D as-built modelling methodology for solar shading analysis of existing buildings. In this method, three types of building envelop components (i.e., external walls, floors and roofs) and surrounding shades are considered. As both works only focus on the reconstruction of building facades, their outputs only support some rough and preliminary energy analysis (e.g., envelope choices, building orientation and shading analysis). They cannot be used for more complex energy analysis like whole-building energy simulation which requires the geometric description of entire buildings including building interiors (i.e. internal thermal spaces).

Semantic as-is modelling of building interiors using point cloud data has also been explored by some researchers, but they do not have a specific consideration for BEM use. In other words, the resulting models usually do not carry all semantic information (see details in Section 2) required by BEM. For example, Xiong et al. [12] proposed a context-based approach to semantically reconstruct building interiors. However, in the resulting models, the semantic information included mainly refers to the component type (i.e., walls, floors, ceilings windows, and doorways) that each 3D surface belongs to. Other required semantic information for a surface are not included, such as the geometric/topologic relationships between this surface and other surfaces and outside conditions (facing to outdoor environment, an indoor space or another surface).

Image-based approaches in 3D as-is condition modelling have received increasing attention in recent years. On one hand, as-is condition capture using digital cameras is more convenient and economic than using a laser scanner [13]. On the other hand, the accuracy loss of point cloud-based approaches due to noisy and missing data could be effectively addressed by image-based approaches [13,14,15]. In the context of as-is BEM creation, a recent work was conducted by Cao et al. [11] who developed an approach to reconstruct building facades from low-resolution aerial images. Building facade components including walls, doors and windows can be recognized. Again, this approach does not handle building interiors so that it cannot produce detailed geometry models required by complex building energy simulation. Another significant limitation of this approach is that it cannot automatically merge building facades reconstructed from different images into a single model. This approach requires additionally manual efforts to combine surface models generated from different images.

To address the limitations in existing efforts, this paper aims to develop a framework for an image-based approach to automatically construct complete and semantic as-is BEM models for existing buildings. This paper specifically focuses on detailed building geometry model creation for accurate whole building energy simulation purpose. The particularities of the proposed framework are threefold: (1) it enables the recognition of building components and the extraction of their surface geometries from images of both building facades and interiors; (2) it provides the mechanism to automatically merge the surface models generated from individual images into one single and uniform model; and (3) it computes all geometry related semantic information required by BEM.

The rest of the paper is structured as follows: Section 2 explains the features of BEM geometry models and the relevant semantic information requirement; Section 3 details the main modules of the proposed framework; and Section 4 concludes this paper and outlines future work.

2 BEM Geometry Model Description

A BEM geometry model mainly consists of three types of information: building geometry, coordinate systems, and geometry related semantic information. Building geometry is composed of basic building elements (e.g., walls, floors, windows, doors, and roofs, etc.) and shading devices, which are usually defined as a collection of planar surfaces [16]. Geometrically, the surfaces of building elements are 3D polygons with a normal pointing to the outside of the zones that they bound [16]. The geometry of each surface is depicted in a given coordinate system, which can be global or local. These coordinate systems enable the integration of these surfaces to form a complete building model. The geometry related semantic information mainly include the building object type that each surface represents and the geometric/topological relationships between those surfaces (i.e. building elements). These kinds of semantic information are detailed later in a specific case.

The organization of these information varies in different BEM tools as they usually have their own internal data models. In this paper, EnergyPlus is selected as the target tool due to its prevalence and wide utilization. Input Data File (IDF) is the native input format of EnergyPlus. In IDF, the building geometry can be described by six classes in an up-bottom approach [17], as shown in Figure 1. The roles of these classes are described as follows [17]:

- *Site:Location*: to define the location of a building.
- *Building and Zone*: to define the hierarchical coordinate systems for the building geometry description.
- *BuildingSurface:Detailed*: to define building components including walls, floors, ceilings and roofs.
- *FenestrationSurface:Detailed*: to define opening elements including windows and doors.
- *Shading:Zone:Detailed*: to define attached shading elements of a building.

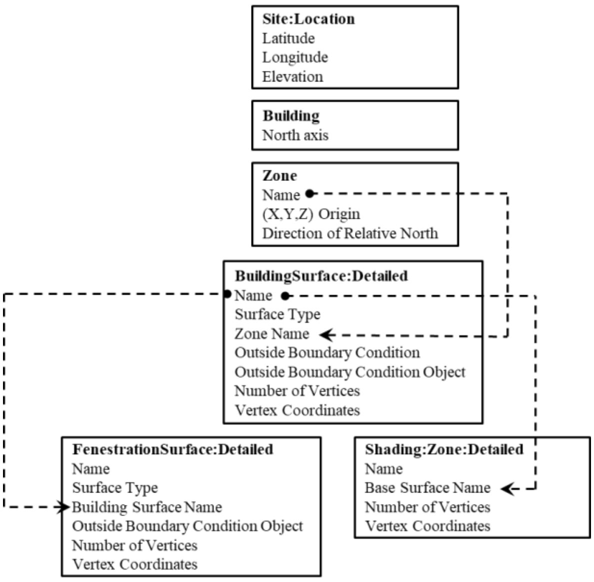

Figure 1. IDF classes for building geometry description. Note: classes providing general surface definition methods are selected; for each class, only geometry definition related attributes are listed; and only attached shading devices are considered.

Essentially, the latter three classes with various attributes provide means of defining building geometry with semantic information. In these classes, common attributes including *"Number of Vertices"* and *"Vertex Coordinates"* are used to define the exact surface geometries of building elements. Other attributes specify the required semantic information, which are summarized as follows [17]:

(1) *"Surface Type"*: to specify the building element type that the surface represents.

(2) *"Zone Name"*: to specify the zone that the surface bounds. This attribute builds the geometrical/topological relationship between building elements and relevant zones.

(3) *"Building Surface Name"*: to specify the parent surface (i.e. a building component) that this surface (i.e. an opening element) is attached to. This attribute builds the geometrical/topological relationship between openings and the building components that host them.

(4) *"Base Surface Name"*: to specify the surface (usually a wall) that this surface (i.e. a shading element) is attached to. This attribute builds the geometrical/topological relationship between shading elements and their influenced walls.

(5) *"Outside Boundary Condition"*: to specify the condition of the other side of this surface. The condition can be outdoors, ground, a surface that bounds another zone, or adiabatic.

(6) *"Outside Boundary Condition Object"*: to specify the surface that is located on the other side of this surface. This attribute together with attribute (5) build the geometrical/topological relationship among non-shading element.

Most efforts on automatic as-is modelling of existing buildings for energy analysis are limited to reconstructing surface geometries of specific building elements (e.g. facades and shading elements) with poor semantic information (usually only includes (1) and (3)). The framework proposed in this paper aims to achieve an automatic creation of complete building geometry with all semantic information required by whole building energy simulation.

3 Framework for Constructing As-is BEM Geometry Model Using Digital Images

The proposed framework consists of four modules (see Figure 2): image and placement data collection, building surface geometry reconstruction, semantic enrichment, and BEM geometry model creation.

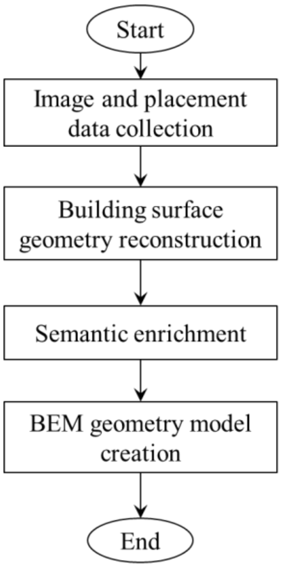

Figure 2. Proposed as-is BEM creation framework

3.1 Module 1: Image and placement data collection

The digital images of building facades and interiors as well as relevant placement data need to be collected for the 3D reconstruction of the entire building. Image data can be conveniently collected by some commonly used and economic devices with the image taking function. In this paper, a drone with an amounted camera is used to capture images of building envelops and a smartphone is used to capture images of building interiors. The placement data refers to a set of measurable parameters that can be used to determine the relative spatial relationships among the building elements in different images. The need of the placement data is because building elements reconstructed from an individual image can only be defined in an assumed coordinate system but the relationships between the assumed coordinates of building elements in different images are unknown. The placement data helps to geometrically link the building elements extracted from different images. Using one-storey building as an example, Figure 3 illustrates the parameters that need to be measured and the principle how these parameters are used to determine the relative spatial relationships between building elements in different images.

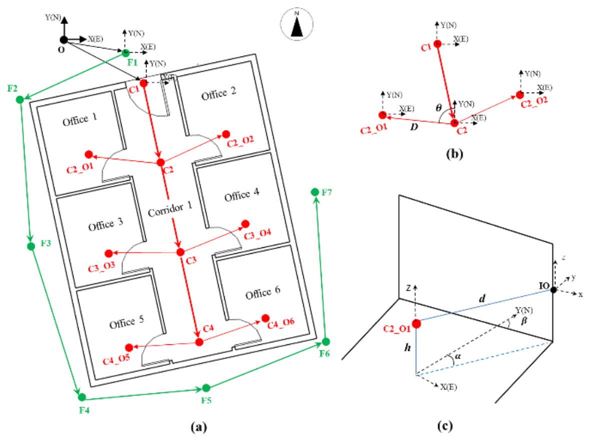

Figure 3. Data collection: (a) reference points setting; (b) parameters required for computing TR_CC; and (3) parameters required for computing TR_IC

In Figure 3(a), two sets of reference points are set up for building facades and building interiors respectively. These reference points work as a medium for geometrically connecting the building elements that can be viewed from these points. The point **O** refers to the root point used for combining the two sets of reference points. Two requirements should be satisfied for setting these points: (1) the range of vision from these points together can cover entire building facades and interiors; and (2) two adjacent points should be able to see each other. The method to obtain the required placement information is detailed as follows.

First, set up two types of 3D coordinate systems:

- Local coordinate system for reference points (see Figure 3(b)): origin (0,0,0) is set at a constant height from a floor (for interior points) or from the ground (for exterior points), axis X refers to East, axis Y refers to North, and axis Z is decided based on X and Y using the right-hand rule.
- Local coordinate system for each image (see Figure 3(c)), more specifically for describing vertical elements in each image: origin (0,0,0) is located on the right edge of the wall surface (when facing the surface at relevant reference point) and at the height same to relevant reference point, axis Z is identical to that of relevant reference point, axis Y is perpendicular to the surface of the vertical element and points to the outside of the space (or outdoors) that the surface bounds, and axis X is decided based on Z and Y using the right-hand rule.

Second, establish the transformation relationships (denoted as TR_IC) between the coordinate system of images and their corresponding reference points. Through TR_IC, a building element surface can be transformed from its own local coordinate system (LCS) to the LCS of the reference point. This means that the geometries of building elements sharing a common reference point can be linked together in the LCS of the reference point. Figure 3(c) illustrates three parameters (i.e., α, β and d) that need to be measured for computing TR_IC.

Third, establish the transformation relationships (denoted as TR_CC) between the coordinate systems of two adjacent reference points. Through TR_CC, a building element surface defined in the LCS of a reference point can be transformed into the LCS of any other reference point. In other words, building elements reconstructed from individual images can be combined as an integrated building model. Figure 3(b) illustrates two parameters (i.e. θ and D) that need to be measured for computing TR_CC.

Among the five parameters, all angular parameters are measured using a smartphone with the embedded compass, and all distance related parameters are measure using a portable and cheap laser rangefinder.

3.2 Module 2: Building surface geometry reconstruction

Based on the images and placement data collected from Module 1, this module reconstructs building surface geometry in two steps: vertical building element reconstruction and horizontal building element reconstruction.

3.2.1 Vertical building element reconstruction

Vertical building elements including walls, windows, doors, and columns are reconstructed from relevant images. First, a neuro-fuzzy system (NFS) based algorithm, as shown in Figure 4, will be established for the automatic recognition of building elements contained in an image. In order to take into account the possibilities of information shortage and inaccuracy in collected images, the fuzzy logic algorithms are investigated, which can reason with imprecise information. Fuzzy logic systems can make decisions even with incomplete or uncertain information. However, individual fuzzy logic algorithms cannot automatically acquire the rules used to make those decisions and have its own limitations. To overcome these limitations, this paper adopts an intelligent hybrid system (i.e., a neuro-fuzzy system), which combines fuzzy algorithms with neuro-computing systems. Interpretability and accuracy, which are main strengths of the neuro-fuzzy method, are the key criteria for choosing algorithms in this module.

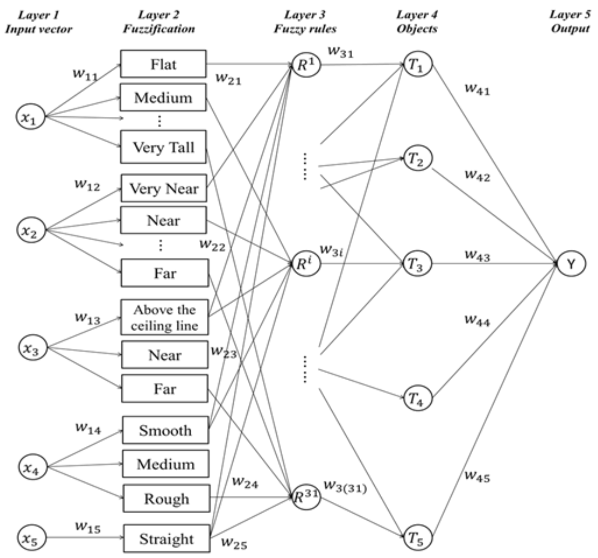

Figure 4. Architecture of proposed NFS for Module 2

Second, an image-driven feature extraction system will be developed to obtain the geometric dimension of these recognized building elements. A ruler will be set in the target scene (i.e. the scene that is to be pictured) for the reference of measuring dimension. Real distances for boundary edges of each recognized element are calculated based on the pixel distance (d_p), which is defined by the Euclidean distance ($d_{Euclidean}$) for a binary image $B[i,j]$:

$$d_p = d_{Euclidean}([i_{1p}, j_{1p}], [i_{2p}, j_{2p}]) = \sqrt{(i_{1p} - i_{2p})^2 + (j_{1p} - j_{2p})^2}, p \in \{l, r\} \quad (1)$$

where $[i_{1p}, j_{1p}]$ and $[i_{2p}, j_{2p}]$ represent the locations of different pixels in the binary image; l is the length of lines (e.g., line 1 and line 2) defined by the pixel distance for each selected component; and r is the length of the reference ruler measured by the pixel distance.

Images of horizontal shading devices like overhangs are processed additionally based on the adjustment on the neuro-fuzzy system and the image-driven feature extraction system.

Finally, each extracted surface is output as a polygon with a list of ordered 3D vertices in its own LCS. The "ordered" for an interior surface means that the resulting polygon is defined with a normal pointing to the outside of the space that the surface bounds, while for an external surface its normal points to the outdoor environment.

3.2.2 Horizontal building element reconstruction

Horizontal building elements including floors, ceilings and roofs are inferred based on the reconstructed vertical building elements. More specifically, the slab and the ceiling of an interior space are extracted from the vertices (with smallest z value and largest z value respectively) of vertical walls and columns that enclose the same space. Specifically, these wall and column surfaces need to be transformed first into LCS of the space (i.e. the LCS of a reference point in the space). Therefore, the resulting slab and ceiling surfaces are defined in the LCS of the space. Similarly, the geometry of a roof is inferred from the vertices (with largest z values) of all external wall surfaces that have been transformed into a same coordinate system.

The expected output of this module is a complete building surface model including building facades and interiors (see the example shown in Figure 5). In the output, all the surfaces are defined in the LCS of corresponding reference points, and the transformation relationships between the LCS of reference points are also stored.

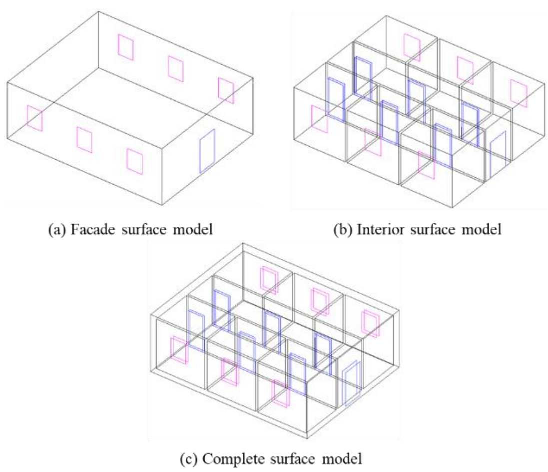

Figure 5. Visualization of the resulting building surface geometry model

3.3 Module 3: Semantic enrichment

So far, for a surface, its geometry defined in the coordinate system of a reference point, and some semantic information (i.e. the space that the surface bounds and the building element type that the surface represents) have been obtained. This module further adds the remaining semantic information required by BEM for each surface. The whole process is implemented in four steps which are detailed as follows.

3.3.1 Building surface geometry transformation

In this step, all surface geometries are transformed from their own coordinate systems to the root coordinate system based on the transformation matrices between control points. In the case of Figure 3(a), the root coordinate system refers to the coordinate system set on the control point **O**. Surfaces defined in the coordinate system on a control point like **C2_O1** can be transformed into **O** by tracing the established image collection route **C2_O1** -> **C2** -> **C1** -> **O**. By this transformation, all surfaces are described in a uniform coordinate system, which enables the geometry operations involved in the following steps.

3.3.2 Semantic enrichment for surfaces of walls, floors, ceilings, columns and roofs

As introduced in Section 2, the IDF class BuildingSurface:Detailed is used for defining surfaces of walls, floors, ceilings and roofs. Columns considered in this paper are treated as walls so that they can be accepted by the IDF data model. For these surfaces, two types of semantic information, i.e. Outside Boundary Condition and Outside Boundary Condition Object, need to be added (see Figure 1). In IDF, the outside condition of a surface can only be one of the situations: Surface (i.e. these is another space on the other side), Adiabatic (i.e. these is a building element on the other side), Outdoors, and Ground, etc. [15]. This means the surfaces reconstructed from Module 2 may need to be spilt by taking the outside conditions into account. A typical example is illustrated in Figure 6(a): the wall surface colored with red has two different outside situations, i.e. space (i.e. Room 2 and Room 3) and building element, while the wall surface colored with green has one outside condition. Therefore, the red wall surface needs to be geometrically spilt into three pieces and the green wall surface does not need (see Figure 6(b)). Only if the outside condition of a surface is Surface, the Outside Boundary Condition Object will be specified (see Figure 6(b)). A specific algorithm to achieve this semantic enrichment process is developed and Figure 7 shows its pseudocode. Figure 8 shows the processing result of the building surface geometry model by this step.

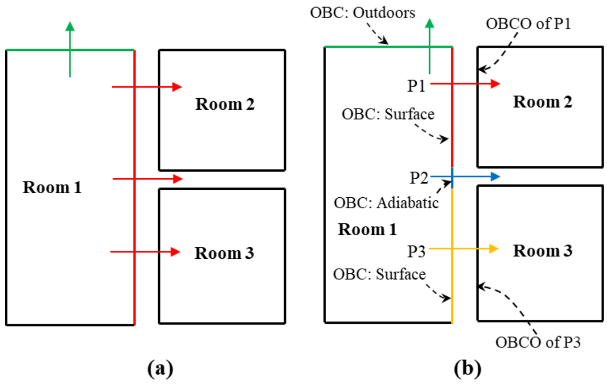

Figure 6. Illustration of the outside conditions of a wall surface. Note: Outside Boundary Condition = OBC; Outside Boundary Condition Object = OBCO.

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Input: Reconstructed building surfaces S
1:  Extract surfaces of walls, floors, ceilings and roofs from S and
    store as S_walls, S_floors, S_ceilings, S_roofs respectively
2:  foreach  s ∈ S_walls do
3:      find all surfaces s_all that represent the same wall to s
4:      foreach t ∈ s_all  do
5:          project t onto (s_all - t) (all other surfaces in s_all) along the
            normal direction of t
6:          spilt t into two parts: Part 1: t ∩ (s_all − t);
            Part 2: t − (t ∩ (s_all − t))
7:          if  Part 1 are internal and not empty  then
8:              set the outside condition of Part 1 as Surface
9:              set the outside condition object of Part 1 as t ∩ (s_all − t)
10:         else if  Part 1 are empty  then
11:             set the outside condition of Part 1 as Adiabatic
12:         else if  Part 1 are external to outdoor environment  then
13:             set the outside condition of Part 1 as Outdoors
14:         else if Part 1 are external to ground  then
15:             set the outside condition of Part 1 as Ground
16:             set the outside condition object of Part 1 as t ∩(s_all − t )
17:         end if
18:         if  Part 2 are not empty  then
19:             set the outside condition of Part 1 as Adiabatic
20:         end if
21:     end foreach
22:     S_walls ← S_walls - s_all
23: end foreach
24: repeat process from Line 2 to Line 21 for S_floors, S_ceilings,
    S_roofs  respectively
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Figure 7. Semantic enrichment algorithm for the surfaces of walls, floors, ceilings, and roofs

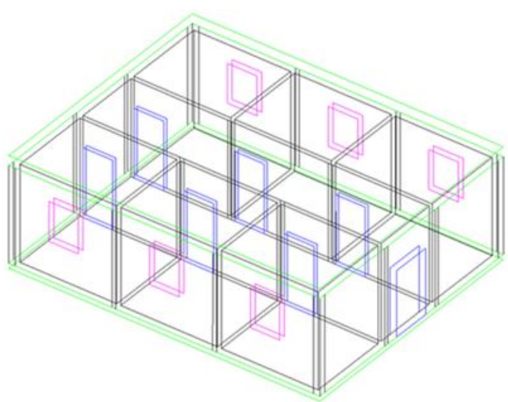

Figure 8. Visualization of the processed building geometry model

3.3.3 Semantic enrichment for surfaces of windows and doors

Surfaces of opening elements (i.e. windows and doors) are defined with *FenestrationSurface:Detailed* in IDF. For these surfaces, two types of semantic information, i.e. "*Building Surface Name"* and "*Outside Boundary Condition Object"*, need to be computed. The first type specifies a parent surface (usually a wall surface) that holds the opening surface. Such parent surface can be computationally detected by finding a surface, the polygon of which geometrically contains all the vertices of the opening polygon.

An opening element (except external openings) is usually defined as a pair of opening surfaces in BEM. For an opening surface, the *"Outside Boundary Condition Object"* specifies another corresponding opening surface, which can be detected by the following procedure: first, identify all other opening surfaces that are parallel to this surface; second, compute the distances between all the identified surfaces and this surface. The surface nearest to the opening surface is thus recognized as the target.

3.3.4 Semantic enrichment for surfaces of attached shading devices

For a shading device surface, the base surface (usually an external wall surface) that it is attached to needs to be specified. The base surface can be easily detected by finding a building facade surface, which geometrically contains one edge of the shading device surface.

3.4 Module 4: BEM geometry model creation

After the semantic enrichment of all building surfaces are finished, an IDF-based BEM geometry model is generated in this module by wrapping these objectified surfaces with corresponding IDF classes following the syntax of IDF schema. Surfaces of walls (columns), floors, ceilings and roofs are defined with the IDF class *BuildingSurface:Detailed* and its attributes; surfaces of windows and doors are defined with *FenestrationSurface:Detailed* and its attributes; and surfaces of shading devices are defined with *Shading:Zone:Detailed* and its attributes. All surface geometries have been transformed into a common coordinate system which takes North as Y axis and East as X axis. This coordinate system is actually identical to the global coordinate system used in IDF [15]. Therefore, a global coordinate system rather than a set of local coordinate systems is used in the resulting IDF geometry model. This means that the values of the attribute *"North Axis"* of *Building* and the attribute *"Direction of Relative North"* of *Zone*, which are used to define hierarchically local coordinate systems for IDF geometry models, can be ignored (i.e. no need to calculate). The geographical location of a building defined by *Site:Location* is usually directly obtained from a weather data file.

Once these geometries, coordinate systems and the semantic information for an existing building are integrated and well organized into IDF format, a corresponding semantic IDF geometry model for this building is achieved. It can be used together with other input data such as local weather data and construction materials to conduct energy performance analysis for the building for various purposes (e.g. assessment of retrofit strategies and optimization of operating schedules).

4 Conclusions and Future Work

In this paper, we present a framework for an image-based approach to automatically construct complete and semantic BEM geometry models for existing buildings. The framework consists of four modules. In the first module, we develop a specific data capture approach which can obtain the "placement" information in the process of collecting images of building facades and interiors. The "placement" information helps to Module 2 to combine surface geometries of building elements extracted from individual images into a uniform building model. Specifically, a neuro-fuzzy system and an image-driven system are presented for recognizing vertical building elements (i.e. walls, windows, doors and columns) from images and reconstructing their surface geometries respectively. The approaches for reconstructing horizontal building elements (i.e. floors, ceilings and roofs) are also introduced. In Module 3, computational approaches for enriching geometry related semantic information required by BEM are proposed. The generation of IDF-based geometry models is explained in Module 4.

This framework is expected to extend existing research by: (1) enabling the reconstruction of building elements from images of building facades and interiors; (2) providing the mechanism to automatically combine the reconstructed elements from individual images into one uniform model; and (3) allowing the addition of all geometry related semantic information required by BEM. The resulting BEM geometry models can be used for accurate and detailed energy simulation purpose.

For future work, all the approaches and algorithms involved in the proposed framework will be compactly implemented and examined. Several multi-storey office buildings with regular shapes and less furniture in building interiors will be selected to verify the proposed framework in terms of the feasibility and the accuracy.

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References

[1] International Energy Agency. Transition to Sustainable Buildings: Strategies and Opportunities to 2050. Online: https://www.iea.org/publications/freepublications/publication/Building2013_free.pdf Accessed: 11/10/2017.

[2] United Nations Environment Programme (UNEP). Why Buildings. Online: http://staging.unep.org/sbci/AboutSBCI/Background.asp, Accessed:14/9/2017.

[3] Ma Z., Cooper P. and Daly D., et al. Existing building retrofits: Methodology and state-of-the-art. Energy and buildings, 55: 889-902, 2012.

[4] U. S. GSA. (2015). GSA BIM Guide 05 - Energy Performance. Online: http://www.gsa.gov/portal/content/102283, Accessed: 11/12/2016.

[5] Maile T., Fischer M. and Bazjanac V. Building energy performance simulation tools-a life-cycle and interoperable perspective. Center for Integrated Facility Engineering (CIFE) Working Paper, 107:1-49, 2007.

[6] Bazjanac V. IFC BIM-based methodology for semi-automated building energy performance simulation. In Proceedings of the CIB W78 conference, Santiago, Chile, 2008.

[7] Cho Y.K., Ham Y. and Golpavar-Fard M. 3D as-is building energy modeling and diagnostics: A review of the state-of-the-art. Advanced Engineering Informatics, 29(2):184-195, 2015

[8] Díaz-Vilariño L., Lagüela S. and Armesto J., et al. Semantic as-built 3d models including shades for the evaluation of solar influence on buildings. Solar energy, 92: 269-279, 2013.

[9] Wang C., Cho Y.K. and Kim C. Automatic BIM component extraction from point clouds of existing buildings for sustainability applications. Automation in Construction, 56:1-13, 2015.

[10] Ham Y. and Golparvar-Fard M. Mapping actual thermal properties to building elements in gbXML-based BIM for reliable building energy performance modeling. Automation in Construction, 49: 214-224, 2015.

[11] Cao J., Metzmacher H., and O'Donnell J., et al. Facade geometry generation from low-resolution aerial photographs for building energy modeling. Building and Environment, 123: 601-624, 2017.

[12] Xiong X., Adan A. and Akinci B., et al. Automatic creation of semantically rich 3D building models from laser scanner data. Automation in Construction, 31: 325-337, 2013.

[13] Lu Q. and Lee S. Image-based technologies for constructing as-is building information models for existing buildings. Journal of Computing in Civil Engineering, 31(4), p.04017005, 2017.

[14] Fathi H., Dai F., and Lourakis M. Automated as-built 3D reconstruction of civil infrastructure using computer vision: Achievements, opportunities, and challenges. Advanced Engineering Informatics, 29(2): 149-161, 2015.

[15] Dai F., Rashidi A., Brilakis I. and Vela, P. Comparison of image-based and time-of-flight-based technologies for three-dimensional reconstruction of infrastructure. Journal of Construction Engineering and Management, 139(1): 69-79, 2012.

[16] Bazjanac V. Space boundary requirements for modeling of building geometry for energy and other performance simulation. In Proceedings of the CIB W78 conference, Cairo, Egypt, 2010.

[17] U. S. Department of Energy (2017). EnergyPlusTM Version 8.8.0 Documentation: Input Output Reference.