BIM-based Simulation Tool for Building Thermal Performance in Built-up Areas

H. Kawai¹,* and T. Asawa¹

¹Department of Environmental Science and Engineering, Tokyo Institute of Technology, Yokohama, Kanagawa 226-8502, Japan

ABSTRACT
This study focuses on the development of tools that link solar radiation calculation, building thermal simulation, and building information modeling (BIM) to simultaneously progress architectural design and assessment in built-up areas. First, simulated model generation methods compatible with BIM are displayed. These methods not only display modeling methods for a target building by composing 3-D windows, walls, and roofs, but also those for the surrounding geometry. The 3-D geometry of the surrounding buildings is simplified by the user operation on BIM software. Additionally, methods to extract the parameters for solar radiation calculation and thermal simulation from BIM are presented. Next, building thermal simulation considering the surrounding geometry is connected with BIM. This simulation considers the effect of surrounding geometry on solar radiation and long-wave radiation on the building’s external surface, which is especially influential on the building thermal environment and energy consumption. Finally, the results of test calculations, assuming the architectural design in an actual site confirm that this tool can show or compare the effect of surrounding geometry on the building heat load to determine building volume and window location.

KEYWORDS
Building information modeling, Building thermal simulation, Passive design, Design support tool

INTRODUCTION
In the case of building design in a built-up area, such as a Japanese urban area, buildings are designed considering the surrounding conditions of the site. In particular, from the viewpoint of environmental design, it is important to analyze the solar radiation that the site receives and to ensure the architecture having taken into account the microclimate. Moreover, outdoor space design (e.g., layout of a fence for privacy, layout of trees in relaxation spaces) is also important in built-up areas so that limited

* Corresponding author email: kawai.h.ac@m.titech.ac.jp
space is used effectively. Outdoor space components such as fences and trees affect the solar radiation that the building receives. These components are influential factors for prediction of the indoor thermal environment and building energy consumption.

A useful method to enhance the performance of environmental design by grasping these complicated conditions in the site is building information modeling (BIM). BIM makes it easy to grasp the 3-D geometry of building design in the design process. Currently, many energy simulations linking BIM (e.g., OpenStudio) and their standards (e.g., IFC and gbxml) are being proposed. However, it is time-consuming to convert BIM data for numerical simulation. Additionally, most of these methods have not been linked with building thermal simulations based on surrounding geometry.

On the other hand, simulation tools that can import BIM data directly have been developed (e.g., Archiwizard). These tools can visualize the solar radiation distribution and building energy consumption quickly. However, with these tools, it is not easy for the user to confirm whether the input parameters are appropriate for the simulation process. Moreover, these visualizations are insufficient for users to understand the heat transfer process, which is more complicated in passive heating/cooling design.

Therefore, in previous methods, users could not understand the spatial relation between solar radiation distribution on the building, determined by its surrounding spatial geometry, and energy consumption at the same time as the design process using BIM. This study aids to link solar radiation calculation, building thermal simulation, and BIM to progress architectural design and assessment in built-up areas simultaneously.

**OUTLINE OF DEVELOPING A SIMULATION TOOL**

Following are the important features of developing the building thermal simulation tool for users to understand the spatial relation between solar radiation distribution and energy consumption in the architectural design process.

Introductions of building thermal simulation considering surrounding geometry for building design in built-up area

In building design, it is important to estimate the amount of solar radiation on the external surfaces of a building in a built-up area because shading by adjacent buildings and external objects, such as fences affect building performance significantly. Moreover, it is necessary for the simulation tool to be applicable to various architectural designs that use solar heat, e.g., a passive heating system with thermal storage material. This study introduces building thermal simulation considering surrounding geometry into BIM. This simulation solves the heat conduction unsteadily and can also apply a passive heating system with thermal storage material.
Direct building thermal simulation using BIM software
In most BIM software applications, we can model the building and its surrounding geometry easily by laying and assembling building parts (e.g., windows, walls, roofs, and slabs). However, in order to use BIM data for numerical simulation, it is necessary to eliminate unnecessary information and convert BIM objects to geometry for numerical simulation manually. This process takes a significant amount of time. Therefore, a tool has been developed to carry out the building thermal simulation directly on BIM software.

Input data visualization—simplified input parameter and geometry of building thermal simulation
Generally, most simulation tools make it difficult for users to know the calculation process explicitly. This problem may lead to a fatal misunderstanding among users. In particular, mistakes in inputting parameters make the accuracy of the simulation result significantly worse. Furthermore, we must be careful about errors caused by converting from BIM data to simulation input data. Therefore, this study enables us to check parameter and spatial geometry inputted into building thermal simulation on BIM software.

Calculation result visualization for thermal design of a building in a built-up area
Several BIM-based simulation tools enable us to visualize the solar radiation distribution and building energy consumption. In addition to these visualizations, it is necessary to show the heat transfer process in each room or building part, such as walls for some building designs. These include a passive heating system with thermal storage material or a building using natural ventilation. The presentation of calculation results helps users to identify the design factors that determine the simulation result. The features or problems in the thermal design of the building are clearer.
To construct the required simulation tool, the following items (a)–(d) were developed. This paper includes items (a)–(c).
(a) BIM linking with building thermal simulation
(b) Input data visualization for building thermal simulation
(c) Building thermal simulation along with surrounding geometry for building design in built-up area
(d) Visualization of calculation result for thermal design of building in built-up area (now developing).

MODEL LINKING BIM WITH BUILDING THERMAL SIMULATION

Modeling of outdoor space and the building
This tool recognizes the surrounding building and external objects, which consist of
computer-aided design (CAD) objects (polygons, walls, roofs, and pillars) on the “external object” layer (Fig. 1). This layer is determined by selecting layers on the dialog of BIM software (this study uses Vectorworks Architect). This tool can use GIS data (.shp file) by importing data to the BIM software. On the other hand, shading by trees must be considered in the solar radiation calculation. In this regard, we try to introduce the shading model of trees.

The building model is created by laying out walls, slabs, roofs, and windows on the BIM software. Each object has information about its material, e.g., sectional components, solar reflectance, heat conductivity, and heat capacity. This method is based on the usual method of BIM. The user can lay out objects on each floor. Rooms

![Diagram of building model creation process](image.png)

**Figure 1. Spatial and material modeling process on BIM software**

![Diagram of simulation input data generation](image.png)

**Figure 2. Generation process of model for building thermal simulation from BIM**

※○ means center coordinate of polygon in building thermal simulation.
are modeled with space objects, and there is information about the schedule of internal gain and air conditioning. In this tool, object information is established in the dialog of the BIM software.

**Making a model for building thermal simulation**
The BIM model input by users is converted into data for building thermal simulation as shown in Fig. 2. This pre-processing method is implemented as follows:

- Objects on selected layers are integrated into a layer for simulation on BIM.
- Pre-processing method recognizes spaces and defines objects by vertical zones. The vertical zone is defined based on the height of the space object. This method can extract a connection between rooms and each building parts even when the building has split floors and open ceiling spaces.
- Walls, roofs, and windows are converted into 3-D polygons. A wall object belonging to more than one vertical zone is converted into several polygons separately. Then, a slab object is converted into several polygons corresponding to the relation between the upper and lower floor plan. Converted 3-D polygon data are output as information on coordinates and geometry into text data.
- Relation between rooms and each building part is analyzed and output automatically by seeking rooms adjacent to each polygon.

**Input data visualization for building thermal simulation**
In building thermal simulation, users have to define many pieces of simulation information, namely the material information on all polygons, and the schedule information in all rooms. It is difficult for users to input and define all this information completely and quickly. Sometimes, mistakes in inputting information cause simulation failure and misunderstanding. The user’s special modeling may

![Linkage check with adjacent rooms by displaying linkage between room and walls](image1.png)

![Check of inputted material](image2.png)

In this figure, objects except in 2nd floor: Displayed by gray color.
Linkage of rooms in 1st floor: Not displayed

**Figure 3. Input data visualization for building thermal simulation**
cause a failure in extracting a connection between rooms. This tool visualizes these input data on BIM software. Visualized input data for each room are stacked by layers, and users can switch and see information about arbitrary rooms or parts by changing layer visibility (Fig. 3).

BUILDING THERMAL SIMULATION CONSIDERING SURROUNDING GEOMETRY

The geometry surrounding the site affects the direct and sky solar radiation transmitted in windows due to its shading. Long-wave radiation received on the building’s external surface is important, when the radiative cooling effect is effective. We have developed a coupling simulation method between the outdoor thermal environment simulation and the building thermal simulation. However, the previous method cannot be applied to long periods or annual simulation. In addition, Higuchi(2001) shows the calculation method of solar and long-wave radiation for building thermal simulation. In this study, by inputting the calculation result of solar and long-wave radiation into the building’s external surface, the building thermal simulation for a long period is enabled.

Calculation of solar radiation

In the calculation of direct solar radiation, ray tracing is carried out in the direction of the sun (Fig.4). In the calculation of sky solar radiation and long-wave radiation, rays (normal set: 256 rays/2π) are released from points isotropically. This study assumes that sky solar radiation distributes isotropically. It is calculated from the sky view factor, which is calculated from ray-tracing and horizontal sky solar radiation in the weather data. Points for ray tracing are set on each polygon (Fig.4). Ray tracing is performed from each set point. The resolution of ray tracing is determined based on the building part. Users can improve the accuracy of radiation calculation in the thermally weak part of the building, such as a window.

![Figure 4. Calculation method of solar radiation and long-wave radiation on building external surface](image)
Calculation of long-wave radiation
Long-wave radiation is calculated using Brunt’s formula. This study assumes that the surface temperature on the surrounding external surface is equal to the outdoor air temperature.

TEST CALCULATIONS ASSUMING ARCHITECTURAL DESIGN IN AN ACTUAL SITE
This paper presents a calculation example involving a site in the urban district in Tsuchiura city, Japan. To demonstrate the effectiveness of the developed tool, which calculates building heat load or energy consumption considering surrounding geometry, this study compares the calculation results in two cases with and without surrounding geometry. Figures 5 and 6 show the calculation condition and results, respectively.

**Figure 5. Test calculation condition**

**Figure 6. Comparison of calculation result between the case with and without surrounding geometry**
As a result of comparison, the building on the east side of the target building and the high-rise building decreases solar radiation on the window of the target building, and the air temperature in the living room decreases by 7 °C. This calculation takes about 1 min on a personal computer. These results reproduce the air temperature variation derived from the shading effect of the surrounding geometry.

CONCLUSION
This study presented the outline of a simulation tool for users to understand the effect of surrounding geometry on building heat load and energy consumption. In this paper, the following items were developed.

- Method to generate models for building thermal simulation from BIM automatically
- Method to check simulation model that user input on BIM software
- Building thermal simulation that considers surrounding geometry

Moreover, as a result of a test calculation involving an actual site, it is confirmed that this tool shows good performance as a simulation tool for determining building volume and window layout. As a future task, we will implement detailed validation using the BESTEST model. We will also show the visualization method for users to understand the heat transfer process of buildings, and incorporate the feedback from the calculation into building design in the next study.

ACKNOWLEDGEMENTS
Development of this tool was carried out by our research group and A&A Corporation under the joint research project.

REFERENCES