DEVELOPMENT OF PASSIVE DESIGN TOOL USING 3D-CAD COMPATIBLE THERMAL SIMULATION
-PREDICTION OF INDOOR RADIATION ENVIRONMENT CONSIDERING SOLAR SHADING BY SURROUNDING TREES AND BUILDINGS-

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ABSTRACT
In this paper, a simulation tool for passive design considering indoor and outdoor radiation environment using a three-dimensional computer-aided design (3D-CAD) system is developed. This tool predicts surface temperature distribution on indoor and outdoor surfaces of a building considering the spatial geometry, materials used, and solar shading. A radiation model algorithm with a high-resolution voxel model was developed to calculate surface temperature distribution and mean radiant temperature (MRT) distribution while considering the detailed spatial design. The results of the application of this developed tool to a passive design housing using direct heat gain and deciduous tree cover confirmed that this simulation tool is useful for evaluating the effect of passive design on the thermal environment at the design stage.

INTRODUCTION
In recent years, sustainable architecture has increasingly attracted attention because of global environmental issues. As a sustainable design method, passive design is an alternative approach for ensuring thermal comfort conditioning inside buildings by taking advantage of local climatic conditions, while lowering energy consumption.

To generate an effective passive architectural design, designers should consider the effect of their passive design on the thermal environment of a building. To this end, there are many building simulation tools such as EnergyPlus, eQuest, and Energy-10 as well as studies on passive design support tools such as the one by Abraham (2009). These building simulation tools simulate room temperature, heat load, and energy consumption of a building. However, most previous studies have not focused on simulating the influence of the design of outdoor and indoor spaces on the thermal environment of a building. We argue that it is important to predict the influence of the design of outdoor and indoor surfaces on the surface temperature distribution of a building. The surface temperature of a building influences the local radiative environment and air temperature. Furthermore, surface temperature has a direct relationship with architectural design parameters such as material position, material types, and spatial geometry of a building. In other words, the detailed spatial geometry of a building decides its position with respect to the sun, and therefore, the amount of solar radiation in the room, and the building material decides the thermophysical properties such as heat capacity and coefficient of thermal conductivity. Thus, it is important to create the passive solar design considering not only the architectural design but also the surface temperature distribution.

In this paper, we developed a simulation tool for passive design that takes into account the indoor and outdoor radiation environments. This tool predicts surface temperature distribution on indoor and outdoor surfaces and the mean radiant temperature (MRT) distribution considering spatial geometry, building material, and solar shading due to surrounding objects such as trees, other buildings. This tool uses an all-purpose three-dimensional computer-aided design (3D-CAD) software package as the pre-post processor because 3D-CAD would be quite useful to architectural designers and developers as practical simulation tools.

PASSIVE DESIGN TOOL CONCEPT
The following three features are important considerations in developing the passive design tool that allows architects to numerically simulate the effects of their passive designs.

(1) The passive tool should predict the thermal influence of passive design of a building

The effects of passive design such as direct heat gain, Trombe's wall, solar shading by deciduous trees and so on, on indoor thermal radiative environment depend on spatial geometry, material position and material types. Thus, it is important to evaluate the influence of difference in these designs on thermal radiation environment. In this tool, the heat balance on the surface is simulated using high-resolution voxel mesh models. This tool evaluates the impact of the design proposed building on thermal comfort within the building in terms of two indices. The two indices for evaluating the thermal radiant environment are surface temperature distribution and mean radiant temperature distribution (MRT).

(2) Input and pre-processing method using the
To create passive design architecture, designers estimate the effects of a proposed design on the thermal environment inside the building at both the planning and the design stages. Thus, pre- and post processing such as inputting calculation data, messng, and visualization of calculation result, obtained from the 3D-CAD system.

(3) Visual expression of the calculation results

Redesigning a proposed buildings design according to calculation results leads to a more effective passive design. Thus, it is important to express comprehensibly the calculation results visually in order to understand and evaluate the effects of spatial geometry and materials on the thermal radiative environment around a building.

**CALCULATION OF SURFACE TEMPERATURE DISTRIBUTION ON INDOOR SURFACES**

The developed tool allows designers to evaluate the thermal radiative environment by enabling them to visualize surface temperature distribution and MRT using 3D-CAD. The said tool builds on the previous outdoor thermal simulation model (Takashi A et al., 2007) by predicting the indoor surface temperature distribution as well. The fundamental algorithm of this simulation model was constructed in a previous study by the authors. The calculation process and the algorithm used in the developed tool are described in the following paragraphs (Figure 1).

**Input method of calculation data from 3D-CAD**

Figure 2 illustrates input and pre-processing using the 3D-CAD software interface. A target building for calculation, the buildings and trees near the target, and ground geometry are generated using 3D objects in 3D-CAD. Simultaneously, the room that is investigated to evaluate the effect of passive design on the thermal radiative environment is drawn. Users can input or select component materials and building members such as walls, roofs, and veranda from various dialog boxes and databases. These material information link databases which store the parameters for the heat transfer calculation including the physical properties of materials and the heat transfer calculation models.

**Voxel mesh generation method**

The 3D-CAD models generated by the above process are then transformed into a 3D-voxel mesh model that includes the calculation parameters required for heat transfer analysis (Figure 3) according to the procedure described in the following paragraph. The 3D-CAD model is sectioned horizontally at a certain height, and a horizontal section of the CAD model is then generated. The 2D figure data of the section is then transformed into mesh data. This
The following steps are involved in the process of determining the amount of sky solar radiation by running a multi-tracing simulation originating from the voxel in multiple directions bound within a hemisphere. First, the tracing direction is established such that the tracing density (interval) comes to have the same form (figure 5). Then, ray tracing is carried out along the tracing direction. The ray-tracing is performed using the same algorithm as that used for direct solar radiation. If the ray extends outside the calculation area, the sky radiance is calculated using the all-sky model-R. Finally, the sky solar radiation is calculated by summing up the sky radiance along each tracing direction.

Heat balance calculation

Figure 4 shows the heat balance calculation

(i) Direct solar radiation

The amount of direct solar radiation received by a voxel is simulated using the ray-tracing method. The ray-tracing is carried out toward the solar position from a voxel. If ray tracing is interrupted by other voxels that have no transmissive attribute, the ray tracing is stopped. However, if the ray tracing interrupted is by a voxel that has the transmissive attribute, such as a glass window and tree crown, the ray-tracing continues after taking into account the influence of the transmittance of materials on solar radiation. The ray-tracing continues until the ray extends outside the calculation area. If the ray extends outside a calculation area, the amount of solar radiation is calculated using the relationship between the solar position and the normal direction of the voxel.

(ii) Sky solar radiation

The amount of sky solar radiation is calculated by considering sky solar radiance distribution. In the developed simulation tool, the sky solar radiation distribution is expressed by means of the all-sky model-R, which was developed by IGAWA (Norio I et al. 2004).

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Specular reflective radiation is calculated such that the tracing simulation toward the direction of the specular reflection is implemented, and the amount

![Figure 3 3D-voxel model](image-url)

![Figure 4. Heat balance calculation](image-url)
of reflected solar radiation is allotted to the voxel at which the tracing terminates. The specular reflection considers the first reflection. The diffuse reflective radiation is estimated under the assumption of isotropic diffuse reflection, following Lambert’s cosine law, and the amount of diffuse reflective radiation incident on a voxel is calculated by performing multi-tracing simulations directed toward surrounding voxels. The method used for performing the multi-tracing simulation is the same as that used for estimating the sky solar radiation. In this tracing process, if trace hits a voxel with a diffuse reflection surface, then the amount of radiation reflected by that voxel is obtained. This tracing is implemented along multiple directions to estimate the total amount of reflected radiation received from the surroundings. Diffuse reflection considers multiple reflection until the amount of reflected solar radiation by a voxel is less than 10W/m² in each reflection.

(2) Long-wave radiation calculation
The amount of long-wave radiation is calculated according to the following steps. First, the heat balance of each voxel is simulated by assuming that the surface temperature of the surroundings is equal to the room temperature. Secondly, long-wave radiation received from the surroundings is simulated based on surface temperature approximated in the first step. Finally, the heat balance of each voxel is calculated again by using the results obtained in the second step, and the corrected surface temperature, which accounts for the effect of long-wave radiation, is then obtained.

In the developed tool, the multi-tracing simulation directed toward the surrounding voxels is implemented to determine the voxels that are used to estimate the radiant flux from the surroundings. The method used for the tracing simulation is the same as the method used for the estimating sky solar radiation and diffuse reflective radiation. This calculation assumes all surrounding subjects to be perfect black bodies with respect to long-wave radiation.

(3) Method for calculating surface temperature distribution
One-dimensional heat conduction in each spatial component is simulated using the above-mentioned heat balance data as the boundary condition for both internal and external surfaces. In this calculation, convective heat transfer (sensible heat flux) is calculated under the assumption that there is no distribution of air/room temperature and wind velocity in the target urban canopy and room. The backward-difference method is used for calculating the unsteady static heat conduction. A simulation is run for five days to obtain a periodic steady-state solution with initial conditions of periodic weather data. The surface temperature obtained on the fifth day is used as the output.

\[
m = \sqrt{\frac{N}{\pi + 1}}
\]

\[
n[i] = \pi \times (2 \times i - 1)
\]

\[
\phi[i] = \cos^{-1}\left(\frac{2 \times i - 1}{2 \times m}\right)
\]

\[
\Delta \theta[i] = \frac{2\pi}{n[i]}
\]

Figure 5 Establishment of tracing directions

Figure 6 Calculation of MRT

Figure 7 House model
Mean radiant temperature (MRT) calculation
In the developed tool, the effect of passive design on the thermal radiation environment is evaluated by using the MRT (Figure 6). The human body is represented by a micro-cube. The relationship of the form factors between a human body and other objects is expressed by the surface-weighting factor on the micro-cube according to the process developed in a previous study (Yoshichi O et al., 2003). The MRT is calculated as per the following steps. The surface temperature distribution is calculated by above processes. A multi-tracing simulation directed toward the surrounding walls, ceiling, and floor surface voxel, is performed to determine the radiant flux from the surroundings to the micro-cube. The tracing simulation is performed using the method used for estimating long-wave radiation. The radiation incident on the human body was calculated; thereafter, the MRT was simulated. In this paper, the long-wave emittance was set to 1.0.

Post-processing method using 3D-CAD
The voxel data from the surface temperature calculation results are converted into surface texture data, and the textures are visually projected onto the 3D-CAD model generated during pre-processing. This allows the user to understand and evaluate the effects of spatial geometry and materials on the outdoor surface temperature from almost any viewpoint.

VERIFICATION OF RADIATIVE CALCULATION PARAMETERS
In this tool, calculation errors mainly occur while simulating the amount of solar radiation. The accurate determination of the amount of solar radiation depends on the voxel spatial resolution and the number of tracers in the multi-tracing simulation. Therefore, in this section, we describe the optimization of the spatial resolution and number of tracers.

Investigation of spatial geometry reproduction
In this tool, radiative analysis is carried out by ray-tracing in the voxel space. Consequently, the accuracy of this radiative analysis depends on the spatial resolution of the voxel space. Therefore, the relationship between the accuracy of the radiative analysis and the reproduction of the spatial geometry is examined.

In this study, a room with south-facing windows and leaf cover was chosen as the building model (Figure 7). Using the method described above, the amount of direct solar radiation transmitted through the glass windows was calculated for several different spatial resolutions in the voxel space. The voxel resolution was varied between 2 and 50 cm, and the 2-cm voxel resolution was used for the comparison.

Figure 8 shows the relationship between the voxel resolution and the amount of direct solar radiation. It can be inferred from the figure that a voxel resolution of less than 5 cm does not significantly influence the simulation result. Thus, the optimum voxel resolution is 5 cm, as mentioned above. Identical results were obtained in examinations conducted on other buildings.

Optimum number of tracers in multi-tracing simulation
The increase in the number of tracers in the multi-tracing simulation used for estimating the sky view factor and radiative heat transfer increases the calculation load; therefore, the optimum number of tracers should be determined for practical use. To this end, we examine the relationship between the number of tracers and the amount of direct solar radiation.
Figure 10. 3D-CAD model

Figure 11. Surface temperature distribution at outdoor space (12:00)

Figure 12. Surface temperature distribution at living room(20:00)

Figure 13. Mean radiant temperature distribution at living room(20:00)
of tracers in the multi-tracing simulation and the calculation accuracy, using the sky solar radiation. The building model used for this examination is the same as that shown in Figure 7. The root mean square error (RMSE) index is used for determining the calculation accuracy. The standard maximum number of tracers for calculating the RMSE is more than 50,000. The relationship between the number of tracers and the RMSE index of the sky solar radiation for the entire floor voxel is shown in Figure 9. The difference in the RMSE is small when more than 3000 tracers are used. This finding confirms that for the multi-tracing simulation, the optimum number of tracers is more than 3000.

SIMULATION TOOL APPLICATION
The effectiveness of the developed tool in evaluating the effects of passive design on a thermal radiative environment of a building was determined by applying the tool to a purpose-built passive solar house. Figure 10 shows the target passive design house. The house has large windows directed toward the south and a large deciduous tree on the wooden deck in front of the windows. During summer, the large tree shades the house from direct solar radiation. In winter, the leafless huge tree transmits direct solar radiation into the house. The concrete floor of the aforementioned room has huge heat capacity and can therefore store heat from the incident solar radiation during winter.

The summer and winter weather conditions used for calculation were representative of days with clear skies in the respective seasons. Figure 11 shows the surface temperature distribution in outdoor space during both summer and winter (12:00). In summer, the surface temperature of the wooden deck is low because it is shaded by the large tree. However, the surface temperature of the wooden deck during winter is the same as that of the ground because the leafless tree directs the solar radiation to the wooden deck. Figure 12 shows the surface temperature distribution in the indoor living space during both summer and winter (20:00). The surface temperature of the floor in summer is low because the large tree prevents the direct incidence of solar radiation into the room during daytime. However, surface temperature in winter is high because the floor, which is made of a high heat capacity material, stores the heat from the solar radiation incident during the day. Figure 13 depicts the MRT distribution at a height of 1.5 m in the living room during summer and winter (20:00). In summer, at 20:00, there is no distribution of MRT. In winter, the value of MRT in the space near the window, which was exposed to solar radiation, is 2°C higher than that in other spaces because of the heat stage. This finding shows that passive design ensures a comfortable radiative environment during both summer and winter.

These results reveal that the developed tool is able to simulate the effects of solar shading by a large tree and direct heat gain on the surface temperature distribution and the MRT. Therefore, this tool can be used to evaluate the effects of passive design on thermal radiative environment around a building.

CONCLUSIONS
In this paper, we described a passive design tool that is capable of predicting the surface temperature distribution and the MRT for both outdoor and indoor surfaces. To allow for the consideration of detailed spatial geometry as well as material positions, material types, and trees, a radiation analysis algorithm with a high-resolution voxel model was developed. Then, the simulation parameters, i.e., optimum voxel size and the number of tracers in the multi-tracing simulation, were established.

The results of applying this tool for creating passive design architecture revealed that it was capable of simulating the effects of passive design such as solar shading of tree, building spatial geometry, and materials on the surface temperature and MRT distribution, and that it could be used to study the passive design at the design stage. In future work, this system will be combined with building heat load simulation for the comprehensive evaluation of a passive design.

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