# Development of Thermal Simulation Tool for Urban Block Design
# -Based on Numerical Simulation System using 3D-CAD-

Akira Hoyano*, Kazuaki Nakaohkubo*, Takashi Asawa*
*Tokyo Institute of Technology, Yokohama, Japan

## Summary

A simulation system has been developed as a computer aided design tool to evaluate the effect of proposed design on the thermal environment during the designing process. This system calculates outdoor surface temperatures in order to evaluate the thermal impact of a design factor in outdoor space.

In this study, the previous heat balance simulation system was improved to predict the surface temperature of a proposed design using 3D-CAD. This system is able to input the complicated outdoor spatial forms efficiently and also to evaluate the surface temperature distribution from any viewpoint.

## 1 Introduction

The urban heat island phenomenon occurs in urban regions of Japan. In recent years, the deterioration caused by the urban thermal environment has been recognized a serious problem during the summer months. Therefore, urban development that takes the urban thermal environment into consideration has become of increasing interest. Administrators recognize heat island mitigation policy is of extreme importance to urban redevelopment. Under such a policy, designers and developers would design architecture and outdoor spaces considering the influences on the thermal environment. In addition, a thermally comfortable environment would be pleasing to people who live and traffic urban areas. Thus, support tools suitable for designing such outdoor thermal environments are needed. However, at present, there are no environmental design support tools available to aid designers and government officials in evaluating a proposed design's effects on the thermal environment at the design stage .

The surface temperatures of buildings, trees, and the ground are the primary factors influencing increases in air temperature and the formation of an outdoor thermal radiation field. Therefore, it is important to consider the outdoor surface temperature distribution when designing architectural structures and urban blocks, especially, in hot and humid climates such as the summer in Japan. In a previous study, the authors developed a heat balance simulation system that can predict the surface temperature distribution of an urban area using GIS data [1].

The purpose of this study is to improve upon the previous simulation, so as to predict the surface temperature distribution of urban blocks taking the actual design of the particular outdoor space into consideration. In addition, this environmental design support tool will be of use to 3D-CAD software users.

## 2 Development of thermal simulation tool

### 2. 1 Concept of simulation tool

In order to develop a practical simulation tool for all users, the following criteria were established as the tool concept.

1. Designers and government officials, who lack specific knowledge of thermal environment analysis, should be able to easily use the support tool.
2. The tool should be able to evaluate the thermal environment of the proposed design quantitatively, considering the actual design of the outdoor space at any stage in the design process.
3. The tool should allow visual communication of the thermal improvements achieved through use of the tool to the general public; in addition, users will be able to visually confirm the outcome of the simulation.

In an effort to meet the above conditions, the tool was constructed on 3D-CAD software.

### 2. 2 Outline of the simulation system

The surface temperatures of buildings, trees, and the ground are the primary factors influencing increases in air temperature and the formation of an outdoor thermal radiation field. Therefore, it is important to consider the outdoor surface temperature distribution when designing architecture and urban blocks,.

The outdoor surface temperature is dependent upon spatial forms and the materials used to construct outdoor spaces, the ground covering, and the shape and position of trees. In order to evaluate the effects of spatial forms and materials on the outdoor surface temperature, this tool reproduces detailed shapes and components of building materials as well as the trees, using 3D-CAD program. The subject spatial scale of this simulation tool ranges from the size of a single building to a span of ordinary urban blocks. The surface temperature calculation results are then visually projected onto the 3D-CAD model. This allows the user to understand and evaluate the effects of spatial forms and materials on the outdoor surface temperature from almost any viewpoint, including a bird’s-eye view and an axonometric projection.

### 2. 3 Composition and flow of the simulation system

The composition and flow of the simulation program are described below (**Fig. 1**).

(1) Building and tree shapes are drawn using the all-purpose 3D-CAD software.

(2) The following data are selected from the "Spatial Component Database."

(a) Buildings: the building structure, building elements, materials and surface color

(b) Trees: the species of the trees and the solar transmittance

(c) Ground: land covering and its composition

Physical properties of materials are selected from the "Material Database". This database is linked to the Spatial Component Database. The next investigation in this series will include an improved database that includes greening methods, such as roof gardens and ivy covered walls.

(3) The CAD models generated from this process are then transformed into a “mesh model”, which is used to calculate radiative heat transfer and the surface heat balance (**Fig. 2**).

(4) Heat balance and one-dimensional heat conduction are analyzed for each mesh. Sky solar radiation and atmospheric radiation are calculated from sky factor of each mesh. Convective heat transfer is calculated assuming that there are no distributions of air temperature and wind velocity in the outdoor space. The weather data used for this calculation comes from the vertical quantity of total solar radiation, air temperature, relative humidity, wind velocity, and cloud amount.

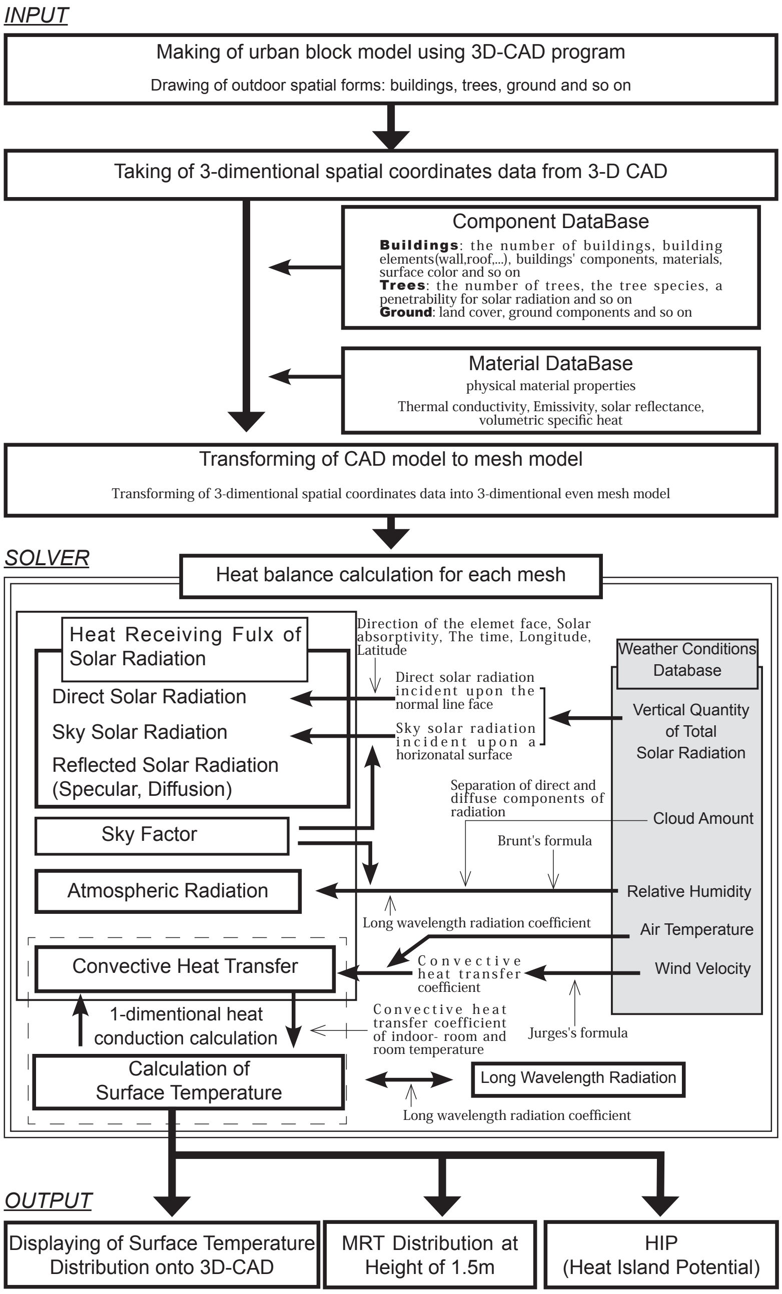



**Fig. 1 The flow chart of this simulation program**

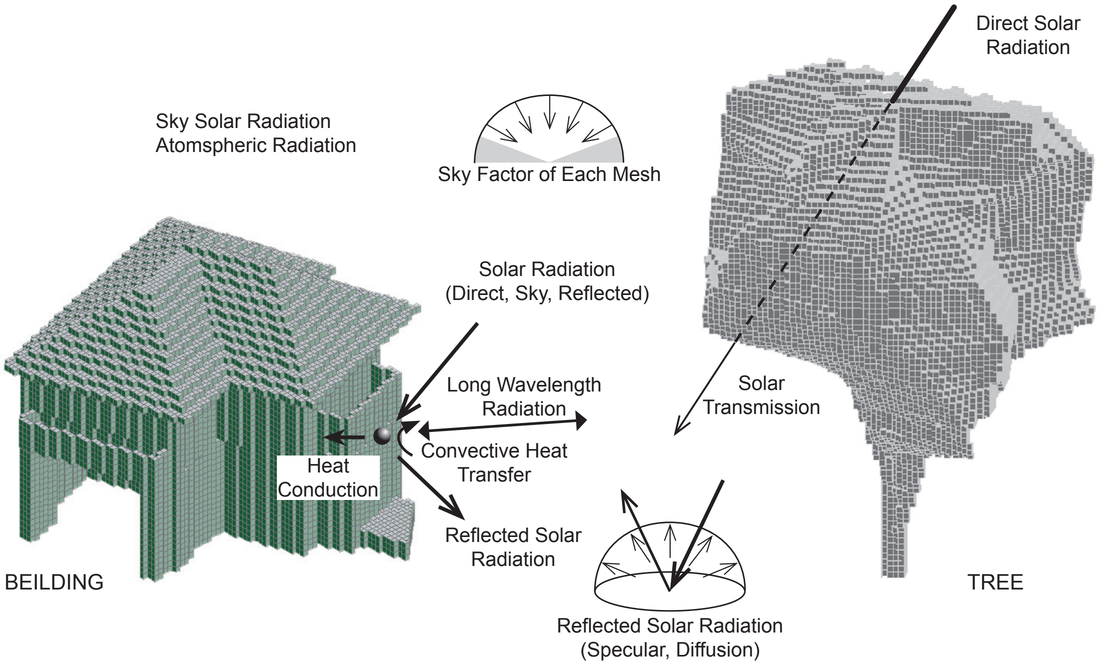



**Fig. 2 "Mesh Model " of Building and Tree, and Heat Balance Calculation at Each Mesh**

# 3 Input/output method and calculation verification

## 3. 1 Verification index

**Table 1** displays all features to be needed to develop the simulation system.

In this study, the following features were examined.

(1) A method was developed to obtain the detailed object data from the 3D-CAD program.

(2) Although a smaller mesh size more accurately depicts detailed outdoor spatial forms, the calculation time for large numbers of elements is tremendous. To solve this problem, an optimum mesh size was determined.

(3) To solve the above problem, a faster calculation method was developed.

(4) A method for visually expressing the calculation results on 3D-CAD was developed.

(5) The reflection of short wavelength radiation on a surface was introduced. This feature was not available in the previous simulation program. Since reflection coefficients vary for different building materials, this feature is necessary.

(6) Because the solar transmittance of a tree's crow is influenced by the shape of tree and the permeating solar radiation course of the crown, new tree models were examined and introduced into the simulation program to accurately reproduce their solar transmittance characteristics.

**Table. 1 The features examined and introduce to develop this system**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| The points which are caused by outdoor spatial design | Building | Forms | C | The points which influenced inside of a building | Building | change of room temperature with time | A |
| | | Height | C | | | spatial distribution of room temperature | E |
| | | Material of surface | A | | | distribution of heat transfer rate of a inside | E |
| | | color | A | | | heat bridge | E |
| | | distribution of glass | B | | | distribution of thermal insulating material | E |
| | | fittings | E | | | position of structual member such as column, beam | E |
| | | the difference of heat conductivity each a solar shading member | C | | | West heat from outdoor apparatus, car and so on | E |
| | Tree | Forms | C | The points which are caused by location | Ground | land undulations | F |
| | | Height | C | | | state out of scope of calculation | F |
| | | species of a tree | A | | | surface of a water such as river, pond | F |
| | | penetrability for solar radiation | C | | | calculation of HIP on urban scale | A |
| | | Change of tree clown for seasons | G | The points which are caused by natural phenomenon such as weather condition | Commonness | value of solar radiation | A |
| | Commonness | Solar absorptivity | A | | | air temperature | A |
| | | long wavelength radiation | B | | | cloud amount | A |
| | | volume specific heat | A | | | wind velocity | A |
| | | convective heat transfer coefficient | A | | | considering rainy weather | G |
| | | land cover | A | | | transfer of latent heat | D |
| The points which are influenced by outdoor spatial design | Commonness | mesh size | B | | | regression calculation of trees, lawn, ground and so on(considering transpiration) | A |
| | | direct solar radiation | A | | | vertical qquantity of total solar radiation | A |
| | | reflected solar radiation(Specular) | A | | | atmosphric radiation | A |
| | | reflected solar radiation(Diffusion) | C | | | convective heat transfer coefficient | A |
| | | sky factor | A | | | | |
| | | Distribution of air temperature and air flow | D | Evaluation | | method of evaluation | C |
| | | long wavelength radiation | A | | | expression method of result of calculation | C |

A: the features applied to this simulation system form the previous simulation system.
B: the features changed from the previous simulation system.
C: the features introduced newly in this system
D: the features that will be examined to be conbined with an air-flow simulation.
E: the features that will be examined to calculate the building heat load.
F: the features that will be examined expect for the above items.
※ :the features was examined and introduced in this system.

## 3. 2 Optimum mesh size investigation

From above indices, this section describes the results of determining the optimum mesh size.

A small mesh size is necessary to accurately reproduce detailed spatial forms such as hoods, pergolas, and the shape of a tree crown. On the other hand, the smaller the mesh, the longer the calculation time. To account for these opposing issues, an optimum mesh size should be used.

A wooden house with a small and complex spatial form was chosen as the building model example. The direct solar radiation quantity was calculated for several different mesh size models. From these results, the relationship between the mesh model and the calculation time were established using Work Station. The mesh size was varied between 0.1 m and 1.0 m, as shown in Figure 3. When the 1.0 m mesh was used, certain spatial forms, such as a hood and a wing wall, could not be reproduced. The calculation time for the 0.2 m mesh was not different from that for the 0.5 m mesh. When the 0.1 m mesh was used, the building details were reproducible, but the simulation took a long time. Therefore, the simulation system uses a 0.2 m mesh, as the optimum mesh size. This size allows for a fast simulation while accurately reproducing detailed outdoor spatial forms.

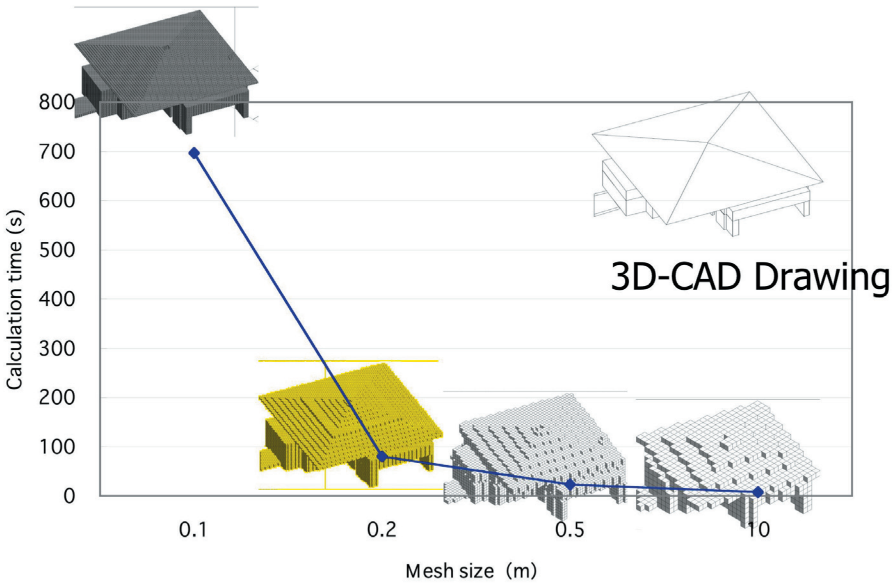


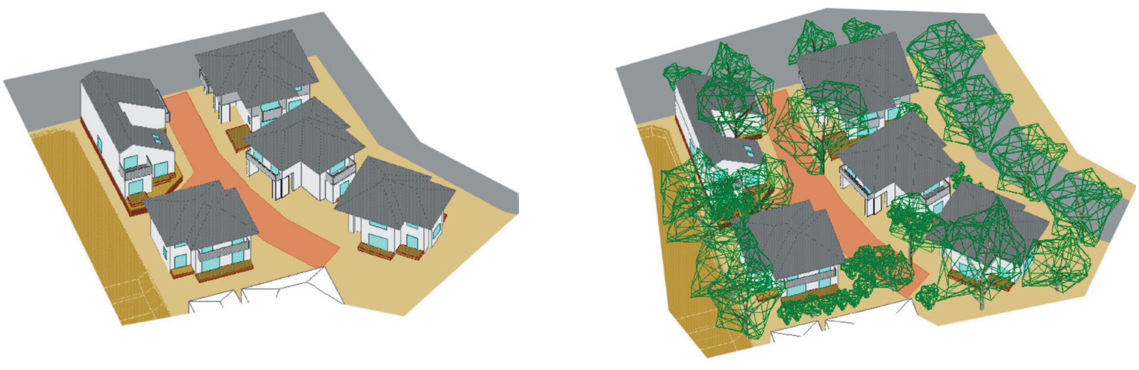

**Fig. 3 Relationship between reproducibility of the mesh and calculation time**

## 4 Simulation system application

### -The effect of tall trees in a detached house area-

In order to verify the validity of the simulation system as a design tool for outdoor thermal environments, the simulation tool was applied to a detached house area having leafy canopy. Then the effects of tall trees to control the thermal environment were examined. An area with five two-story houses was established for the analysis. The detailed weather conditions used in the calculation consisted of a summer day with clear skies.

The calculation was performed for three different cases. In the first case, there were no trees in the area (Case 1). Case 2 and 3 have different amounts and positions of trees and include trees that are taller than the houses (**Fig. 4**). The tree model was mainly reproduced a zelkova tree. The solar transmittance at each mesh was established as the same value, assuming that there is no distribution of leaf density in the crown.



< Case 1: There is no trees > < Case 2: There are many tall trees >

**Fig. 4 3D-CAD Models of The Detached House Area**

## (1) Surface Temperature Distribution Expressed on The 3D-CAD Model

**Figure 5** shows that the differences of surface temperature distribution between these models are quite obvious. In the Case 1, which has no trees, surface temperatures of roofs and ground increase to approximately 50°C due to directly exposed to solar radiation. In the Case 3, on the other hand, relatively low temperature areas, equivalent to the air temperature, increase due to the tall tree's shading. Also in this simulation tool, the solar shading effects of trees are visually confirmed as a walk-through animation (**Fig. 6**).

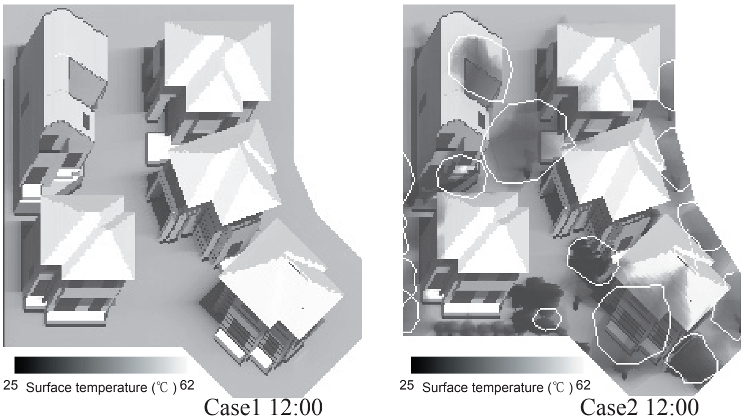



**Fig. 5 Brid-eye view of surface temperature distribution**

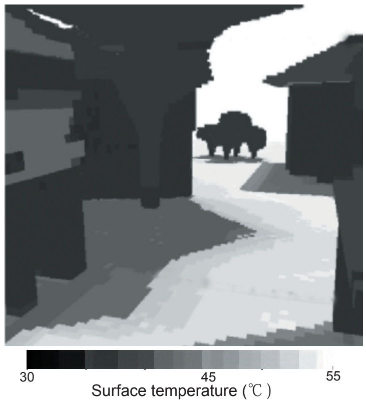



**Fig. 6 Perspective of surface temperture distribution (Case 2)**

## (2) MRT Distribution at The Height at 1.5m

The 1.5m-high MRT distribution of **Figure7** shows that MRT under the tall tree's crown is 32°C, approximately 10°C lower than that at sunny area, because the differences of surface temperature of ground and building between these spaces largely influence to these thermal radiant fields. This result shows that tall tree prevents the deterioration of thermal radiant field under its crown, and keeps the spatial MRT at the air temperature level.

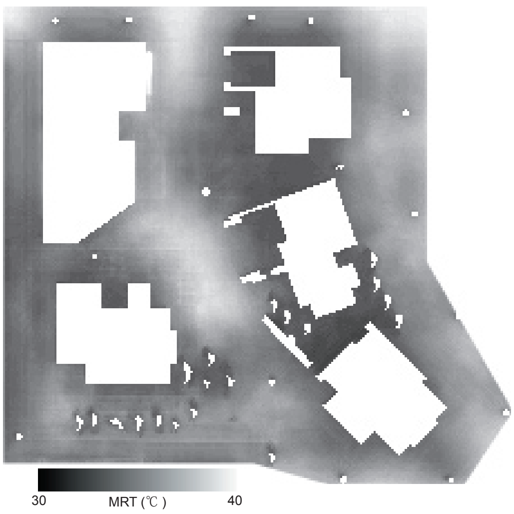



**Fig. 7 MRT distribution at a height of 1.5 m (Case 2)**

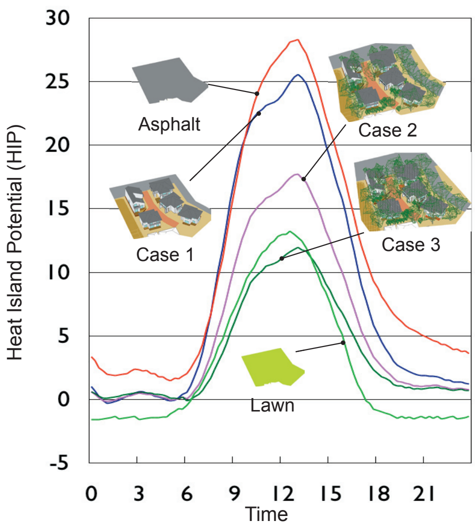



**Fig. 8 Diurnal change of the HIP**

### (3) HIP (Heat Island Potential)

HIP diurnal change of **Figure 8** indicates that HIP drop largely by the tall tree planting. The difference of HIP between CASE1 and CASE2 at noon is approximately 10°C. It is confirmed that tall trees are effective to restrain the sensible heat flux from the whole outdoor surfaces.

These results reveal that the simulation system is able to successfully simulate the effects of building shapes and tree's shading on the surface temperature distribution, index MRT and HIP. Therefore, this simulation system is confirmed to be able to effectively evaluate the thermal design for outdoor environment including tree planting.

## 5 Conclusion

A simulation system has been developed that will enable a user to predict and evaluate the effect of his design on the area's thermal environment at any design stage.

The following features were included in this simulation program to allow for the consideration of complex outdoor spatial forms: an input method that uses 3D-CAD, an optimum mesh scale, a calculation method that requires only a short simulation time, and a method to visually inspect the calculation results.

A detached house area was chosen to validate the proposed simulation system. This application confirmed that the surface temperature distribution could be analyzed from any viewpoint and at any point in the design process.

The next study in this series will focus on improving the simulation system database and will be combined with an air-flow simulation. A latent heat model will be introduced to evaluate the effect of rainfall and the efficiency of water-permeable pavement.

## Acknowledgments

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## References

[1] A. Iino and A. Hoyano, 1996, Development of a method to predict the heat island potential using remote sensing and GIS data, Energy and Building 23 199-205.