The Urban-Scaled EnergyPlus Simulation Using Korean GIS to Aid Development of Energy Normalization for Shading Effect

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Abstract

It is widely recognized that the shading effect between buildings significantly contributes to cooling and heating loads, independent of individual building performance. This necessitates energy normalization for the shading effect to ensure a more objective building performance assessment, requiring an urban database containing the geometric interactions between buildings for analysis. However, in the real world, obtaining data about shade and solar radiation reduced or generated by adjacent buildings is challenging. Such data are crucial for energy normalization concerning the shading effect, and it necessitates the introduction of scientific tools to complement them. With this in mind, the authors suggest the urban-scaled building shading simulation based on the geographic information system (GIS) to address the data acquisition challenge. The GIS serves as an urban database, integrating diverse city information such as buildings, energy, finance, demographics, and transportation, with spatial information as its core, based on a coordinate system. This study utilized the GIS called "Road Name Address System", managed by the Korean government to foster the address-based industry, as the primary input data. EnergyPlus, the whole building energy simulation, was employed as the virtual experiment tool about the geometric interactions between buildings and to quantify the shading and solar radiation on building surfaces. In this paper, the authors discuss how the database of shading and solar irradiation on building surfaces was constructed based on the urban-scaled EnergyPlus simulation and anticipate that the data augmentation with the virtual experiments will contribute to a better explanation of the macroscopic dynamic characteristics of buildings.

1. Introduction

As is widely known, the shading effect significantly impacts the heating and cooling loads of buildings. This effect is independent of the building energy system design, and the energy normalization for the geometric interactions between buildings is required to enable objective decision-making in building energy benchmarking. However, currently, the energy benchmarking problems are primarily focused on individual buildings, and there is less discussion on energy normalization for the effects of building groups. Furthermore, the authors believe that the lack of an urban-scaled database available in the development of the energy normalization indicator for the shading effect is one of these barriers. Meanwhile, essential data such as shade and solar irradiation projected on the building surfaces are difficult to collect through measurements in the real world, and virtual experiments can be useful in the acquisition of the inaccessible information. In this context, the authors suggest the construction process of the database of the projected shade and solar irradiation on the building surfaces using EnergyPlus simulation (Crawley et al., 2001) and geographic information system (GIS). The EnergyPlus is the dynamic building energy simulation tool that includes a shading module, which calculates the shade and solar irradiation incident on the building´s surfaces considering interactions between buildings. The GIS serves as an urban database, integrating diverse city information with spatial information as its core. In this study, the Road Name Address System, a type of Korean GIS, was utilized, and urban-scaled virtual experiments linked with EnergyPlus were conducted to collect the shading and solar radiation data necessary for the database

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construction. Further, the authors wish to discuss that, beyond being a tool for performance evaluation, the urban-scaled building simulation is useful as the data augmentation tool for energy normalization concerning the shading effects in cities. Furthermore, the purpose of this paper is not to discuss the functional advantages of the research findings in comparison with specific packages, but rather to share the data augmentation process from an academic perspective, thereby contributing to the advancement of building energy academia. Fig. 1 illustrates the entire process of this study, and the following items will be addressed in detail: (1) Korean GIS and weather data used in this study, (2) organization of IDF (EnergyPlus model file) generator, (3) database construction.

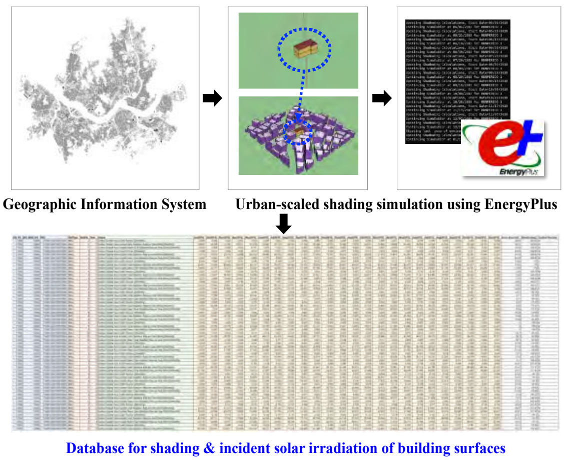

Fig. 1 – Overall process of this study

2. Road Name Address System (GIS)

The Road Name Address System is the GIS developed by the Korean government to promote the address-based industry and adopts the shapefile format (SHP) widely used in the GIS industry. The SHP has a matrix form, where each row and column represents the individual building and the building's attribute, respectively, and has 31 columns (Table 1), including the primary keys of GIS such as 'SIG_CD' and 'BUL_MAN_NO', the spatial attributes including the address, the building polygon (2D), the number of floors. Note that concatenating the address-related items in Table 1 in order yields a 19-digit parcel number (PNU) mainly used to identify parcels in Korea, and this study also utilizes it for building identification.

Table 1 –Road Name Address System (*: primary key of this GIS)

Category	Column (Description)
building geometry	geometry (polygon)
# of floors	GRO_FLO_CO (above-ground), UND_FLO_CO (basement)
serial number	**BUL_MAN_NO (building)***, EQB_MAN_SN (building group) RDS_MAN_NO, BSI_INT_SN (road)
building name	POS_BUL_NM, BULD_NM, BULD_NM_DC, EQB_ENG_NM
building type	BDTYP_CD
building address	**SIG_CD (district code)***, EMD_CD, LI_CD, MNTN_YN, LNBR_MNNM, LNBR_SLNO
road name address	RN_CD, RDS_SID_CD
postal code	BSI_ZON_NO (state basic district system),
main building and annex classification	BULD_MNNM (main number), BULD_SLNO (sub number) BUL_DPN_SE (indicator)
data history management	OPERT_DE< MVMN_DE, MVMN_RESN, MVMN_RES_CD, NTFC_DE

In order to perform the 3D modelling through the EnergyPlus scheme, it is necessary to know the coordinate system rules of the GIS, such as the coordinate reference system (CRS) that defines the reference position of the GIS, the ellipsoid (Fig. 2) that approximates the shape of the Earth with a mathematical form, and the projected coordinate system that defines how to transform the 3D coordinate information (XYZ coordinates) into the plane coordinate information (XY coordinates). In case of the Road Name Address System, the International Terrestrial Reference Frame (ITRF) was first adopted as the CRS. This is the 3D coordinate system whose origin, x-axis, and y-axis correspond to the center of mass of the Earth, the direction where the Greenwich meridian intersects with the equator, and the direction of 90 degrees east longitude, respectively.

Second, the ellipsoid is the Geodetic Reference System 1980 corresponding to the global geodesic system. This has a semi-major axis of 6,378 km, and an eccentricity of 0.00818, respectively, and the ellipsoidal coordinates (latitude φ, longitude λ) can be transformed to the 3D Cartesian coordinates (XYZ coordinates) with the trigonometric functions.

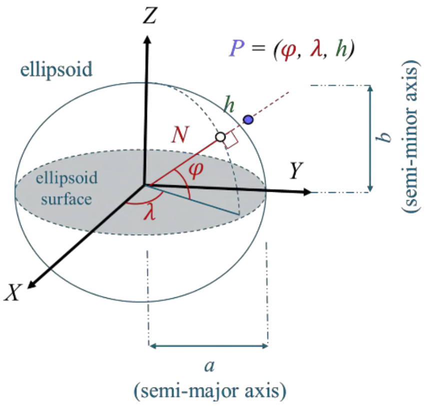

Fig. 2 – Ellipsoidal coordinate system

Third, the universal transverse Mercator (UTM) projection (Fig. 3), a type of cylindrical projection method, was applied as projected coordinate system. For reference, distortion needs to be reduced in the process of projecting coordinates from ellipsoid to cylinder, and for this purpose, the approach of projecting zone-by-zone was adopted instead of projecting the entire ellipsoid at once. And the origin of each zone is usually adopted by the equator, where the higher or lower latitude can increase the degree of projection distortion, so in this GIS, the specific origin (latitude: 38°, longitude: 127.5°, Gapyeong-gun, Geongggi.do) adjusted to the Korea was applied. In this study, 547,615 buildings in Seoul (25 districts), Korea, were considered as the subjects of EnergyPlus modeling and simulation, and Fig. 4 shows them with the map.

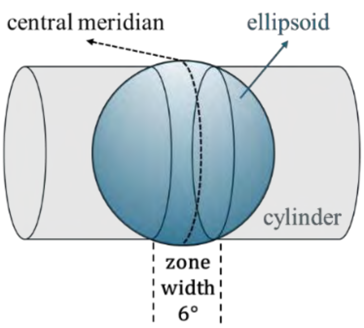

Fig. 3 – Universal transverse Mercator projection

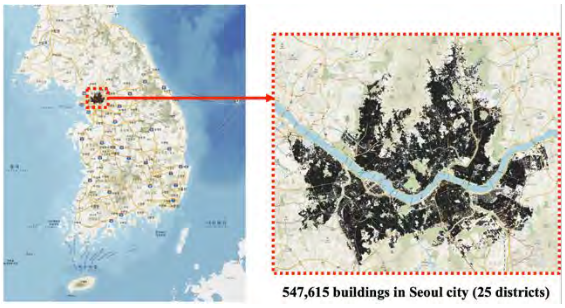

Fig. 4 – Target buildings in this study

3. Weather Data (Solar Radiation)

To perform urban scaled shading simulations, it is required to prepare weather data files with specified format, EnergyPlus Weather format (EPW), in advance. Especially, it is more useful to secure both direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI) decomposed results rather than only the global horizontal irradiation (GHI) when calculating the shade and solar radiation introduced to each exterior wall of the building accurately. In this regard, the National Solar Radiation Data Base (NSRDB, Fig. 5) (Sengupta et al, 2018) developed by US National Renewable Energy Laboratory (NREL), which deals with decomposed solar irradiation, was used as raw data. The NSRDB was constructed based on the direct insolation simulation code (DISC) model (Maxwell, 1987) as a theoretical background and provides DNI and DHI data at the international scale, including the United States. In this study, the NSRDB data corresponding to Seoul city (latitude: 37.58°, longitude: 126.97°) were used , and data corresponding to Incheon city (latitude: 37.48°, longitude: 126.63°) were applied only for buildings belonging to Ogok-dong, Gangseo-gu, Seoul in consideration of proximity to the weather station.

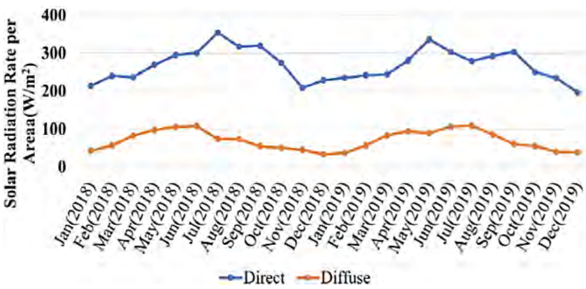

Fig. 5 –DNI (blue) and DHI (red) data of NSRDB for Seoul city

4. IDF Generator (Python Language Used)

To automatically generate large amounts of EnergyPlus model files (IDFs) from SHP files, the authors made the program for IDF generation (Fig. 6). This program was written based on Python 3 language and contains the extraction of building polygon information, the conversion of geometric information from GIS to EnergyPlus, search for adjacent buildings, and generation of IDF objects. In this program, the following open-source libraries were used for tasks such as SHP file processing, polygon processing, coordinate system, plane modification, and writing the IDF: (1) GeoPandas (Jordahl et al., 2021) for SHP file processing, (2) Shapely (Gillies et al., 2023) for polygon control, (3) Pyproj (Snow et al., 2020) for coordinate system control, (4) tripy (Bolgert, 2024) for pre-processing of concave polygons for EnergyPlus modeling, (5) Eppy (Philip et al., 2024) for IDF writing. The following sections will cover the main functions of the IDF generator.

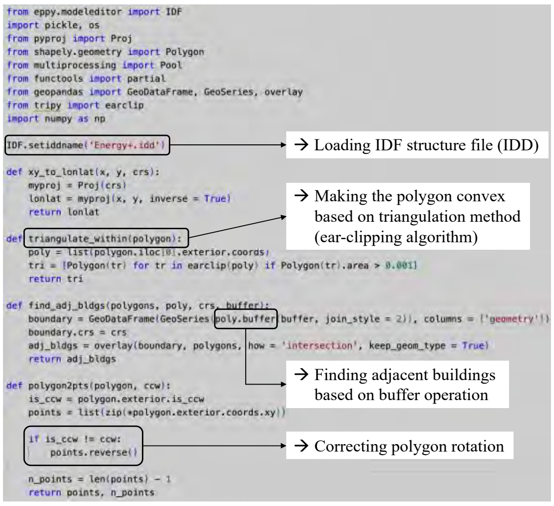

Fig. 6 – Python program used in this study

4.1 Model Configuration

Considering that more than 100,000 dynamic simulations were required in this study, the models were made to reflect only what was necessary to obtain shading data of building surfaces. Firstly, only one zone was placed on each floor, and windows were not placed. Further, internal heat loads (people, lighting, equipment) and the HVAC system were not considered in modeling since this study only focuses on the shades and solar irradiation projected on the building surfaces. The authors set the version of EnergyPlus models to 9.0 for compatibility with higher and lower versions, and the save interval of the simulation results was set to the month. In future work, the authors will discuss the impact of the save interval on the development of the shading indicator, and three output variables related to the solar irradiation and the shade projected to the building surfaces were applied as follows.

- Surface Outside Face Sunlit Fraction (0-1, the fraction of building surface area where beam solar radiation reaches)
- Surface Outside Face Incident Solar Radiation Rate per Area (W/m^2)
- Surface Outside Face Incident Beam Solar Radiation (W/m^2)

4.2 Triangulation for Concave Polygons

Based on the EnergyPlus 9.0 version, polygon clipping algorithms such as the Weiler-Atherton (Weiler et al., 1977) and the Sutherland-Hodgman (Sutherland et al., 1974) are utilized to prevent redundant calculations of shades reaching the building surfaces. However, these polygon clipping algorithms only work precisely on convex planes, and consequently, modeling the concave planes is not recommended in the EnergyPlus scheme. For this reason, the authors introduced the process of splitting the original GIS polygon into n triangles so that no concave plane exists. In the realm of computer graphics, a variety of plane triangulation algorithms have been introduced. Among them, this study utilizes the Ear-clipping algorithm (Eberly, 2008; Fig. 7), renowned for its versatile application across diverse plane types. This clipping algorithm sequentially searches the ear (p(i) in Fig. 7), the vertex that makes the polygon concave since the angle between two edges is less than 180 degrees, and every time the ear is found, the polygonal segmentation is carried out.

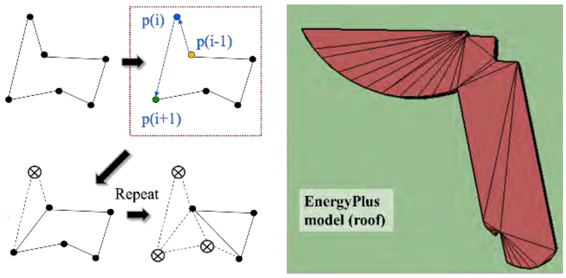

Fig. 7 – Polygon triangulation by Ear-clipping algorithm

4.3 Modelling of Shading Objects

The buffer analysis is often used in GIS work to assess proximity, accessibility, or environmental impact of features such as roads, rivers, or land parcels. The buffer corresponds to a zone (e.g., red colored area in Fig. 8 (a), applied distance: 5 m) of a specified distance around a geographic object such as each node of the polygon or the specific point on the map. Conducting buffer analysis on building footprints allows us to obtain expanded areas while maintaining the shape of the original polygon. According to this context, the buffer analysis with 50 m extension distance (Fig. 8 (b)) was performed in this study to derive the shading area of the target building, and the buildings located within the generated area were regarded as shading objects (i.e. neighborhood buildings). And the shading objects were reflected in the EnergyPlus model by applying the shading related class (shading:building:detailed, Fig. 8 (c)).

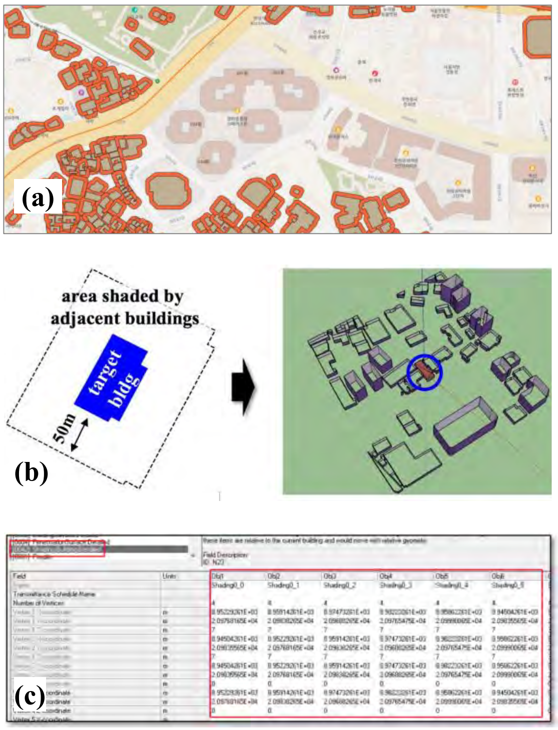

Fig. 8 – Buffer analysis (upper) shading modeling (middle & lower)

4.4 IDF Generation and Simulation

The GeoPandas library was used to read the SHP file for Seoul city, and the whole GIS data was divided into 25 subsets based on district of Seoul city. In addition, each separate GIS data was exported as a binary file (Parquet file), and the program was organized to convert the buildings' information within the binarized SHP file into IDFs based on the

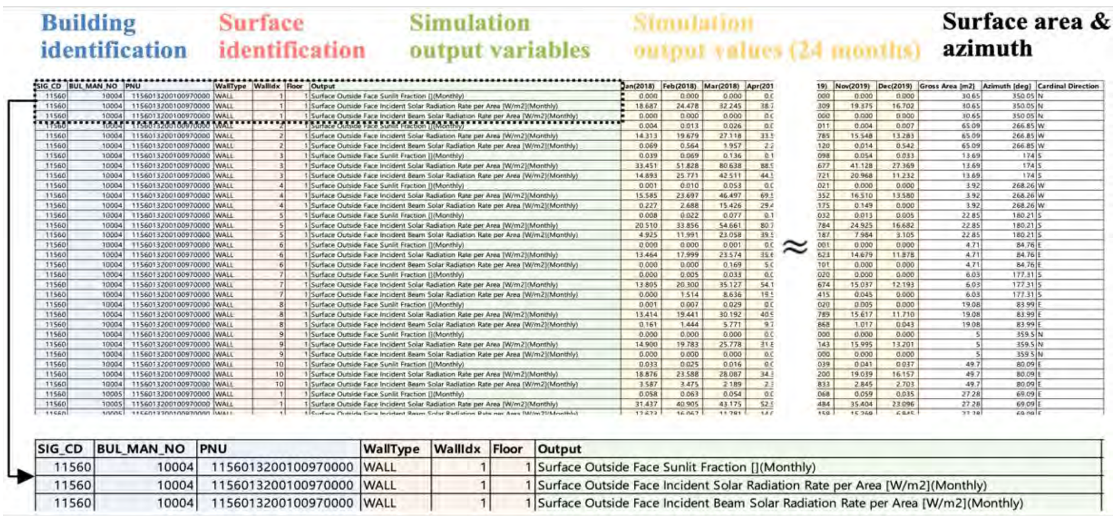

Fig. 9 – Database for shading and incident solar irradiation of building surfaces based on urban-scaled EnergyPlus simulation

Eppy library, script based IDF editing tool. And the coordinates of each building surface were placed to rotate counterclockwise when the plane was viewed from the outside according to the geometry rule of the EnergyPlus. Generating IDFs and EnergyPlus simulations were carried out by the district and the batch file (RunDirMulti.bat) provided by EnergyPlus was utilized for parallel simulations. It should be noted that the run period of the EnergyPlus simulation was from January 2018 to December 2019 (24 months) and the additional parser was used to extract the values of three output variables from the output files (csv format) and the information for the building surfaces' area and orientation from the summary reports file. The simulation computation time took approximately 1 day per district under the following hardware conditions, and in this study, the multi-processing was considered at the district level: AMD Ryzen Threadripper PRO 5975WX (CPU) & 128Gb RAM

5. Database Construction

Fig. 9 shows the database constructed in this study. Considering that it will be used to develop energy normalization index for shading caused by geometric relationships with adjacent buildings, the database was designed to integrate the following information: (1) the building identification (two primary keys of GIS, PNU), (2) the building surface identification (surface type, index and floor), (3) the simulation output type (three variables), (4) the monthly simulation result (Jan(2018) to Dec(2019), 24 months), (5) the figure information of the building surface (area and orientation). The Pandas DataFrame, the widely used database structure in data science, was applied and the database was exported as the binary file (Parquet file), considering deployment and information reuse. Moreover, utilizing this database enables easy retrieval of ingress the shading and the solar irradiation information for buildings at specific time points, and allows the construction of building-level indicators by combining the area and the orientation information of the building surfaces. Furthermore, by utilizing the SIG_CD and the BUL_MAN_NO, which correspond to the primary keys in the original GIS, it is possible to trace the raw data, and by using PNU, integration with other urban databases in Korea (such as building energy, social factors) is enabled. Fig. 10 visualizes the data of July 2019 for three variables using the database of Fig. 9. It illustrates the case where the indicators at the building level were calculated by taking the weighted average of the building surface areas. The brighter the color (indigo color to yellow color), the less shading occurs due to surrounding buildings. It indicates that the values of the three output variables can vary depending on the density of buildings in the area.

6. Conclusion

The shading and insolation entering the facade serve as fundamental information for developing shading indicators, but obtaining this through on-site measurements is challenging from the economic perspective. To overcome this, the authors suggest GIS-based virtual experiments (urban-scale shading simulations) and explain the process of information conversion between heterogeneous information (GIS, EnergyPlus). Finally, the authors show the case study that analyzes the shading effects of buildings using the shading/solar irradiation database, demonstrating that geometric interactions between buildings are appropriately reflected in the database. This study corresponds to the foundational phase for establishing shared knowledge assets regarding the shading effect, and the authors will develop the energy normalization index for buildings consideration of the following items: (1) climate change, (2) terrain geometry, (3) impact of seasons (4) correlation analysis between the shading indicator and the building energy use, (5) urban factors such as urban heat island and microclimate.

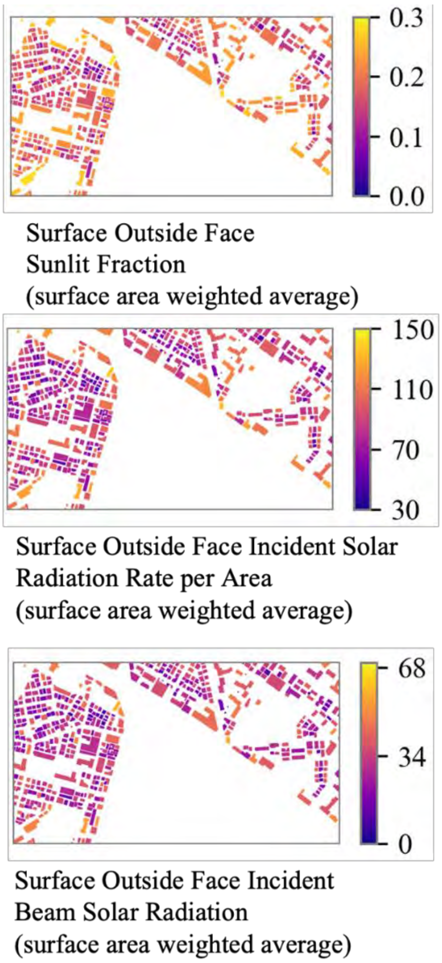

Fig. 10 – Visualization example of the constructed database

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