A study on parametric design tool for residential buildings securing valid sunlight hours on the winter solstice

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ABSTRACT
This study developed a design tool intended to suggest mass forms that can satisfy the standard of two consecutive sunlight hours on the winter solstice and achieve the maximum floor area ratio by identifying the relations between the relevant mass and surrounding buildings within and outside of the urban block, based on the plan created by an architect in line with design concepts at the initial stages. As a basic method to obtain two hours of consecutive sunlight, vector lines were drawn to connect the solar position and the two vertices at the bottom of the elevation. The plane created by the solar vector and the three-dimensional form created by the said plane were used to exclude the mass of adjacent buildings, subsequently preventing the entry of the buildings into the said three-dimensional shape in order to secure sunlight hours. In a bid to verify the design algorithms developed in this study, a variety of simulations were conducted, encompassing from buildings within a single block to nine multiple blocks on the three azimuth angles. The outcomes generated were able to meet the standard of two hours of consecutive sunlight, ensure sunlight hours for the adjacent buildings, and enable high-density development.

1. Introduction
The energy design of urban areas largely concerns solar and sunlight access for both buildings and outdoor spaces. Optimizing urban density is a key component of the strategy to maximize energy performance and sustainability (Cody 2017). Increasing urban density can potentially lower the consumption of resources and energy through transportation by reducing the overall distances traveled. Creating a urban and architectural design plan that satisfies a high-density development and sunlight access is a prerequisite for eco-friendly design (Erell, Pearlmutter, and Williamson 2011). To implement eco-friendly planning in a mild climate region, which faces distinct seasonal changes and a broad annual temperature range, maximizing hours of sunlight in the winter season is a precondition for reducing heating load, and it is necessary to block the excessive sunlight by sun shade in summer (Levy 2011).

In South Korea, the standard for securing the right to sunlight in collective housing design is prescribed in Article 53 of the Building Act and Article 86 of the Enforcement Decree of the Building Act. The relevant Article of the Enforcement Decree stipulates two methods to secure the right to light: securing specific distances between opposing buildings to uphold the right to receive sunlight or ensuring two or more hours of continuous sunlight for every household within the site concerned between 9:00 a.m. and 3:00 p.m on the winter solstice. The Building Act allows the individual determination of distances between buildings in cases where the condition of securing a minimum of two hours of continuous sunlight has been satisfied, but in actuality, collective residential buildings are designed to place multiple buildings with the same form at the minimal distance required by law (Lee 2011). This design method in practice is limited in terms of securing minimum hours of sunlight for every household and diminishes sunlight performance due to mutual interference between buildings and permanent shadow on the lower part of the building (Kim, Moon, and Kim 2014).

Previous studies on day-lit environments of collective housing include studies on day-lit environments of linear-type, courtyard-type and tower-type residential buildings (Lee 2011; Kim, Moon, and Kim 2014; Kang and Jang 2005; Hwang, Bae, and Kim 2011; Jung and Yoon 2015; Cha and Oh 2020; Kim, Kim, and Design 2015; Kim and Design 2017; Kim and Kim 2018). Lee, 2002 (Lee 2011) developed a residential building arrangement method utilizing the characteristics of shadows. The study by Kang, 2004 (Kang and Jang 2005) suggested a ~30° azimuth angle as the optimum azimuth angle in an analysis to identify a favorable layout angle in day-lit aspects, and the study by
Hwang, 2011 (Hwang, Bae, and Kim 2011) examined a marginal analysis of applying the current standard for distance between buildings to the context of block-type collective housing. Jung and Yoon (Jung and Yoon 2015) studied the influence of Building Coverage Ratio and Floor Area Ratio on sunlight environment and outdoor thermal environment in multi-family housing complexes. The study by Cha and Oh, 2020 (Cha and Oh 2020) analyzed the impact of geometry of urban residential street canyons represented by aspect ratio and street orientation on the outdoor thermal environment. The studies by Kim (Kim, Moon, and Kim 2014; Kim, Kim, and Design 2015; Kim and Design 2017; Kim and Kim 2018) presented the design optimization methodology for securing two hours of continuous access to sunlight along with high development density in courtyard-type and street-oriented housing.

The results of these studies confirmed that securing the right to sunlight in a city has a close relationship with not only the building typology but also urban structure, organization, density, scale and azimuth angle. Cody also pointed out that the main challenge is whether it is possible to develop high-rise, high-density urban environments with attractive streets and square without comprising day lighting and solar access even on the lower floors of buildings (Cody 2017). Therefore, it is essential to use environmental performance simulation from the early design stage in order to secure sunlight hours and improve environmental performance while proceeding with high-density development. It is necessary to evaluate diverse alternatives at the early design stages, which involve the repetitive process of the generation, analysis, evaluation, selection, and determination of an alternative (Kim and Kim 2014). Conventionally, architects and urban designers repeatedly conduct relative comparisons of their designs against alternatives using separate simulations, modify the mass design to address issues, and carry out additional simulations, which is a cumbersome and time-consuming process (Singh and Kensek 2014). In this process, devising and applying the algorithm that combines environmental performance evaluation programs with parametric design tools may enable the generation of numerous alternatives while simultaneously conducting environmental performance evaluation. Under the conventional method, an environmental performance evaluation was separately carried out for only one alternative at a time, and a trial-and-error process was conducted on a somewhat random basis. Since the combination of a form generating tool with an environmental performance evaluation program would allow the simultaneous execution of form generation and performance evaluation regarding heat, light, energy, and ventilation, it is effective in producing a design plan that meets the target indicators (Eltaweel and Su 2017; Hernandez 2006; Konis, Gamas, and Kensek 2016; Penya, Kim, and Choo 2020; Schumacher 2015; Zani et al. 2006; Toutou, Fikry, and Mohamed 2018; Touloupaki and Theodosisiou 2017; Park, Lee, and Kim 2015).

Parametric design refers to a representation method that allows variables that affect the shape of a mass, such as its dimensions or structures of a particular part, to be easily changed by defining them in a particular way. This representation method is used to generate an optimal form to meet complex design requirements, and since the late 1990s, formal experiments have been carried out through parametric modeling or generative capabilities of digital scripting (Dasgupta and Michalewicz 1997; Mitchell 1996; Rasheed, Hirsh, and Gelsey 1997). Parametric design methodology functions as a new toolkit in designers’ formal experiments. This allows designers to define diverse variables that determine a form and their relationships in advance and construct a design algorithm to adjust the displacement value, which leads to the production of creative variations in controlling the form in a rational manner. In its early stages, parametric design started from a purely formal approach as a way to generate a complex form in a system environment. Today, however, the scope of its usage has been expanded to address diverse issues from the visual, synesthetic, material, structural, and environmental perspectives (Schumacher 2009; Woodbury 2010).

This study examined methods to secure minimum two hours of sunlight on the winter solstice which is a performance restriction prescribed in the Enforcement Decree of the Building Act, and applied the findings to design logic to develop a parametric algorithm that can calculate a volume with the maximum height as a way to secure higher density and determine the final design. The design support tool developed in this study combines environment performance-based simulations and parametric design methodology. It is designed to layout building masses while automatically determining the highest height of each mass that satisfies sunlight hours for both the block concerned and neighboring buildings. In addition, it can adjust the form in real time to reflect changes in sunlight hours that are caused by shifting the location of the mass as necessary.

In the first phase of this study, basic simulations were conducted by rotating the azimuth angle by 15 degrees to investigate the efficient time period to secure sunlight hours between 9:00 a.m. and 3:00 p.m. on the winter solstice while maintaining maximum density. In the second phase, the design
algorithm was developed by defining design parameters that affect hours of sunlight and applying design rules based on the correlation between design parameters. In this phase, design logic and rules for building shape classification and mass formation methodology were established. In the third phase, the proposed parametric algorithm was tested at different azimuth angles, and the effect of the height of the surrounding buildings was examined for verification. In the fourth phase, the design generation results for the various plan shape in a single urban block, the influence of the shape of the rightmost bottom blocks, the results for the different types of plan shapes in nine urban blocks were summarized. In the fifth phase, the building masses generated by the parametric algorithms and the single-height building masses under the condition of equal density were compared in order to validate the effectiveness of the parametric design tool developed in this study for securing two hours of continuous sunlight on the winter solstice.

This study devised a design algorithm by linking Ladybug to Grasshopper 3D, the most popular among parametric design tools (Roudsari, Pak, and Smith 2014). Grasshopper 3D is a graphical parametric form generating tool that is integrated into Rhinoceros 3D. An open-source parametric plugin called Ladybug is used to support further environmental analysis within the Rhinoceros/Grasshopper interface. Ladybug imports standard Energy Plus Weather files to conduct and draw weather data analysis and environmental strategies, while carrying out day lighting and energy simulations.

2. Materials and methods

2.1. Overview of the proposed design algorithm

Creating a rational form in terms of sunlight separately from the architect's design concept and logic is a task that must be based on environmental simulations and requires considerable knowhow. The algorithm developed in this study is a tool or design guide that is intended to assist architects to make more rational judgments when configuring a form in the design process. It automatically produces a volume based on a plan shape of the layout and visualize it in an optimal form that meets the standard for securing at least two hours of continuous sunlight on the winter solstice, by understanding its relations with all masses within the block and neighboring masses outside the block. Taking into consideration the height of adjacent blocks that the concerned mass may affect or be affected by, the design logic was established to meet the standard of at least two hours of continuous sunlight on both the inside and outside of the mass generated. In this process, the user is able to coordinate design details while modifying and altering the mass form or layout.

The proposed design tool can be used to review and compare early design plans and produce numerous alternatives, while examining sunlight hours, floor area ratio, building coverage ratio, and building height in real time. Subsequently, the architect may regard the proposed shape as the maximum volume and make detailed adjustments based on aesthetic standards and other factors, determining the form based on rational judgments even in areas that had been decided arbitrarily under the conventional architectural method. Figure 1 shows an example of the mass generated by proposed algorithm.

2.2. Climate characteristics of seoul

The climate characteristics of Seoul were examined with regard to sunlight and solar radiation. Seoul, South Korea is located at 37°34'N, 126°57'E, 87 meters, and has a humid continental climate with severe, dry winters, hot summers and strong seasonality. The annual average temperature is 12.5°C, the coldest month is January with the monthly average temperature of –2.4°C, and the warmest month is August with the monthly average temperature of 25.7°C. The annual average wind velocity is 2.3 m/s, while the annual average relative humidity is 64 percent. The major climate conditions calculated using the Ladybug weather tool are shown in Table 1. High levels of solar radiation during the wintertime indicate high potential for passive solar heating and therefore window sizing and thermal mass should be taken into account. The daily radiation of a west-facing building is higher than the annual average radiation of a south-facing building during the overheated period of time, which suggests that excessive sunlight may be an issue for a building facing west. Therefore, it is favorable for residential buildings in Seoul to be more closely oriented towards the south or east. In this study, the orientation of a living room in each unit was set to be oriented south or east with an azimuth angle of 0° with their orientation being adjusted to south-east or south-west depending on changes in the azimuth angle.

| Seoul, Korea |
|-------------|
| 37°34'N, 126°57'E |
| 87 m |
| Solar Radiation (Total Annual) |
| E | 362.90 Kwh/m² |
| S | 519.04 Kwh/m² |
| W | 363.97 Kwh/m² |
| Climate Type | 4 (ASHRAE) |
| Max. Direct solar | 649.42 W/m² |
2.3. Conducting basic simulations to establish a design logic

Parametric design automatically updates designs by specifying the most important key parameters of the project and mutually reflecting changes thereof. In order to fully utilize the advantages of parametric design, it is necessary to appropriately define input parameters and geometrical logic to ensure formal excellence and functional efficiency. This process allows the development of a more efficient design and the evaluation of a broader range of options, thereby resulting in a more optimized shape.

One of the traditional ways of securing sunlight hours is to maintain an appropriate distance between two masses so that the mass located in the front does not interfere with the solar access of the other mass in the rear (Kim, Moon, and Kim 2014; Kang and Jang 2005; Hwang, Bae, and Kim 2011). In a preceding study, this author ascertained that sunlight hours can be secured through the calculation of a separation distance that satisfies the standards of assuring two hours of continuous sunlight or four hours of accumulated sunlight at each azimuth angle. For parts that generate self-shadows, the right to light can be acquired by placing the distance between buildings as 1.8 times the height (1.8 h) in the direction of due north (Kim, Kim, and Design 2015; Kim and Design 2017; Kim and Kim 2018). However, applying these methods may further complicate the algorithm because additional consideration has to be given to self-shadows and unpredictable composite shadows. Thus, this study sought to identify relatively simple, universal rules to secure sunlight hours while satisfying the maximum floor area ratio.

First, this study organized rules to select the most efficient time period in order to secure valid sunlight hours for a certain surface that must be exposed to sunlight. As a basic method to obtain two hours of consecutive sunlight, vector lines (hereinafter the solar vector) were drawn to connect the solar position and the two vertices at the bottom of the elevation as shown in Figure 2. The plane created by the solar vector and the three-dimensional form created by the said plane were used to exclude the mass of adjacent buildings, subsequently preventing the entry of the buildings into the said three-dimensional shape in order to secure sunlight hours.

The aim of the basic simulations was to identify the most efficient time period to secure sunlight hours at each azimuth angle while maintaining the maximum floor area ratio. Conventionally, it may be speculated that the most efficient method is to select the two-hour period in which the sun is at the highest altitude, which may elevate the height of adjacent masses. However, a greater portion of the plan may be cut off depending on the azimuth angle, resulting in a reduction of the overall volume of the mass as shown in Figure 3. Therefore, simulations were conducted for each azimuth angle to identify a specific time period in which the floor area ratio of adjacent masses can be secured to the highest possible extent. The simulations were carried out under the condition where the direction of due north is set at an azimuth angle of 0° by rotating the azimuth angle by 15 degrees in a clockwise (+) or counterclockwise (-) direction. In the simulations, the width of the road was set at 25 meters, with a rectangular-shaped courtyard-type

![Figure 1](image-url). Example of the mass generated by algorithm (a) Plan (b) Axonometric (c) Sunlight hours simulation spectrum.
mass of 100 meters in length and 20 meters in height, facing a bar-shaped building of 40 meters in height. The height of the bar-shaped building was set higher in order to clearly confirm the difference of the removed areas caused by changes in the azimuth angle and altitude of the sun.

Figure 2. Example of the basic simulation to select the most efficient time period (Azimuth Angle of 30°, Grey: Plan shape of each floor generated – first floor from the left).

![Diagram showing time periods and floor shapes](image)

The Figure 2 shows an example with an azimuth angle of 30°. The red-colored portion in the Figure 2 indicates a volume created within the solar path by linking a solar position with the two vertices at the bottom of the elevation, while the grey parts represent the plan that may exist on the adjacent mass from the left side and the first floor, which shows the maximum size of each floor plan. The results of this process indicated that the time period between 9:00 a.m. and 11:00 a.m. is most favorable for the given plane at an azimuth angle of 30° in terms of the standard of securing two hours of sunlight and maximizing the volume of the adjacent building’s mass. In the case of an azimuth angle of 0°, when the longitudinal mass became oriented due south, the

Figure 3. Final selection of the effective time period (Azimuth Angle of 30°) (a) the three-dimensional form created by the solar vector plane (b) the mass of adjacent building with the mass to be removed.

![Diagram showing three-dimensional forms](image)
adjacent mass sees its floor area ratio highest at the time period between 11:30 a.m. and 1:30 p.m. Because the mass faces due south, the time period with the sun at the highest altitude is most favorable in ensuring a larger volume for the adjacent building that is closely oriented due south. The following Table 2 presents the comprehensive results of basic simulations and Azimuth Angle diagrams.

### Table 2. Effective time period selected based on the basic simulation (+: clockwise, -: counterclockwise).

| Azimuth Angle | Effective Time Period | Building Orientation | Azimuth Angle | Effective Time Period | Building Orientation |
|---------------|-----------------------|----------------------|---------------|-----------------------|----------------------|
| 0             | 11:30–13:30           | S                    | -15           | 13:00–15:00           | S                    |
| +15           | 10:30–12:30           | S                    | -30           | 13:00–15:00           | SE                   |
| +30           | 09:00–11:30           | SW                   | -45           | 13:00–15:00           | SE                   |
| +45           | 09:30–11:30           | SW                   | -60           | 12:30–14:30           | SE                   |
| +60           | 10:30–12:30           | SW                   | -75           | 11:30–13:30           | E                    |
| +75           | 11:30–13:30           | W                    | -90           | 10:30–12:30           | E                    |
| +90           | 12:30–14:30           | W                    |               |                       |                      |

#### 2.4. Application of design rules

When designing a building within a urban block of a downtown area, the building mutually influences the street system and buildings located in the surrounding blocks in terms of sunlight hours. Where Building A is oriented south, east or south-east in relation to surrounding areas, as seen in Figure 4, the sunlight hours of Facades 1 to 6 of nearby buildings are affected by the

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**Figure 4.** The way of mass shaping in application of design rules in urban context.
mass newly created in Building A. Thus, in order to avoid the violation of sunlight hours for adjacent buildings, it is necessary to apply a design rule that removes parts of the mass in Building A by applying solar vectors corresponding to each azimuth angle set at Facades 2, 3 and 6 to each of Facades 1 to 6. For example, if the azimuth angle is 0° and Building A is a mass stretching along the east-west axis, no parts of the mass should exist within the three-dimensional shape created by solar vectors drawn from two vertices at the bottom of Facades 1, 4 and 5 to the solar position during the period between 11:30 a.m. and 1:30 p.m. when the azimuth angle becomes 0°. At the same time, for Facades 2, 3 and 6, the solar vectors are applied at the time period between 10:30 a.m. and 12:30 p.m. at the azimuth angle of −90°. Consequently, the mass of Building A is formed in a way that does not affect the standard of securing two hours of consecutive sunlight for Facades 1 to 6.

2.5. Content and usage of algorithm

In general, if a user provides the plan information about the layout, the height of a mass can be calculated at a level that meets the requirement for two hours of consecutive sunlight in order to configure the maximum size of the volume. As a result, the generated mass is set not only to secure two hours of consecutive sunlight for adjacent buildings in surrounding areas but also to consider the mutual interference of new masses to be drawn later. The algorithm also calculates other elements including the maximum height, floor area ratio, building coverage ratio, and number of floors in real time as well as sunlight hours, while instantly displaying the available sunlight hours by using a spectrum to express the sunlight hours for an exterior plane of the mass. The

**Figure 5.** Process of form generation.
volume, which is automatically produced at the maximum size based on the plan drawn, helps to create an optimal form in terms of the sunlight environment and the maximum density of development. As shown in Figure 5, the configuration and usage of the algorithm are as follows:

(1) The user establishes the scope of analysis and the azimuth angle of the site, and inputs basic data such as grid interval as an analysis unit, analysis date and location, site, street system, surrounding topography and geographical features, and adjacent buildings.

(2) The user creates a grid on the plan of the site and draws an approximate shape of the mass.

(3) As the mass's shape drawn on the plan is recognized, it is converted into a grid size measured to be the closest to the original, and adjacent parts that can be connected to each other are automatically connected, which completes the organization of the plan.

(4) The algorithm applied divides masses into two types, longitudinal and transverse types, and identifies the orientation of each mass depending on the site's azimuth angle. It recognizes a length that is longer by even a slight margin to be set as the orientation.

(5) Based on the organized plan, each mass can be configured in order to ensure at least two hours of sunlight for its orientation.

(6) Data on the building is calculated along with the formation of the mass.

(7) The location and shape of the mass is adjusted in reference to the spectrum of sunlight hours displayed on the surface of the mass generated through the algorithm.

The overall parametric algorithm structure is shown in Figure 6.

3. Results

3.1. Grid system and information on surrounding buildings

Since sunlight hours constitute a factor that is sensitively affected by external conditions of the site, it serves as the starting point to model surrounding conditions as precisely as possible. In an actual project, modeling should be conducted to reflect the actual surrounding environment. This study established a medium-sized block 150 meters long and 100 meters wide, which is suitable for both perimeter block housing buildings and high-rise tower buildings.

As the first step in setting a grid, a simple test was conducted on the width of the street outside of the block and the height of neighboring buildings, the results of which are shown in Table 3. In doing so, the prerequisite was to determine the width of the street to satisfy two hours of consecutive sunlight on the first floor without placing any further separation distance in the site at an azimuth angle of 0°, when the height of a neighboring building is set 15 meters. Based on the simulation results, the height of the adjacent building and width of the street were derived at 15 meters and 25 meters, respectively. The azimuth

![Figure 6. Overall structure of parametric algorithm.](image-url)
angle of 0° was set as the minimum standard, since neighboring buildings have a greater impact on securing the right to light in the site at an azimuth angle of 0°, compared to other azimuth angles. The household unit is oriented south-east at an azimuth angle of 0°, southeast-southwest at an azimuth angle of 30° and 60°.

In the sunlight spectrum, the blue portion signifies a minimum of two hours of sunlight hours and black portion indicates sunlight hours under 2 hours. At an azimuth angle of 0° and 60°, when the height of the surrounding buildings is 20 meters or higher, the condition of securing two consecutive hours of sunlight for the surrounding buildings is satisfied, but the buildings erected within the site begin to experience permanent shadows on their bottom floors due to insufficient distances from the buildings situated to the south. Therefore, in this case, in order to uphold the right to light from the first floor, the buildings are required to be laid out while securing greater distances to the north.

In the extreme case that the height of the surrounding buildings located to the south and east of the site reached 80 meters, it was found that the buildings adjacent to the site experienced problems with securing sunlight hours, and that the site became a permanently shadowed area. Thus,

| Height of Surrounding Buildings (South and East) | Azimuth Angle of 0° | Azimuth Angle of 30° | Azimuth Angle of 60° |
|-----------------------------------------------|---------------------|---------------------|---------------------|
| 15m                                           | ![Image](image1)     | ![Image](image2)     | ![Image](image3)     |
| 20m                                           | ![Image](image4)     | ![Image](image5)     | ![Image](image6)     |
| 80m                                           | ![Image](image7)     | ![Image](image8)     | ![Image](image9)     |

Table 3. Simulation results in relation with grid system and surrounding buildings at each azimuth angle.
in an actual situation where the height of the surrounding buildings is high, it is an important starting point for securing the right to light to find the appropriate location of the mass on the plan.

The shapes in the bottom row of Table 3 are the shapes of the surrounding buildings generated by proposed algorithm in which the buildings within the site can satisfy 2 hours of continuous sunlight for the main orientation of the buildings.

### 3.2. Impacts of surrounding buildings

Section 3.2 ascertained whether the algorithms operated appropriately by altering the length and location of the surrounding buildings, while keeping the height of the surrounding buildings and the width of the street unchanged. The previously set conditions of a street at 25 meters in width and surrounding buildings at 15 meters in height caused no problems in terms of securing the right to light for the south and east surfaces of the block. In this regard, each block to

| Azimuth Angle of 0° | B.C.R (%) | F.A.R (%) | Max. Height (m) | Azimuth Angle of 0° | B.C.R (%) | F.A.R (%) | Max. Height (m) |
|---------------------|-----------|-----------|-----------------|---------------------|-----------|-----------|-----------------|
| CASE 0              | 66.67     | 540.5     | 64              | CASE 1              | 66.67     | 609.63    | 88              |
| CASE 2              | 66.67     | 518.44    | 95              | CASE 3              | 66.67     | 629.89    | 64              |
| CASE 4              | 66.67     | 453.36    | 88              | CASE 5              | 66.67     | 460.19    | 64              |
| CASE 6              | 66.67     | 491.78    | 64              | CASE 7              | 66.67     | 490.8     | 64              |
the west and north of the site were altered to identify their impact on the buildings to be generated in the site. As shown in Table 4, Case 0 refers to a basic type where the basic shape was formed by the lines connecting from the bottom of the masses located in the northern and western sides to the solar position, which caused no problem related to ensuring sunlight hours for the surrounding blocks. In order to allow incoming sunlight to the southward façade of the northern mass facing the courtyard, the number of floors of the southern mass was adjusted. And to ensure sunlight hours for the eastward façade of the western mass, the corner where the southern mass and the western mass met was cut off.

Cases 1 through 4 divided the mass of the adjacent building to the north into two and shifted their locations. The results indicated that the farther to the north the adjacent mass was situated, the higher the height of the created mass became. In Cases 5 through 7, there were changes identified according to the varying distances between the relevant mass and the adjacent masses to the west. An increase in such distances could also raise the height of the generated mass.

### 3.3. Singular urban block

The design algorithms were utilized to apply different plans for the respective azimuth angles of 0°, 30° and 60°, and the results are described in Table 5. It was also possible to calculate and compare the building coverage ratio, floor area ratio, and maximum height during the mass formation process, while the height of buildings was limited to 100 meters.

An azimuth angle of 0° signified that the long side was at an angle of 0° and the short side was at −90°. At an azimuth angle of 30°, the long side was at 30° and the short side was at −60°. As described in Section 2.3, forms were created for each azimuth angle. The transverse mass and the longitudinal mass were formed using the solar vector in order to ensure two hours of continuous access to sunlight at different azimuth angles. Because it is practically impossible to ensure sunlight hours for all sides and orientations of a mass, this study aimed to set an orientation as described above and enable the side corresponding to the orientation to achieve sunlight hours.

The results indicated that an azimuth angle of 30° or 60° was more favorable than an azimuth angle of 0° in terms of the floor area ratio, and that the height and shape of the mass varied significantly even for the identical plan. This is because an azimuth angle of 30° or 60° had the advantage of upholding the right to light even with shorter distances between buildings and had less of an impact on surrounding masses, compared to an azimuth angle of 0°. The surrounding buildings of all types received sunlight continuously for two hours, and the orientation of the mass erected within the site satisfied the standard of two consecutive hours of sunlight.

Type 1 sets the building coverage ratio at 100 percent for the entire block, and can be regarded as the maximum volume that does not prevent the surrounding masses from receiving two hours of sunlight. This type provides basic information on the areas in which the highest height can be achieved within the site. The maximum height is 64 meters at an azimuth angle of 0° and 96 meters at other azimuth angles.

Types 2 through 5 show the necessity to ensure the right to light in blocks whose forms are created by the layout of linear, bar-type masses. The illustrated examples also outline the formation of masses in a way that secures two hours of continuous sunlight by setting the orientations at due south and due east at an azimuth angle of 0°, and at south-west and south-east at azimuth angles of 30° and 60°. The results from Types 2 through 5 demonstrate that an azimuth angle of 30° or 60° is favorable for attaining the volume in terms of floor area ratio, compared to an azimuth angle of 0°, and the floor area ratio varies depending on the plan forms.

Interestingly, Types 3 and 4 illustrate that even if the floor areas are identical, the floor area ratios greatly differ at the same azimuth angle when the plans face in opposite directions. This signifies that architects should weigh the advantages of different types of buildings in terms of solar access and floor area ratio at the design stages. Type 7 shows the results of the configuration of three towers in which the long side of the rectangle on the plan is set as the orientation. Architects first examine the automatically created mass based on the plan and adjust the design by moving, deleting and adding to the mass. The simplest way to conduct this process is to alter the plan values, instead of directly modifying the created mass.

### 3.4. Multiple urban blocks

#### 3.4.1. Four blocks

In this section, simulations were conducted at an azimuth angle of 0°, 30° and 60° to ascertain the formation of multiple blocks as shown in Table 6. The simulations examined how the mass of a block located to the rightmost bottom on the plan changed at different azimuth angles, and altered the shapes of the northern block and the western block, which influenced the shape of the relevant block, in consecutive order. Based on the characteristics of the algorithms, the four blocks were generated simultaneously in recognition of their orientations according to the plan forms.
Table 5. Simulation results with various plan shapes.

| Building Type | Azimuth Angle of 0° | Azimuth Angle of 30° | Azimuth Angle of 60° |
|---------------|---------------------|----------------------|----------------------|
|               | B.C.R. (%) | F.A.R. (%) | Max. Height (m) | B.C.R. (%) | F.A.R. (%) | Max. Height (m) | B.C.R. (%) | F.A.R. (%) | Max. Height (m) |
| Type 1        | 100       | 990.24     | 64              | 100       | 1421.91    | 96              | 100       | 1497.84    | 96              |
| Type 2        | 77.78     | 581.75     | 64              | 77.78     | 821.6      | 96              | 77.78     | 806.89     | 96              |
| Type 3        | 61.11     | 454.86     | 64              | 61.11     | 570.87     | 96              | 61.11     | 621.84     | 96              |
| Type 4        | 61.11     | 576.72     | 64              | 61.11     | 812.05     | 96              | 61.11     | 709.3      | 96              |
| Type 5        | 55.56     | 371.89     | 52              | 55.56     | 572.91     | 96              | 55.56     | 623.21     | 96              |
| Type 6        | 42.22     | 444.35     | 64              | 42.22     | 625.28     | 96              | 42.22     | 509.3      | 80              |
| Type 7        | 30        | 218.79     | 64              | 30        | 316.73     | 96              | 30        | 371.11     | 92              |
Table 6. Simulation results with four blocks.

| Plan | Azimuth Angle of 0° | Azimuth Angle of 30° | Azimuth Angle of 60° |
|------|---------------------|----------------------|----------------------|
|      | B.C.R (%) | F.A.R (%) | Max. Height (m) | B.C.R (%) | F.A.R (%) | Max. Height (m) | B.C.R (%) | F.A.R (%) | Max. Height (m) |
| R1   | 55.56     | 645.62    | 96              | 55.56     | 519.34    | 96              | 55.56     | 635.03    | 96              |
| R2   | 55.56     | 712.91    | 96              | 55.56     | 742.78    | 96              | 55.56     | 669.08    | 96              |
| R3   | 55.56     | 638.98    | 96              | 55.56     | 646.9     | 96              | 55.56     | 625.0     | 96              |
| S1   | 55.56     | 358.76    | 96              | 55.56     | 594.14    | 96              | 55.56     | 644.62    | 96              |
| S2   | 55.56     | 711.86    | 96              | 55.56     | 521.69    | 96              | 55.56     | 568.54    | 96              |
| S3   | 55.56     | 357.2     | 64              | 55.56     | 466.36    | 96              | 55.56     | 530.77    | 96              |
R1-3 and S1-3 had the same building coverage ratio overall. The right top and bottom blocks were fixed in R1-3, while the southern left and right blocks were fixed in S1-3. This experiment ascertained that changes in the surrounding forms altered the shape of the right bottom block. The resulting data derived from the right bottom block are exhibited on the Table 6.

According to the simulation results, despite the identical C-shaped plan opening toward the south, the form generated could differ depending on the surrounding masses. If the surrounding masses had a wider opening toward the right bottom block, an additional separation distance could be obtained, allowing the buildings to be higher.

### Table 7. Simulation results with nine blocks.

| Plan | Azimuth Angle of 30° |
|------|----------------------|
|      | B.C.R (%) | F.A.R (%) | Max. Height (m) |
| B1   | 45.43     | 511.82    | 100            |
| B2   | 45.43     | 533.12    | 100            |
| B3   | 28.15     | 423.23    | 100            |
| B4   | 28.02     | 496.34    | 100            |
3.4.2. Nine blocks

The following example in Table 7 was designed to test the algorithms on a large group of nine blocks at an azimuth angle of 30° and to examine the maximum level of density and the maximum number of floors when proposing street-oriented block housing. In addition, in order to allow the maximum height of the relevant buildings to increase, this experiment expanded the street and raised the height of the surrounding buildings. The width of the street (road) was set at 40 meters, and the height of the surrounding buildings was set at 20 meters. There was a gap in the maximum height of the buildings between the linear mass type (50 meters) and the tower type (100 meters).

B1 was designed to connect the exterior spaces of the building blocks to each other on the plan layout so as to improve the efficiency of the exterior spaces, which in turn led to an advantage in ensuring the height of the building blocks. As a result of the application of the algorithms, the maximum height was identified at 100 meters, and the surrounding buildings and the buildings within the blocks were able to satisfy the condition of securing a minimum of two hours of continuous sunlight in all orientations. B2 was designed to rearrange the corners and height of the mass generated in B1 and added a mass to the area where the two exterior spaces were connected, in a bid to identify the extent to which the floor area could be secured, which resulted in additional floor area of almost 20 percent.

B3 was intended to test a tower-type layout. The layout focused on ensuring sunlight hours of the exterior spaces by fully utilizing the characteristics of tower-type blocks, whereby three towers were alternately laid out in one building block. B4 also designed the same tower-type blocks, but their forms and layout were differentiated from those of B3 to raise the floor area ratio, which increased the floor area ratio by about 70 percent. This demonstrates that, even in identical tower-type blocks, it is necessary for architects to contemplate their forms and layout in consideration of ensuring sunlight hours for the exterior spaces and floor area ratio, as well as sunlight hours for the surrounding buildings and the buildings concerned.
4. Discussions

4.1. Characteristics of respective azimuth angles on the identical plan

The following Figure 7 summarizes the results of Types 1 through 7, which were created at each azimuth angle in a single block in Section 3.3. Because the plan forms by type are identical, the building coverage ratio of each type is the same. The building coverage ratio gradually decreases and the form becomes closer to the tower type from Types 1 through 7. The maximum height of the linear forms from Types 1 through 5 is higher at an azimuth angle of 60° than at an azimuth angle of 30°. As seen in Type 1, where the entire block is erected up, the maximum height is higher at an azimuth angle of 60°, and the range of higher floors is wider at an azimuth angle of 30°.

An azimuth angle of 0° is undoubtedly less favorable than other azimuth angles in terms of the floor area ratio. However, the mass forms differ depending on whether the azimuth angle is 30° or 60°. At a 0° azimuth, it is necessary to extend the distances between buildings for a south orientation to receive sufficient sunlight hours. Therefore, it is difficult to ensure density in the case of a mass whose width stretches from east to west, and the height matters in the case of a mass whose length stretches from north to south.

The application of the results of this study to urban planning indicates that, when a street system is established, an azimuth angle between 30° and 60° has an advantage in terms of the sunlight environment in comparison to an azimuth angle of 0°. Aside from density, at an azimuth angle of 0°, the other side of a building has an azimuth angle of −90° due to orthogonality. Under this condition, the east-facing building is able to receive up to 2.5 hours of sunlight a day, which satisfies the standard of two consecutive hours of sunlight, but it is difficult to obtain longer sunlight hours.

As Type 1 is practically impossible to create without an atrium, it was designed to examine the maximum volume formation. In reality, Types 3 and 5, with an opening toward the southern exterior space, are favorable compared to other types in terms of solar access of the exterior space as well as density. The masses generated by the algorithms established in this study can ensure higher density and two hours of continuous sunlight or longer on the winter solstice, demonstrating that high density can be ensured even through an environmental performance-based design.

4.2. Results of comparison with a single-height building mass in terms of the sunlight environment

This section compared the mass forms generated in Section 3.3 and 3.4.2 with a general single-height building mass in order to understand the extent of the impact yielded by each mass type. This comparison enabled the examination of the practical efficiency of the algorithms suggested in this study. For the comparison, a single-height building with the identical building coverage ratio and floor area ratio as the type suggested by the algorithms was created for each type and each azimuth angle. Subsequently, this study calculated and compared the unsatisfactory level for the condition of two consecutive sunlight hours for the orientation of the relevant building mass and those of the surrounding buildings affected by the relevant mass. The following Figure 8 shows the scope for the analysis of the orientation of the created building mass and those of surrounding buildings.

4.2.1. Singular block of single-height building mass

In this section, a number of floors that can ensure an identical floor area to the building mass generated by the design algorithms referred to in Section 3.3 was calculated based on the building coverage ratio and floor area ratio of the relevant building mass. The number of floors was determined by rounding off its value, and a single-height building mass with a similar floor area ratio to that of the form generated in Section 3.3 was created on the basis of one floor with a height of four meters. No shadows were cast on the front façade of the newly created mass, due to
### Table 8. Simulation results of single-height building mass (Singular block).

| Plan   | Azimuth Angle of 0° | Azimuth Angle of 30° | Azimuth Angle of 60° |
|--------|---------------------|----------------------|----------------------|
|        | Un satisfactory level (%) | Un satisfactory level (%) | Un satisfactory level (%) |
|        | Building Height (m) | Building Height (m) | Building Height (m) |
| Type 1-F | 15.57 | 40 | 10.64 | 48 | 13.44 | 60 |
| Type 2-F | 16.98 | 28 | 19.87 | 40 | 14.84 | 40 |
| Type 3-F | 13.49 | 28 | 10.61 | 36 | 15.86 | 40 |
| Type 4-F | 10.03 | 36 | 11.52 | 52 | 9.93 | 48 |
| Type 5-F | 11.86 | 28 | 7.93 | 44 | 8.05 | 44 |
| Type 6-F | 8.59 | 44 | 4.33 | 60 | 7.54 | 48 |
| Type 7-F | 6.67 | 28 | 3.33 | 44 | 2.81 | 48 |
the street system and the height of the surrounding buildings at an azimuth angle of 0°, which is the most unfavorable in terms of sunlight hours. Therefore, it is necessary to examine a portion of unsatisfactory sunlight resulting from changes caused by the created mass in sunlight hours for the rear façade of the building, as well as the part receiving unsatisfactory sunlight due to the self-shadowing on the mass formed in the building block. As shown in Table 8, from Types 1-F through 7-F, the building coverage ratio decreased and the unsatisfactory level of sunlight declined. When there was a long mass located to the south, it caused self-shadows, thereby increasing the permanently shadowed area. Overall, when the surrounding masses located to the rear are taken into account, the unsatisfactory level of sunlight ranged from 2.81 percent to 19.87 percent, which greatly differed from the type outlined in Section 3.3 that satisfied sunlight-hour requirements for every household.

4.2.2. Multiple blocks of single-height building mass

This section compared the four building masses generated at an azimuth angle of 30° and a single-height building mass with the identical building coverage ratio and floor area ratio, and the results are shown in the following Table 9. The results of multiple building blocks were similar to those of the single mass: The unsatisfactory level of sunlight for tower-type masses ranged from 2.03 percent to 4.15 percent, while that of linear masses ranged from 4.10 percent to 7.45 percent. This proved the utility of all the masses created by the algorithms, since they were able to ensure two consecutive sunlight hours, regardless of singular or multiple blocks.

5. Conclusion

This study developed a design tool intended to suggest mass forms that can satisfy the standard of two consecutive sunlight hours on the winter solstice and achieve the maximum floor area ratio by identifying the relations between the relevant mass and surrounding buildings within and outside of the building block, based on the plan created by an architect in line with design concepts at the initial stages of a construction project. In the design algorithms developed in this study, the architect outlines a mass on a plan in a grid system, and the algorithms identify the width and length of the relevant mass and set the longer part as its orientation. The orientation of each household is set to the direction faced by the living room as the biggest space that can receive the most amount of incoming sunlight as well as the hub of indoor residential life. The orientation of each building mass is set to the south or the east at an azimuth angle of 0° and shifts towards the south-east or the south-west.

| Azimuth Angle of 30° | Unsatisfactory level (%) | Building Height (m) | Azimuth Angle of 30° | Unsatisfactory level (%) | Building Height (m) |
|----------------------|--------------------------|---------------------|----------------------|--------------------------|---------------------|
| B1-F                 | 7.45                     | 44                  | B2-F                 | 4.10                     | 44                  |
| B3-F                 | 2.03                     | 60                  | B4-F                 | 4.15                     | 72                  |

Table 9. Simulation results of single-height building mass (Multiple blocks).
according to changes in azimuth angles. Upon determining the side that is required to receive two hours of consecutive sunlight in relation to the surrounding buildings and the mass created within the site, the bottommost vertices of the relevant side are linked to the position of the sun for the relevant two-hour period to create a three-dimensional shape. As the relevant mass is intersected by using the three-dimensional shape, sunlight hours can be ensured for the two hours concerned. In a bid to verify the design algorithms developed in this study, a variety of simulations were conducted, encompassing from buildings within a single block to nine multiple blocks on the basis of three azimuth angles. The outcomes generated by the simulations were able to meet the standard of two hours of consecutive sunlight, ensure sunlight hours for the adjacent buildings, and enable high-density development. Despite disparities based on type, an azimuth angle of 30° or 60° appeared to be more advantageous in term of the sunlight environment than an azimuth angle of 0°, which made it easier to achieve density. In comparison with a single-height building under the condition of equal density, all seven types of buildings (Type 1–7) showed an improvement of the sunlight environment at an azimuth angle of 0° (6.67 percent to 16.98 percent), an azimuth angle of 30° (3.33 percent to 19.87 percent) and an azimuth angle of 60° (2.81 percent to 15.86 percent). Moreover, the simulations on nine blocks at an azimuth angle of 30° indicated that the sunlight environment of four types (B1-4) improved at a range between 2.03 percent and 7.45 percent. Consequently, the design algorithms utilizing the design rules suggested in this study for the sunlight environment were ascertained to be considerably effective as an assistive tool for architectural design. This study conducted modeling by producing three-dimensional forms based on the height of the cross-section of the plan and cutting their upper parts through the application of design rules with the aim to ensure two hours of natural sunlight. This study, however, focused largely on three-dimensional forms extending vertically as its basis. A follow-up study should develop a methodology in which forms can be produced in a more three-dimensional way by manipulating plan forms that are at different azimuth angles from the azimuth angle of the site, while adding openings or adjustments of cross-sections, based on the design rules established in this study.

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