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Building Mass Optimization to Reduce Solar Radiation in High Rise Building by Using Parametric Approach

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Abstract

Buildings use 40% of global primary energy, therefore their design and use affect climate change. Building performance analysis can assist architects predict performance before construction with parametric design tools. Radiance can be reduced via a parametric mass, lowering cooling load and energy use. The study uses theoretical and computational research to explain, forecast, and analyze events, whereas parametric design optimizes complicated geometries using mathematical parameters and algorithms. Environmental analysis in Grasshopper with the Ladybug plugin uses Rhinoceros. This plugin provides solar radiation, and climate analysis capabilities. To determine the most energy-efficient building design, the research links independent and dependent variables such solar radiation intensity and building mass. The study uses Surabaya weather data and high rise buildings. The land is formed like a square, with a 15-degree slope to the north and is flanked by low-rise buildings. As a result, the location receives the most direct sunlight during the day. Then, solar radiation analysis. It helps optimize passive solar design solutions. According to the modelling results, solar radiation on the top and west sides are particularly large and dominant in 65.37 and 32.69 kWh/m^2. Meanwhile, the north, east and south sides receive very little solar radiation. The following simulation considers the optimal direction, which is to extend west-east and face to the south. A multi-towered megastructure is a high-rise building that responds best to solar radiation. The total solar radiation value is 3,718,100 kWh. It can accommodate large spaces with large mass composition but relatively low total solar radiation values. The building towers provide shade to each other, thereby reducing direct radiation from the sun to the building. The sides of the building's podium are also shaded, so the top of the building is partially red.

INTRODUCTION

Global warming and climate change are two major problems currently confront our planet. If the current rise continues, global warming is expected to exceed 1.5°C by 2030-2050. It is called The Urban Heat Island (UHI) effect. A phenomenon in which all parts of the planet experience increased temperatures. They come from increasing energy use and pollution. (Ricci et al., 2021)

Buildings consume 40% of total primary energy worldwide. As a result, the design and usage of buildings significantly impact mitigating the effects of climate change. (Ricci et al., 2021) Minimizing energy usage is critical, especially given the amount of power consumed. Air conditioning consumes a substantial amount of electricity. (Salim et al., 2020) This is especially important in tropical climates, where cooling loads are significant. (Golzan et al., 2023)

The building envelope is critical for controlling heat transmission between the inside and outside environments. (Ricci et al., 2021) Regarding energy usage, the skin façade plays a vital role in improving interior environmental conditions. (Golzan et al., 2023) Several climatic zones and season studies have indicated that green walls (GWs) have the ability to save energy, improve the thermal environment, provide noise insulation, reduce dust, and promote biological variety. (Lin et al., 2023) A building's energy use is substantially influenced by its form, too. Building orientation can lower the cooling load by limiting solar penetration and absorbing it through windows, walls, and roofs. (Jalali et al., 2020) The necessity of good shading strategies has been highlighted in architecture. These components are necessary for high-performance architecture. (Goharian et al., 2022)

Daylighting design is also an essential part of building systems. It uses measurements to determine how much of a building's illumination requirements may be met exclusively by daylighting. (Panya et al., 2020) A sun-based façade model idea must be created to adapt to variations in daylight direction. This allows the facade to be partially closed during peak hours and receive more natural light during off-peak hours. (Ozerol Ozman & Arslan Selcuk, 2023) Several variables, such as time of day, season, latitude, and weather conditions, influence how much solar radiation reaches a specific location on the Earth's surface. Solar radiation may significantly affect how energy-efficient and pleasant a structure is, particularly in architecture. Buildings can utilize solar energy for illumination. However, much sunlight can produce warmth, necessitating the usage of air conditioning. As a result, when designing, it is critical to consider how solar radiation may affect the finished product carefully.

Because of their size and density, high-rise constructions require a lot of energy. (Wang et al., 2016) Solar radiation has a significant impact on the energy efficiency of tall buildings. A building's orientation may significantly influence the amount of solar heat gain it gets, determining how much heating and cooling it requires. A well-oriented structure may reduce solar heat gain, reducing air conditioning demand. (Lee et al., 2014) High-rise structures can dramatically minimize their energy consumption and environmental effects by considering variables including building orientation, envelope design, and energy-efficient equipment.

Building performance analysis helps architects to predict building performance before it is constructed. (Khidmat et al., 2020) The usage of parametric design technology may be the solution to this problem. This technique allows architects to conduct multiple interactions and track modifications, resulting in a better final design. A parametric facade technique can significantly reduce irradiance, lowering the cooling demand and, thus, energy consumption. (Salim et al., 2020) This approach allows for investigating several objectives at once and generating many optimal alternatives between the two extremes of each target. (Pilechiha et al., 2020) The Ladybug tool, a Grasshopper plug-in program for environmental design applications, may be used in the early design phase to generate environmental data. Automated optimization and building simulation are powerful tools for evaluating various design possibilities. (Jalali et al., 2020)

Despite extensive studies on the link between building design, energy efficiency, and parametric design, specific research gaps remain. Much of the research is focused on case studies. The ability to generalize findings to a broader situation may be limited since case studies often focus on a single or a small number of objects. Case studies are frequently complex and contextualized, making it difficult for other researchers to replicate the study and corroborate the findings. As a result, the aim of this study is theoretical inquiry into the interaction between building façade, energy efficiency, and parametrics. It is significant because theoretical study offers a complete understanding of concepts and events. It helps explain why specific results occur and can provide a basis for understanding complex operations. Theories may guide empirical research by providing a framework for creating hypotheses and examining outcomes.

Theoretical research on building mass design, solar radiation, energy efficiency, and parametric design has greatly benefited the development of simulation-based design methodologies. The significance of building mass has been demonstrated through theoretical studies. The outer design of a building influences its energy efficiency in two ways: thermal comfort and natural light. The building facade is an essential aspect of energy-efficient architecture. Theoretical research has also resulted in the creation of simulation tools to assess and anticipate the performance of various design alternatives. They may be combined with parametric design approaches to improve the energy efficiency of building facades and other structural elements. Finally, theoretical research has provided simulation-based design methodologies in buildingdesign, energy efficiency, and parametric design with the necessary fundamental knowledge and resources. These technologies enable architects and designers to develop structures that are not only visually appealing but also ecologically and energy-efficient.

METHODS

Theoretical and Computational Research

The research being conducted here is theoretical and computational. Theories are developed in theoretical research to explain, predict, and comprehend events. Because theoretical research frequently employs logical reasoning, it may be built upon a computational research framework. This theoretical examination will be processed via computational research. This necessitates using computer simulations and models to evaluate complicated systems that would be difficult or impossible to investigate directly via experiments. Computational research may be used to explore how systems behave under different situations and develop new theories.

Parametric Approach

The parametric method, widely used in design and architecture, includes manipulating and optimizing complex shapes using mathematical parameters and algorithms. This technology permits the creation of adaptive and flexible designs that are easily modified by changing the input parameters. Using parametric design tools, designers may create various facade designs and assess their efficacy under varied scenarios.

Rhinoceros with Ladybug Plugin as a Tool

Rhinoceros is a 3D computer graphics and computer-aided design (CAD) application software, sometimes known as Rhino. Because of its versatility and broad capabilities, it is widely used in architecture, industrial design, and product design. The Ladybug Rhino plugin enables environmental analysis in the Rhino/Grasshopper environment. It includes a suite of tools for energy modelling, daylighting analysis, solar radiation analysis, and climatic analysis. Ladybug creates accurate and detailed environmental simulations utilizing meteorological data, which may be used to inform and enhance design decisions. When coupled, Rhino and the Ladybug plugin provide an effective tool for ecologically responsible and resource-saving design. These tools allow designers to create complex 3D models in Rhino, which can be analyzed and improved for environmental performance using Ladybug.

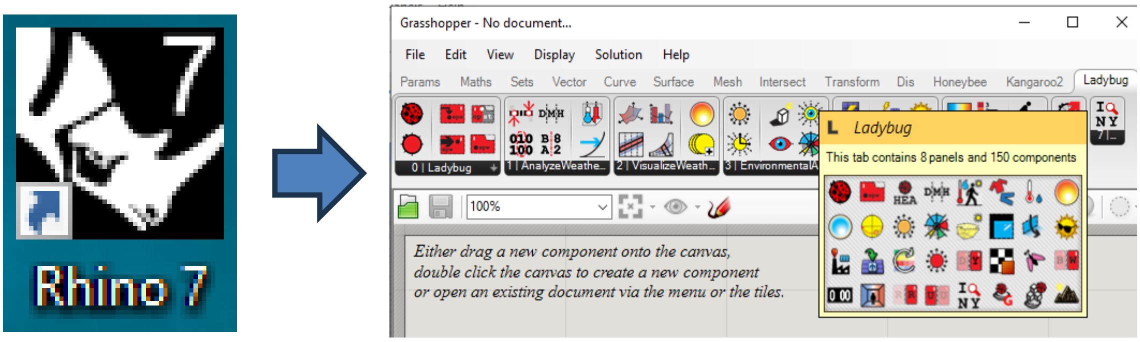


Fig. 1. Rhinoceros with Ladybug Plugin as a Tool
(Source: author)

Parametric Approach

The steps used to perform a simulation to achieve the study aims are as follows:

a. Site Analysis
Analyzing direct sunlight on the site by inputting climate data location.

b. Solar Radiation on Building Mass
  (1) Import climate data location
  The EPW location import component compensates for the local climate in the region selected using the website https://www.ladybug.tools/epwmap/.
  (2) Create a sky matrix
  The skymatrix component displays the sky conditions based on the month, day, and hour. In addition, this element is responsible for determining the location's coordinates.
  (3) Time Analysis
  Analysis of time, often known as time or period, is a component that governs the months, days, and hours so that the generated environment represents current time-based situations.
  (4) Incident Radiation
  Incident Radiation links elements in the Grasshopper software and objects in the Rhinoceros program and the output of the Grasshopper components.

Scope of Research

This study aims to establish a relationship between the independent and dependent variables. Solar radiation intensity is the fixed variable, measured in kWh/m2. The independent variables are mass of the building. It is finding the best building design based on the criteria above that reduces the transmission of solar radiation to the building surface. The following are some of the research limitations: high-rise structures and meteorological data from Surabaya.

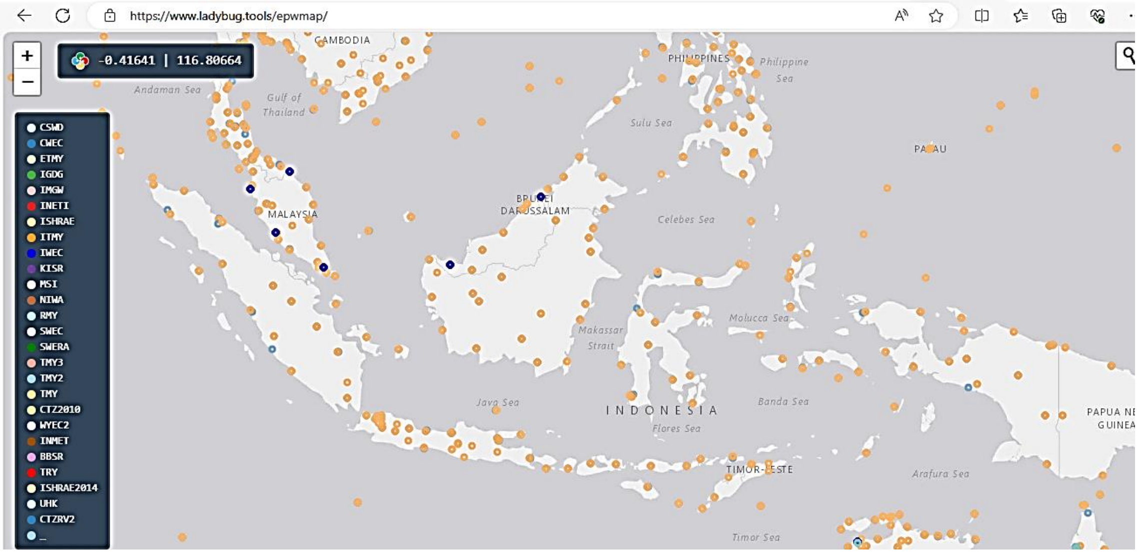


Fig. 2. EPW Map of Indonesia
(Source: author)

RESULTS AND DISCUSSION

Site Analysis

The site chosen for the high-rise building design simulation is located in the city of Surabaya. The site has a land area of 25,275 m2, shaped like a square, with a slope of 15 degrees from the north. (Fig. 3) Because the land is surrounded by low-rise structures, solar radiation has no barrier to penetrate.

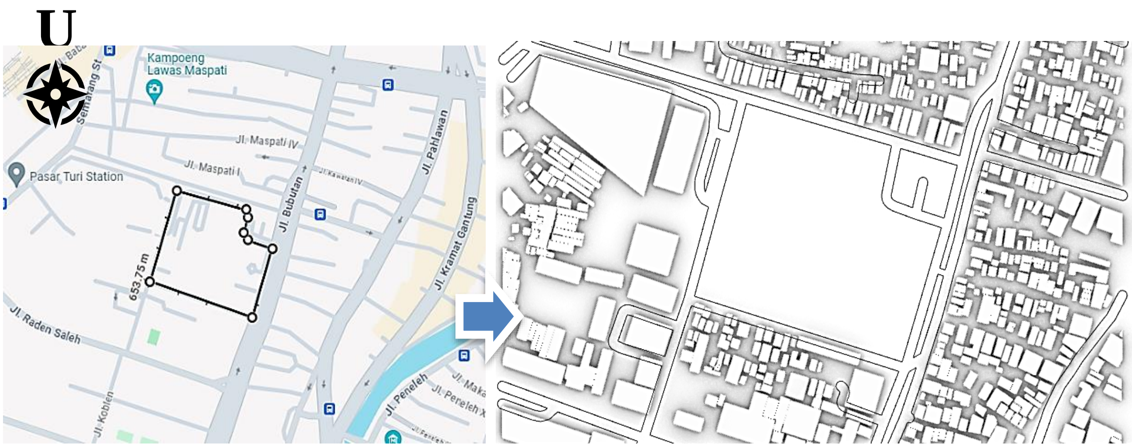


Fig. 3. Site for Design Simulations
(Source: author)

Understanding the site's qualities allows designers to adapt their concepts to take advantage of the natural features. Fig. 4 and 5 illustrate site analysis. Location study focuses on how direct sunlight interacts with the location. Understanding the sun's path during the day and finding which areas of the site receive direct sunlight and for what duration. Fig. 3 depicts the algorithm, and Fig. 4 illustrates the simulation outcome.

The site simulation results indicate yellow results on every side of the site. This means that the place receives the most direct sun energy throughout the day.

This location offers enormous potential for harvesting solar energy, particularly through the installation of solar panels or solar thermal systems. With significant sun radiation throughout the day, the potential energy that may be generated is quite high. While maximal sun radiation is helpful for energy efficiency, it must also be addressed for thermal comfort. Intense sun radiation can induce overheating within structures or open areas, necessitating careful planning measures to reduce the danger of overheating. Buildings in these locations must consider orientation, natural lighting, and other passive measures to maximize comfort and energy efficiency. Designs that use sunlight can help lessen the demand for artificial heating and cooling. It is also critical to consider visual balance. Excessive direct sunlight may cause glare or visual discomfort for site visitors.

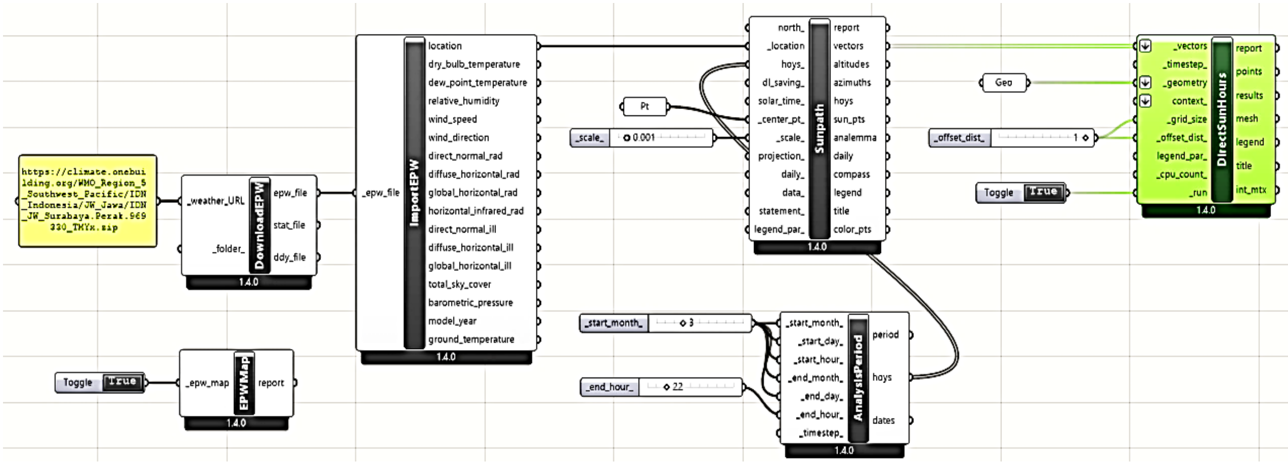


Fig. 4. Algorithm for Site Analysis
(Source: author)

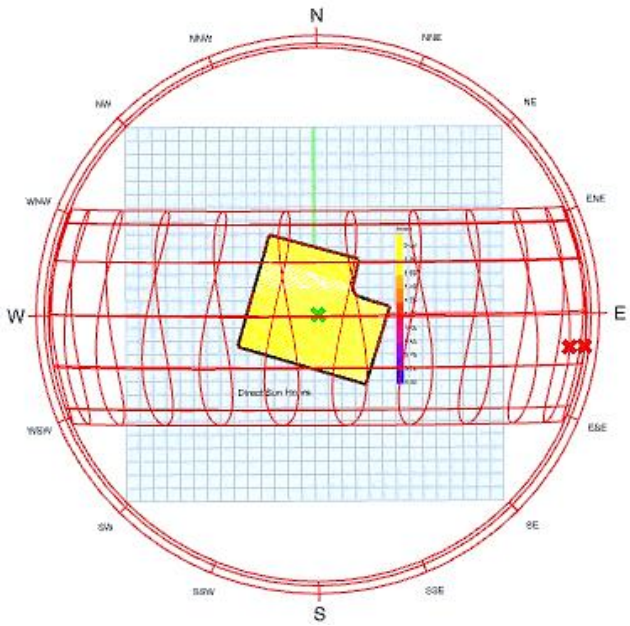


Fig. 5. The Simulation of Direct Sunlight on The Site
(Source: author)

Solar Radiation on Building Mass

Orientation

Solar radiation analysis helps optimize passive solar design solutions. Understanding the sun's course during the day and throughout the seasons allows designers to optimize or reduce solar exposure as needed for cooling and daylighting. The algorithm for assessing solar radiation on building mass is developed by entering data about the period of solar radiation from the chosen climate area (Fig. 6).

The sky dome symbolizes the visible hemisphere of the sky and is an essential concept in architectural design for studying daylighting and solar exposure within structures. The simulation results found that the areas with the highest solar radiation were in the west and east areas. This is indicated by the simulation results, which are dominated by orange and yellow. The simulation runs throughout the year, from January 1 to December 31. The simulation runs between 06.00 and 18.00 when the sun is most visible.

As illustrated in Fig. 7, when the simulation results are blue, it indicates that the level of solar radiation on the building is relatively low. When the simulation results show red, the building receives high solar radiation. This image also shows that the sides of the sky dome, if traced from those with the lowest solar radiation, are the south, north, east, and west sides.

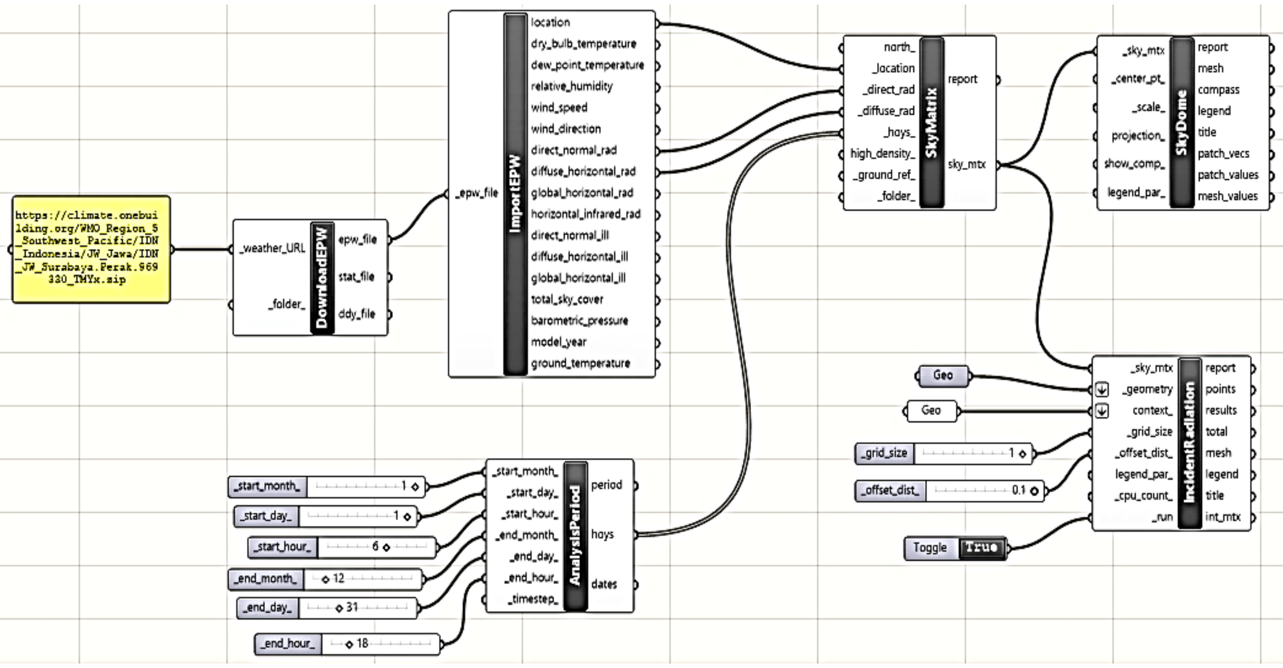


Fig. 6. Algorithm for Solar Radiation on Building Mass
(Source: author)

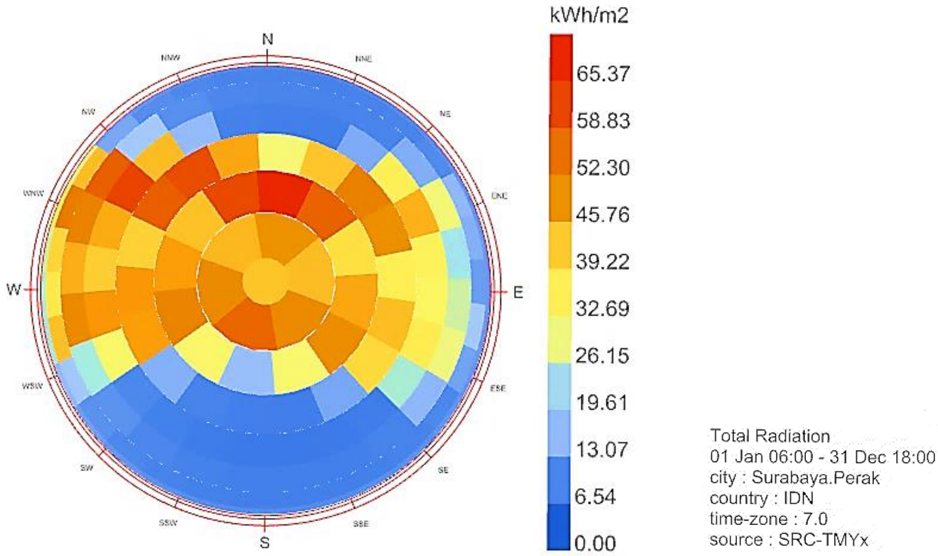


Fig. 7. Sky Dome on The Location
(Source: author)

The simulation was run to get a more particular analysis by changing the direction of the building mass on the site. The simulation used four different orientation directions to determine the pattern of solar radiation levels on the building mass. This is seen in Table 1.

The simulation findings in Table 1 are identical to those of the sky dome simulation in Fig. 7. The top side receives the most solar radiation from the five sides of the simulated high-rise building. The west side comes next. Meanwhile, the north, east and south sides receive very little solar radiation. Either of the four simulated orientation directions produces the same color on either side. Table 2 displays the solar radiation for each side of the simulated building.

Solar radiation levels vary on each side of the building. When the figures in Table 2 are converted to percentages, solar radiation on the top and western sides is extremely big and dominant. On the north side, solar radiation comes after the new third level. As a result, the building's east and south sides get the least amount of solar radiation. Because the top, west, and north sides get the most solar radiation, reducing the building's orientation toward these directions is critical.

Table 1. The Simulation of Solar Radiation Levels on The Building Mass

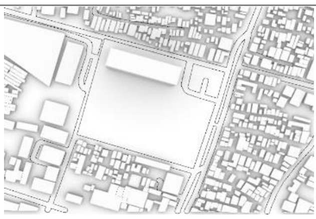
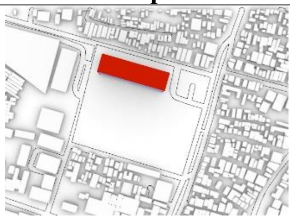
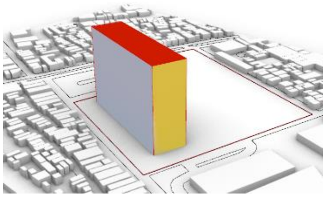
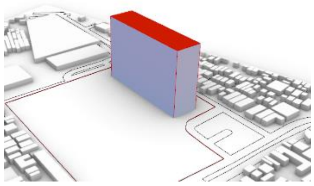
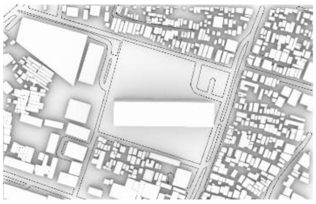
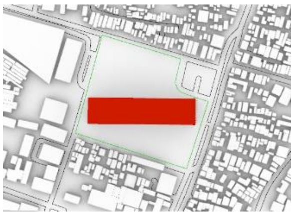
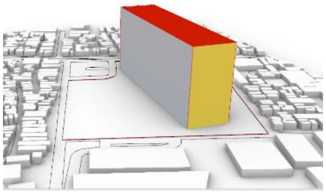
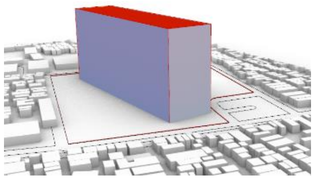
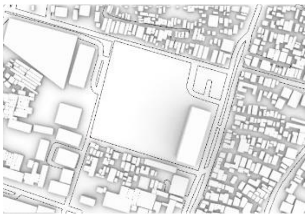
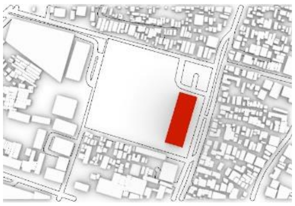
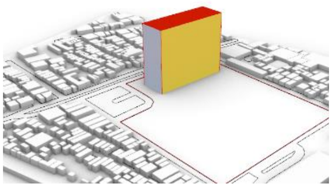
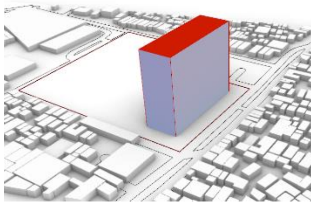
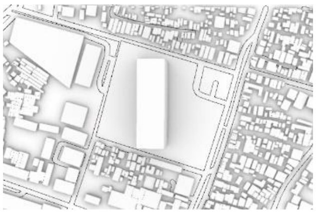
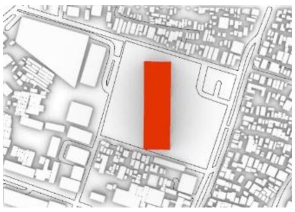
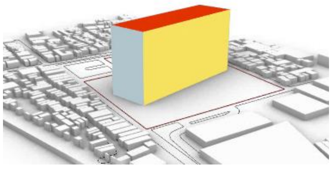
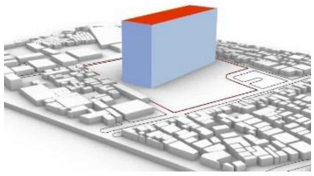
No	Orientation	Top	North & West	South & East
1				
2				
3				
4				

Table 2. Solar Radiation Value for Each Side of the Building

No.	Side of The Building	Simulation Color	Score (kWh/m^2)
1	Top		65,37
2	North		19,61
3	West		32,69
4	South		6,54
5	East		13,07

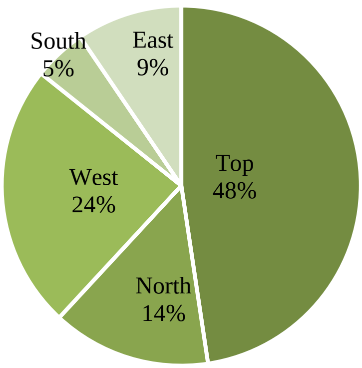


Fig. 8. Percentage of Solar Radiation Value on Each Side of the Building
(Source: author)

Massing

In the design of high-rise building, four typologies are frequently used : mixed-use building tower, multi-towered megastructure, freestanding structure with pedestrian connection and combination. Based on this, Ladybug simulates the efficiency of building masses to reduce solar radiation. The following simulation takes into account the optimal direction, which is to extend west-east and facing to the south. The majority of the building's sides face north-south, which is in line with the simulation results in Tables 1 and 2. Because the next simulation has a more complex structure to be measured, it not only displays the colour but also graphic charts and mathematical numbers of the level of solar radiation. Fig. 9 shows an algorithm for counting solar radiation on building mass.

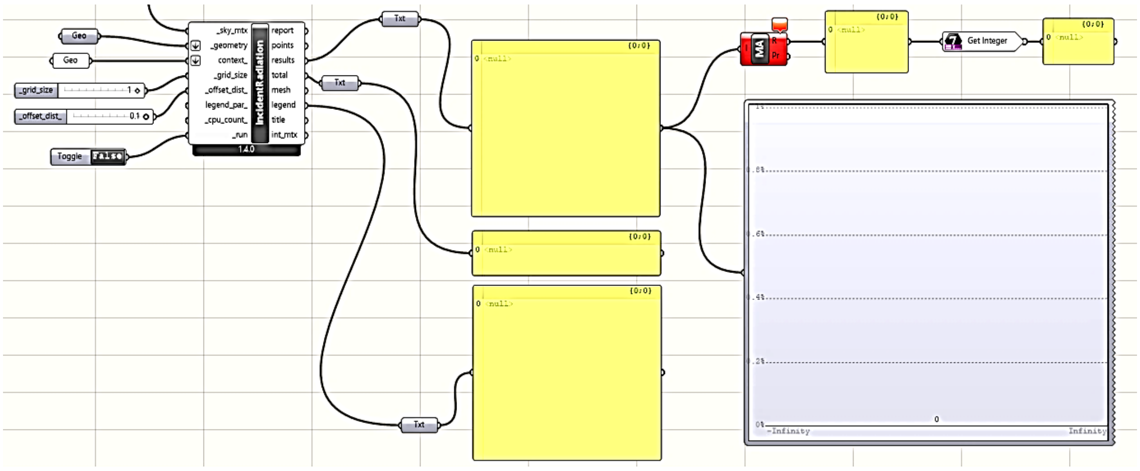


Fig. 9. Algorithm for counting solar radiation on building mass
(Source: author)

Table 3. The Simulation of Solar Radiation Levels on The Four Typologies of High Rise Buildings

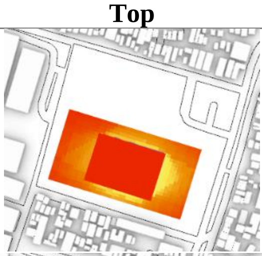
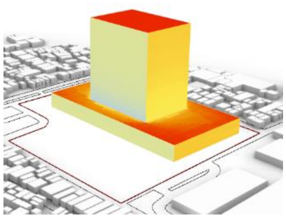
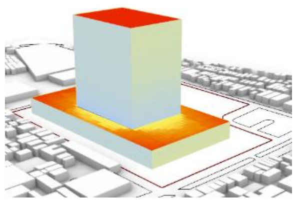
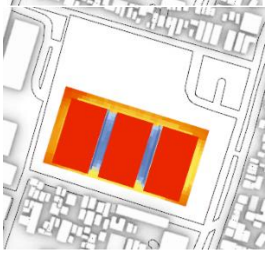
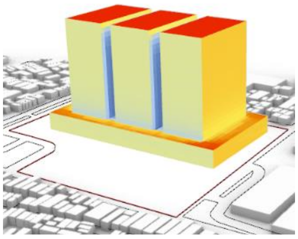
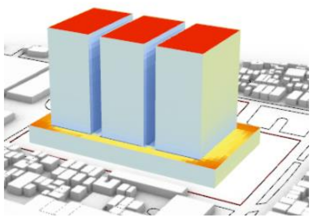
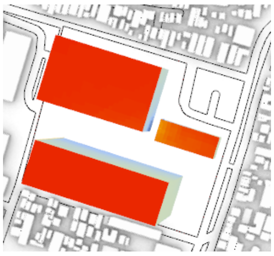
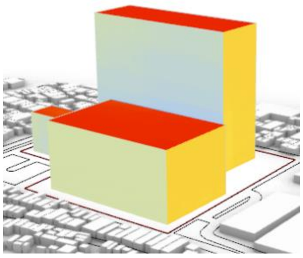
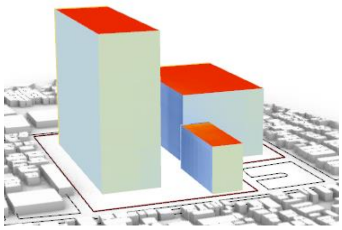
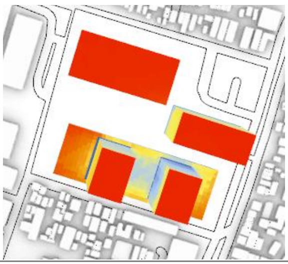
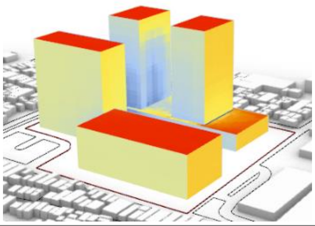
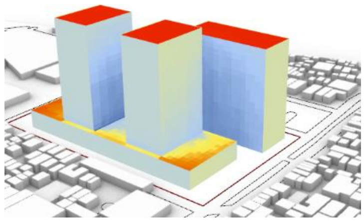
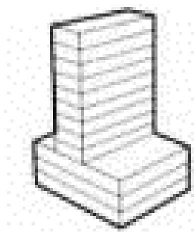
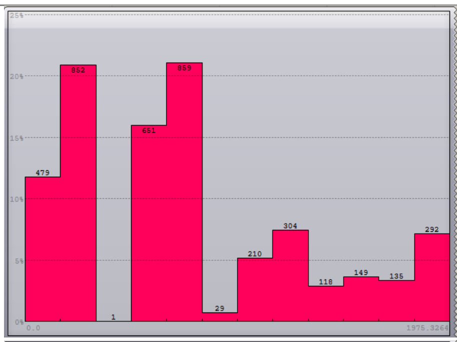
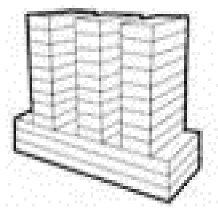
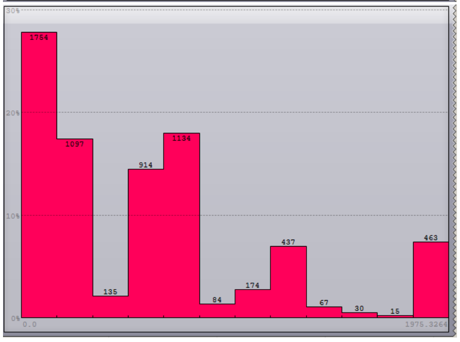
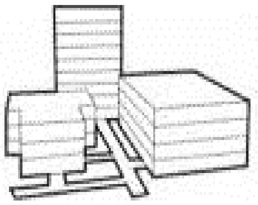
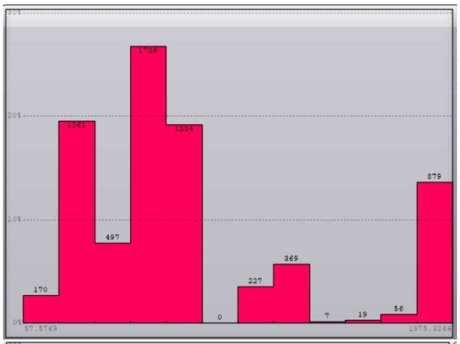
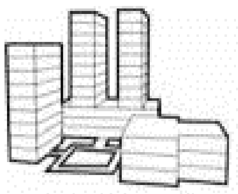
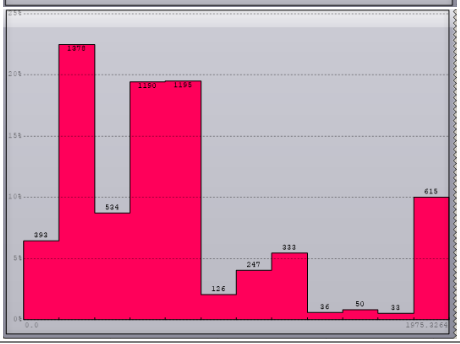
No	Typology	Top	North & West	South & East
1	Mixed-use building tower			
2	Multi-towered megastructure			
3	Freestanding structure with pedestrian connection			
4	Combination			

Table 3 presents the simulation findings for the four high-rise building typologies. The data presented focuses on colour visualizations that depict the amount of solar radiation on the building. Because the form is more complicated than the geometric composition in Table 1, several colour gradations were seen due to shadowing in the simulation.

Table 3 displays modelling results for the top, north & west, and south & east sides. The numbers shown for each colour still refer to the information in Fig. 7. Table 3 confirms what Table 1 found: the top side of the building is always red. It shows that there is very high solar radiation at the top. However, this does not apply to the building's roof side, which has become the podium of the high-rise building. Due to the shadowing from the taller towers, some sides of the roof are orange, yellow and even blue. It shows a decrease in solar radiation in the shaded area.

Table 4. The Simulation of Solar Radiation Levels on The Building Mass

No	Typology	Illustration	Bar Graph	Solar Radiation Total (kWh)
1	Mixed-use building tower			3.134.200
2	Multi-towered megastructure			3.718.100
3	Freestanding structure with pedestrian connection			5.227.800
4	Combination			4.394.200

Simulation results on the west and north sides also show the same thing. In the simulation of these four buildings, west and north sides still have the second and third highest solar radiation, indicated by the appearance of yellow, and light green. On the other hand, the east and south sides are the areas with the least amount of solar radiation. Shading from the other side of the building also contributes to reducing solar radiation. It is characterized by the appearance of a darker blue colour in the shaded area.

The simulation results in Table 3 are quantified into graphic chart information to calculate the total value of solar radiation hitting the building. It is shown in Table 4. The apparent graphic chart is divided into 12 levels of solar radiation values. The colour dots that appear from each m2 of the building are grouped into 12 levels by the ladybug system (x axis). Next, calculate the frequency of occurrence (y axis).

The 12 levels of solar radiation in issue range from 0.00 to 1975.33 kW/m^2. The left side bar begins at 0.00 kWh/m2, and the right side bar ends at 1975.33 kWh/m^2. Of the four high-rise building typologies in Table 4, the multi-towered megastructure typology receives the most frequency of solar radiation with a low level of value, but the frequency of high solar radiation values is shallow. On the other hand, the freestanding structure with pedestrian connection typology gets the most sun radiation and has a high degree of value. In contrast, the frequency of low solar radiation values is minimal.

The total solar radiation value is shown in the rightmost column, and it is calculated by multiplying solar radiation values by the frequency or number of sites that have that radiation value. This number comes out automatically from the algorithm, which results in Ladybug. The mixed-use building tower has the lowest overall value because of its tiny proportions. Even though the combination type high-rise building appears to have the most significant dimensions, this does not necessarily imply that it has the highest overall solar radiation value. The Freestanding structure with pedestrian connection type building has the highest total solar radiation rating. This is because this freestanding structure with pedestrian connection type building contains several sites with moderate solar radiation, as seen in the graph. The building receives a lot of mild radiation since it has numerous huge regions at the top that get minimal shade from the rest of the structure. Aside from that, the west and north sides have a high level of radiation. As a result, the overall amount of solar energy that emerges increases significantly.

CONCLUSION

According to simulations, Surabaya locations receive significant direct sun radiation, mainly if the surrounding region is densely populated with low-rise buildings. Because the sun shines all day, with varying solar radiation levels depending on time and orientation, it is critical to make the correct decision. It can impact the energy required for air conditioning to overcome the presence of solar heat that strikes the building facade. According to the findings of Surabaya simulations, it would have a highly positive impact if the building was orientated longitudinally in a west-east orientation, with the front mainly facing south rather than north. The multi-towered megastructure type is the best for mass composition for high-rise buildings. It can accommodate large spaces with large mass composition but relatively low total solar radiation values. The building towers provide shade to each other, thereby reducing direct radiation from the sun to the building. The sides of the building's podium are also shaded, so the top of the building is partially red. On the other hand, the freestanding structure with pedestrian connection type is the least effective because it creates many building masses separated by large distances, so they do not provide shade for other buildings on the site. It makes a massive solar radiation reception in each building on each side.

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