

Assessing the Effects of Building Mass Configuration and Form on Solar Radiation Gain: A Hypothetical Study

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ABSTRACT

Urbanization has continued to grow from year to year, leading to one of its major impacts—the rising population in urban areas. This population increase is directly proportional to the growing demand for housing, which in turn drives up property prices. Therefore, government support in the form of subsidized housing for low-income communities (MBR) becomes essential. However, subsidized housing is often criticized by the public for its unsatisfactory quality. Moreover, the development of such housing is feared to exacerbate the ongoing issue of global warming, as it has the potential to increase ambient temperatures in residential areas. The objective of this study is to identify the influence of changes in building mass configuration and form on the reception of solar radiation at outdoor site surface. A quantitative research method was applied by simulating hypothetical building mass models of subsidized housing using Rhinoceros – Grasshopper – Ladybug software. The findings indicate that modifications in building mass configuration and form can reduce the amount of solar radiation received by outdoor site surface. On sites oriented west–east, the best case modification was able to reduce radiation values by up to 32.5% compared to the base case, while on sites oriented north–south, the most effective modification achieved a reduction of up to 25.3% compared to the base case.

Keywords:

Mass Configuration
Mass Form
Solar Radiation
Ladybug
Subsidized Housing



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1. Introduction

Urban development, particularly in major cities, directly influences population growth and the expansion of urban activities [1]. This phenomenon, commonly referred to as urbanization, continues to shape demographic and spatial dynamics in Indonesia. According to [2], the proportion of the population residing in urban areas is projected to exceed half of the national total by 2035, reaching approximately 66.6%. The increasing urban population inevitably drives higher demand for housing, while simultaneously intensifying land requirements for residential purposes. This pressure often leads to escalating land and property prices in urban centers [3]. Rising costs disproportionately affect low-income households, making it difficult for them to access adequate housing. To address this challenge, government intervention has become essential, particularly through subsidized housing programs. For low-income groups, such

programs serve as a critical avenue to achieve homeownership at affordable prices [4]. However, the provision of subsidized housing faces significant challenges beyond affordability, especially concerning construction quality and thermal comfort. These issues are frequently overlooked as the primary focus remains on cost reduction. Studies highlight that many subsidized housing projects are criticized for substandard building quality and inadequate energy efficiency, resulting in discomfort and higher long-term operational costs for residents [5][6]. Thus, while subsidized housing addresses accessibility, it raises important concerns about sustainability, resilience, and the overall well-being of its occupants.

The rising demand for housing also drives higher energy consumption in the residential sector [7]. Electricity is projected to dominate household energy use, with its share increasing from 60% in 2018 to nearly 90% by 2050, largely due to the growing reliance on appliances

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such as air conditioners, refrigerators, and water pumps [8]. As a result, urban areas have become major contributors to overall energy consumption [9], while buildings themselves account for about one-third of global energy use and nearly one-quarter of carbon dioxide emissions, positioning them as critical players in the climate change crisis [10]. Among building systems, HVAC represents one of the largest energy demands [11], and its energy use is highly sensitive to both indoor and outdoor temperatures, which directly influence heating and cooling needs [12]. In the tropical climate of Indonesia, high temperatures increase the demand for cooling systems to ensure indoor comfort, forcing HVAC systems to work against heat gains primarily caused by solar radiation [13]. This underscores the urgency of design strategies that minimize indoor heat loads to prevent escalating HVAC energy use. One effective passive design approach is modifying building configuration and form to reduce incident solar radiation (insolation). Since the amount of insolation received by building surfaces is a primary driver of cooling demand, it directly impacts energy consumption [14]. Previous studies confirm that urban building massing is a key determinant of energy use and solar energy potential [15]. Furthermore, there is strong evidence linking urban form, local climate conditions, and building energy consumption [12]. Local climate also plays a central role in shaping indoor thermal comfort levels, further highlighting the need for climate-responsive building design [16].

Urbanization brings positive impacts, particularly in the economic sector, but it also carries potential environmental drawbacks if not properly managed—especially within residential housing areas. In many cases, subsidized housing developments appear to be built with minimal considerations, often neglecting both indoor comfort and the quality of the surrounding environment. One of the main challenges in creating thermally comfortable subsidized housing is limited funding, which restricts investment in higher-quality design and materials. As a response, passive design strategies—such as modifying or adjusting building

massing and configuration—offer a cost-effective approach to improving thermal performance and creating more livable environments.

Most existing studies on massing and configuration adjustments have been conducted at the urban scale, focusing on city blocks or larger clusters of buildings. In contrast, this study applies such design modifications at a smaller scale, namely within residential neighborhoods. Research on how variations in building massing influence solar radiation and outdoor thermal conditions at the scale of housing developments remains scarce, leaving a clear gap in the literature. This study aims to address that gap by identifying the influence of building mass configuration and form variations on solar radiation exposure at outdoor site surface through quantitative analysis, using simulation methods applied to a hypothetical case study.

2. Methods

This study employs a quantitative method using an experimental strategy supported by computer-based simulations conducted with *Rhinoceros–Grasshopper–Ladybug*. *Ladybug* functions as a plugin within *Grasshopper*, while *Grasshopper* itself is a plugin for the *Rhinoceros* software. The process begins with 3D object modeling in *Rhinoceros*, after which the model is transferred into the *brep* component in *Grasshopper* to run solar radiation simulations using the *Ladybug* plugin. The simulation requires local climate data in the form of an *EnergyPlus Weather* file (EPW). For this research, the EPW dataset is sourced from the Sultan Aji Muhammad Sulaiman Sepinggan International Airport weather station in Balikpapan City, East Kalimantan. Balikpapan City was selected to represent cities with similar geographical conditions, particularly those located near the equator. The solar radiation simulation is executed with input parameters covering a full 24-hour cycle, from 00:00 to 24:00, and across an entire year from January through December. The overall workflow of the simulation process is illustrated in Figure 1.

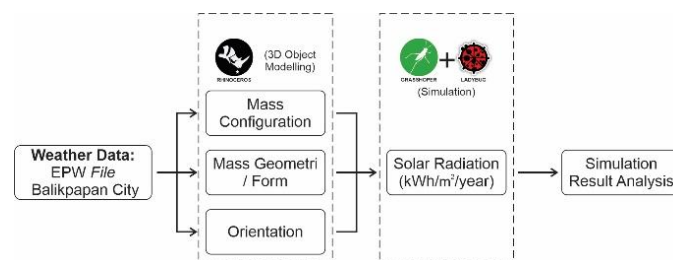


Figure 1. Simulation process.

Based on land use and building size regulations outlined in [17], the 3D object modeled in this study represents a subsidized housing unit with a building size of 36 m² on a land plot of 72 m² (type 36/72 house). The study site consists of eight plots, each with its own building mass. In total, the site measures 28.8 m x 26 m. A road runs through the center of the site, dividing it into two sections and creating four facing plots with opposing building masses. While the configuration and shape of each building mass vary, they are constrained to cover 50% of the plot area. All buildings share the same height of 5 meters, ensuring that each unit has identical

footprint area, height, and volume despite differences in form. Three study groups are established for observation, as illustrated in Figure 2. The first group serves as the base case, representing the typical building mass commonly found in subsidized housing developments, while the second and third groups provide comparative alternatives. Case Study Group 1 had a building mass width of 7.2 m and no spacing between building masses. Case Study Group 2 had a building mass width of 6 m, while Case Study Group 3 had a building mass width of 4 m.

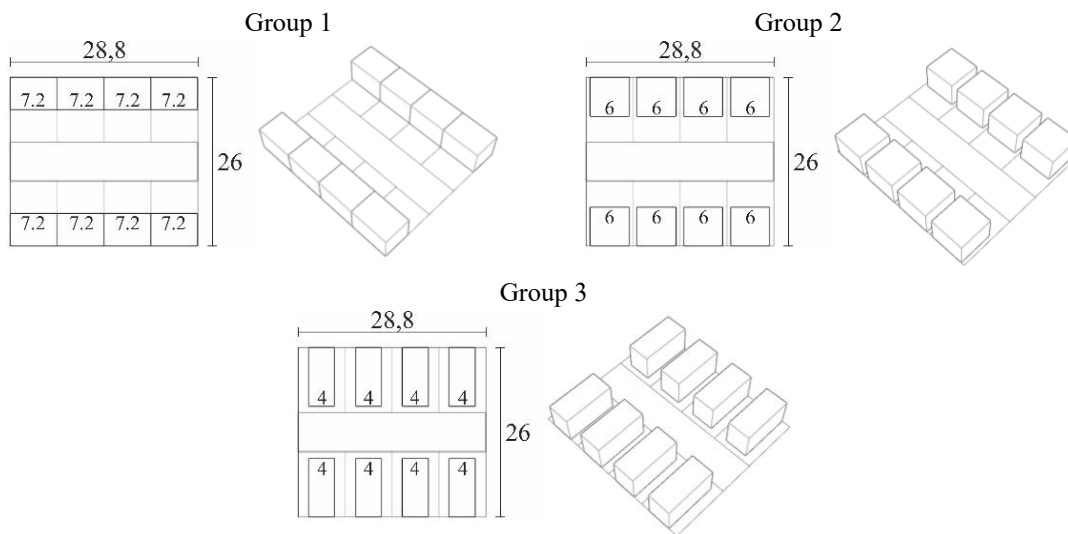


Figure 2. Floor Plan and Perspective of Three Case Study Groups.



Figure 3. Types of Building Mass Forms .

From the three study groups, each building mass will be transformed into three distinct variations, resulting in a total of nine simulated case studies. The modifications are derived from building mass forms commonly found in real housing developments (Figure 3), which are then simplified into 3D objects for the purpose of simulation and analysis.

Only the facade of the building mass facing the street was modified, while the other sides remained unchanged. Mass form A serves as the base case, representing the building’s condition prior to any modifications. The three variations of modified building masses are presented in Figure 4.

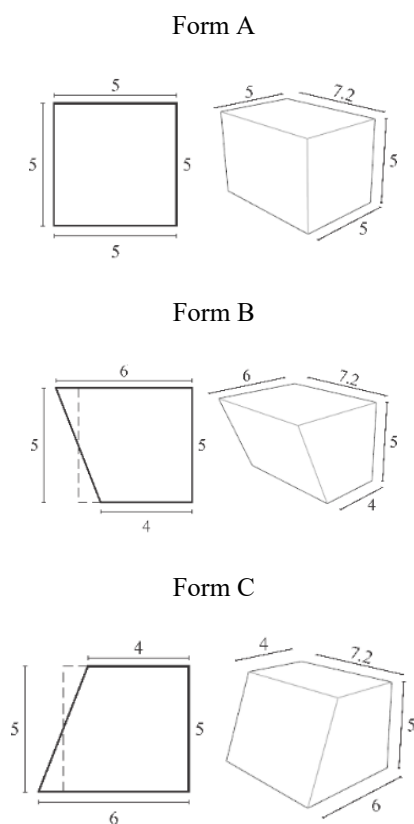


Figure 4. Side View and Perspective of Three Types of 3D Models of Building Mass Forms.

Subsidized Housing

Subsidized housing is one of the government’s initiatives to provide decent and affordable homes for the public, particularly for low-income households (MBR) [4][6]. These houses are typically developed within residential complexes and supported by government incentives such as tax exemptions and low-interest mortgage schemes [18]. According to [17], regulations have set minimum land area and building floor area requirements for subsidized housing which can be seen in Table 1 .

Table 1. Land Area and Building Area of Subsidized Houses.

| Type of House | Site Area (m ²) | | Building Floor Area (m ²) | |
|-------------------|-----------------------------|---------|---------------------------------------|---------|
| | Lowest | Highest | Lowest | Highest |
| Subsidized Houses | 60 | 200 | 21 | 36 |

Research exploring the relationship between subsidized housing, solar radiation, and building massing remains limited. Existing studies have primarily focused on the quality of physical elements in subsidized housing [6][4], the performance of existing buildings [16][5][19], sustainability aspects [20], and factors influencing the decision to purchase subsidized homes [21][22][23]. Most research on subsidized housing in Indonesia has relied on case studies of specific housing projects, with no studies identified that use hypothetical scenarios. Furthermore, no prior studies have specifically examined the role of building massing and configuration in subsidized housing. One relevant study on settlement-scale massing was conducted by [24], which analyzed its influence on microclimate conditions in residential areas. However, that research relied on existing buildings and field measurement methods, leaving significant gaps that this study aims to address.

Solar Radiation and Building Mass

Solar radiation is electromagnetic energy produced through nuclear fusion processes occurring in the core of the sun [25]. According to [26], solar radiation can be expressed in two main ways: as the density of energy flux or instantaneous power received on a surface (radiation, measured in W/m²), and as the total quantity of energy received per unit area over a given period (irradiance, measured in J/m² or Wh/m²). The cumulative amount of solar energy received by a surface per unit area within a specific timeframe is referred to as insolation, typically expressed in kWh/m² per day, month, or year.

Previous studies have revealed a strong correlation between insolation and the configuration or form of building massing. Compact or densely arranged building blocks tend to reduce the exposed surface area, thereby lowering insolation values, while more open configurations increase exposure to solar radiation. [15] emphasized that the form of urban building blocks is a crucial factor influencing both the utilization of solar energy potential and overall building energy consumption. Research on urban building massing has often been conducted using homogeneous block models, where a single type of block mass design is applied [27][28][29]. In contrast, other studies have adopted heterogeneous

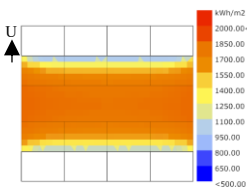
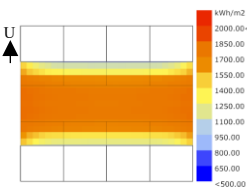
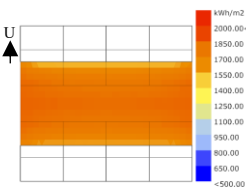
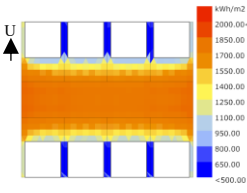
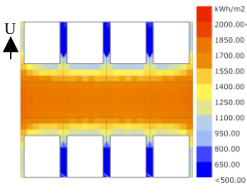
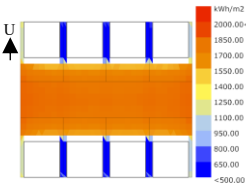
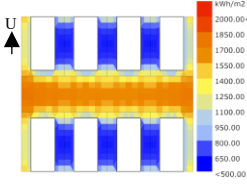
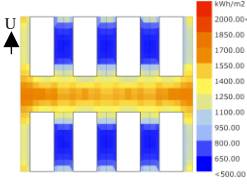
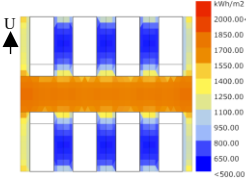
block models, which incorporate a combination of varied block massing designs to better represent urban complexity [30] [12][31].

3. Results and Discussion

The solar radiation simulation on the site surface was carried out under the assumption that the radiation values on each plane were influenced only by the building mass objects placed above it, without interference from other elements or objects. In addition, the site was tested under two different orientations (west–east and north–south) to evaluate their impact on solar radiation levels. Each case study, with its distinct building massing configuration, was analyzed to assess how variations in form affect the distribution and intensity of solar radiation received across the site. The simulation was first conducted on the west–east orientation, followed by the north–south orientation. The results of these simulations are presented in Table 2. Then, a bar chart of the simulation results presented in Figure 5.

Based on each group of building mass form categories, case study group 3 (3A, 3B, 3C) recorded the lowest solar radiation values compared to groups 1 (1A, 1B, 1C) and 2 (2A, 2B, 2C), as illustrated in Figure 6. Group 3 features elongated, slender masses oriented along the north–south axis, which create larger shaded areas than those in groups 1 and 2. In contrast, group 1 exhibited the highest radiation values among all groups. This is primarily because the masses in group 1 are directly adjacent to one another, unlike groups 2 and 3 where spacing between the buildings is present. The simulations demonstrate that as the distance between buildings increases, the level of solar radiation received decreases. This effect is most evident in group 3, which has the widest spacing among all cases. Moreover, the results confirm that even with identical footprint areas and building volumes, variations in massing that introduce wider inter-building spacing significantly reduce solar radiation exposure. In other words, the degree of shading produced by building separation plays a decisive role in shaping the overall radiation levels on the site surface.

Table 2. Average Annual Solar Radiation Value at Sites with West-East Orientation.

| Case Study 1a (<i>Base Case</i>) | Case Study 1b | Case Study 1c |
|---|---|---|
|  <p>Radiation Analysis</p> <p>1,517.1 kWh/m²/year</p> |  <p>Radiation Analysis</p> <p>1,310.7 kWh/m²/year</p> |  <p>Radiation Analysis</p> <p>1,663.5 kWh/m²/year</p> |
| Case Study 2a | Case Study 2b | Case Study 2c |
|  <p>Radiation Analysis</p> <p>1,261.4 kWh/m²/year</p> |  <p>Radiation Analysis</p> <p>1,126.5 kWh/m²/year</p> |  <p>Radiation Analysis</p> <p>1,337.5 kWh/m²/year</p> |
| Case Study 3a | Case Study 3b | Case Study 3c |
|  <p>Radiation Analysis</p> <p>1,124.1 kWh/m²/year</p> |  <p>Radiation Analysis</p> <p>1,024.4 kWh/m²/year</p> |  <p>Radiation Analysis</p> <p>1,148.4 kWh/m²/year</p> |

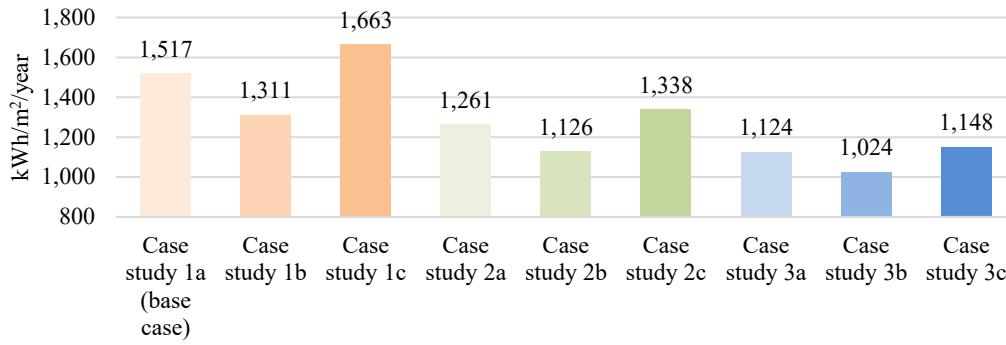


Figure 5. Average Solar Radiation Simulation Results / Year on West - East Site Orientation.

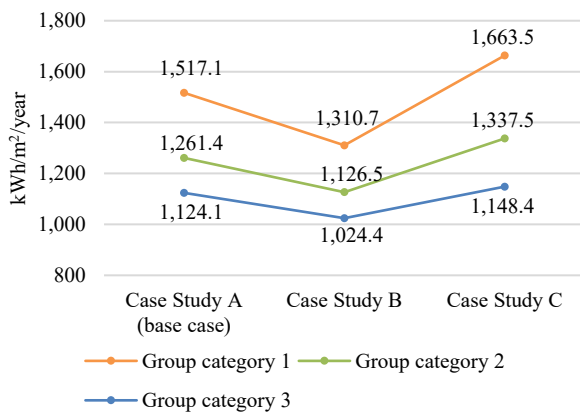


Figure 6. Average Solar Radiation Simulation Results / Year Based on Mass Form Category Groups in West - East Site Orientation.

As shown in [Figure 6](#), building mass form B (1B, 2B, 3B) consistently produced the lowest solar radiation values compared to forms A (1A, 2A, 3A) and C (1C, 2C, 3C). The geometry of form B increases the extent of shaded areas, thereby reducing the site surface exposed to direct solar radiation and lowering the overall radiation levels. In contrast, form C recorded the highest solar radiation values, as its configuration reduces shaded areas and increases the portion of the site exposed to sunlight. This results in higher solar radiation intensity across the site surface. A similar study by [\[32\]](#), examined facade modifications by adjusting the tilt of building facades relative to solar angles. The findings demonstrated that the most optimized facade design reduced incident solar radiation, subsequently lowering cooling energy demand by approximately 20%–23%.

The simulation was then extended by reorienting the site from its initial west–east alignment to a north–south orientation, allowing for a comparative analysis between the two configurations. The results of the simulation for the north–south orientation are presented in [Table 3](#).

A comparative analysis of the solar radiation simulations for both orientations revealed several consistent patterns alongside some notable differences. As illustrated in [Figure 7](#), a similar trend is observed in case study group 1 (1A, 1B, 1C), which consistently recorded the highest solar radiation values compared to groups 2 (2A, 2B, 2C) and 3 (3A, 3B, 3C). Furthermore, when examining variations in building mass forms within each group, the results show that form B consistently produced the lowest radiation values, while form C recorded the highest.

Under the west–east orientation, Case Study 3B (1,024.4 kWh/m²/year) reduced solar radiation by 32.5% compared to the base case 1A (1,517.1 kWh/m²/year). In contrast, under the north–south orientation, Case Study 3B (1,036.7 kWh/m²/year) reduced solar radiation by 25.3% relative to the base case 1A (1,387.5 kWh/m²/year). These results indicate that site orientation also plays an important role in reducing solar radiation exposure on the site surface. This finding is consistent with the study conducted by [\[27\]](#), which identified site orientation as one of the most significant parameters affecting solar radiation exposure on buildings. The study likewise reported that the north–south orientation was the most effective in reducing solar radiation gain compared to other orientations.

Table 3. Average Annual Solar Radiation Value at Sites with North-East Orientation.

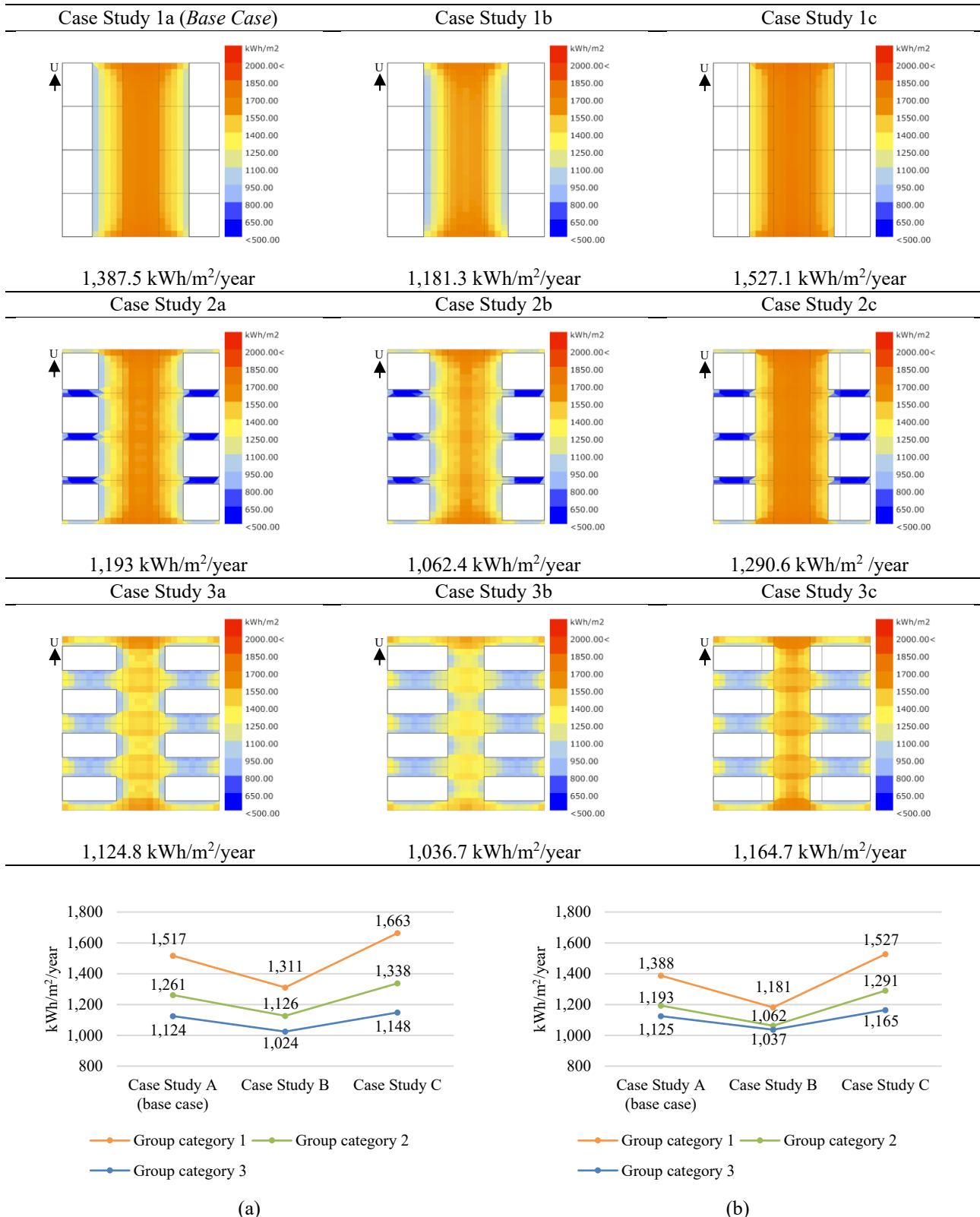


Figure 7. Comparison of Average Solar Radiation Simulation Results per Year Based on Mass Form Category Groups in West - East (a) and North - South Site Orientations (b).

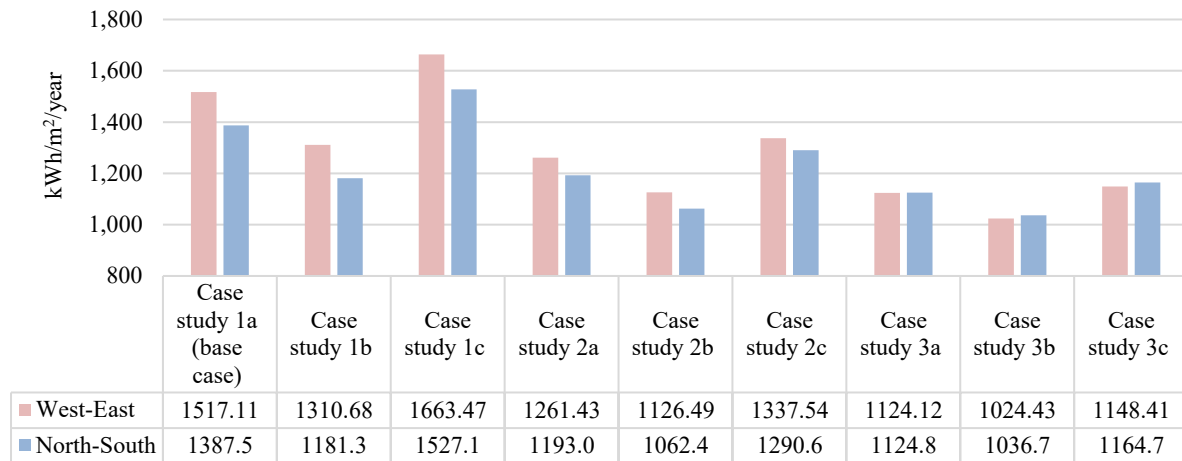


Figure 8. Comparison of Solar Radiation Simulation Results/Year at Sites with West-East and North-South Site Orientations.

Sites with a west–east orientation generally exhibited higher solar radiation values than those with a north–south orientation ($WE > NS$), as observed in Case Study Groups 1 and 2 (Figure 8). However, the opposite pattern was found in Case Study Groups 3, where the north–south orientation resulted in slightly higher solar radiation values than the west–east orientation ($WE < NS$), although the differences were relatively small. When Case Study Groups 3 were arranged on a west–east-oriented site, the elongated building masses were oriented north–south, resulting in larger shaded areas generated by the buildings. In contrast, when the same case study groups were arranged on a north–south oriented site, the elongated building masses became west–east oriented, producing smaller shaded areas. Theoretically, this phenomenon is closely related to the daily solar path, particularly during the morning and afternoon periods when the solar altitude angle is relatively low. These findings indicate that site orientation remains an important parameter in solar radiation control strategies for housing design in warm-humid tropical climates.

4. Conclusions

Based on the analysis and discussion, it can be concluded that building configuration and massing significantly influence the reduction of annual average solar radiation. Overall, the simulations indicate that greater spacing between buildings results in lower solar radiation values. In the west–east site orientation, case 3B recorded the lowest solar radiation, with 1,024.4 kWh/m²/year. This configuration reduced radiation by 32.5% compared to the base case, 1A, which recorded 1,517.1 kWh/m²/year. For the north–south orientation, Case 3B achieved the lowest radiation value at 1,036.7 kWh/m²/year, representing a 25.3% reduction compared to the base case, 1A, with 1,387.5 kWh/m²/year. The best performing modified cases in both orientations also demonstrated that increased shaded areas generated by building configurations and

forms directly reduce solar radiation exposure. This study is expected to provide valuable insights and practical considerations for architects and other professionals in designing subsidized housing developments. By applying passive strategies through thoughtful massing and configuration, outdoor thermal comfort can be enhanced by mitigating solar radiation exposure.

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