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Effects of built mass arrangement and morphology on external thermal comfort within subsidized dwellings

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ABSTRACT

Urbanization has resulted in a continuous escalation of land values and housing prices in urban regions, while the demand for residential units in cities persists in increasing. As a result, government-provided subsidized housing has become a crucial option for low-income communities. Nevertheless, these subsidized housing projects are frequently criticized for their insufficient construction quality. Growing concerns have emerged that such developments may unintentionally intensify global warming by elevating ambient temperatures within the residential environment. This study investigates how variations in building mass configuration and architectural form influence outdoor temperature as a passive design strategy to improve thermal conditions in subsidized housing areas. The analysis employs a hypothetical massing model of subsidized housing simulated using Rhinoceros, Grasshopper, and Ladybug. The results demonstrate that adjustments in building mass configuration and form are capable of lowering outdoor temperatures, although the impact remains relatively modest. Case Study 4B, which uses asphalt as the site's surface material and represents the scenario with the most favorable UTCI values in both orientations, achieves a UTCI reduction of 1.8 °C for the West–East orientation and 1.6 °C for the North–South orientation when compared to the base case.

Introduction

According to projections from the United Nations (UN 2015) as cited in (Ahmadi et al. 2022), approximately 60% of the world's population will be living in urban areas by 2030. In Indonesia, demographic forecasts similarly estimate that by 2035 more than half of the national population, specifically 66.6%, will reside in cities (Badan Pusat Statistik 2023). This rapid urbanization will inevitably drive continued growth in urban housing development (Prasetya, Ho, and Kubota 2023). Urban expansion simultaneously influences land and property values, as increasing demand for urban housing correlates directly with rising land prices (Sabitha 2022). Consequently, government intervention through housing subsidies becomes essential for low-income populations. Subsidized housing remains particularly significant for low-income households because it enables access to the formal housing market at affordable prices (Bramantyo, Tyas, and Argyantoro 2019). Data released by the Ministry of Public Works and Public Housing (PUPR) in early 2020 indicate that Indonesia still required approximately 7.64 million housing units to meet national housing needs. Of this total, 6.48 million units were needed by low-income households with non-fixed earnings, 1.72 million units by low-income households with fixed incomes, and 0.56 million units by non-low-income households (Soeranto, Marpaung, and

Situmorang 2020). These figures demonstrate the government's ongoing urgency to accelerate the development of subsidized housing to meet this demand.

Despite their necessity, subsidized housing projects are often criticized for their poor construction quality (Widya Wardani et al. 2024). These projects tend to prioritize affordability and cost efficiency frequently resulting in limited consideration for environmental quality and outdoor thermal comfort, for example through the reduction or removal of green corridors and shading vegetation (Soewarno 2024). Meanwhile, accelerating urbanization has transformed natural landscapes into built environments, fundamentally altering local microclimatic conditions (Yang et al. 2023). The conversion of soil and vegetation into asphalt and concrete surfaces contributes to the intensification of Urban Heat Island (UHI) effects (Qaoud et al. 2023). Human activities and high urban density further compound this urban warming (Ahmadi et al. 2022). These conditions reinforce the need for passive design strategies capable of improving outdoor thermal comfort and mitigating UHI effects while remaining economically feasible. One such passive approach is the modification of building mass configuration and architectural form.

A substantial body of research has examined how the arrangement and morphology of building masses influence outdoor thermal environments through strategies involving urban geometry (Abd Elraouf et al. 2022) (Muniz-Gäal et al. 2020), building morphology (Zhang et al. 2022), height variation (Shareef and Abu-Hijleh 2020), and building density (Zhu et al. 2023). Studies focusing specifically on building mass configuration include work by (Afif et al. 2020), whose results show that adjustments to mass configuration can improve outdoor thermal comfort. Similarly, (Mousaeipour et al. 2025) confirm that the configuration of urban blocks significantly influences outdoor thermal conditions, with block spacing identified as one of the most critical variables. Research conducted by (Abd Elraouf et al. 2022) further indicates that compact and organically developed urban morphologies produce more favorable outdoor thermal conditions compared with grid-based layouts, thereby shaping the microclimate of their respective areas. In addition, studies on building mass form demonstrate its influence on outdoor thermal performance. (Sun et al. 2023) show that optimizing building mass form can reduce overall outdoor thermal stress, while (Kakon and Mishima 2012) find that massing models with reduced site coverage and taller structures yield more comfortable outdoor environments than high-coverage models in dense tropical cities. Collectively, these findings suggest that integrating building mass configuration with massing form offers potential for enhancing outdoor thermal comfort. However, most research on configuration and form has been conducted at the urban or district scale, and investigations at smaller scales, such as subsidized housing clusters, remain limited. This gap raises an important research question: do building mass configuration and form influence outdoor thermal conditions when applied to subsidized housing contexts, and to what extent can these parameters function as passive design strategies for improving thermal comfort?

In parallel, architectural research on subsidized housing in Indonesia has expanded considerably, yet studies examining how building configuration, morphology, or massing geometry affect outdoor thermal comfort remain scarce. Existing research predominantly evaluates the performance of individual buildings, with relatively few studies addressing multi-building or cluster-scale environments. (Soewarno 2024), assessed both indoor and outdoor thermal performance using a single-building model, while (Mufida et al. 2022) and (Riskillah et al. 2021) also examined indoor thermal performance at the scale of individual units. Although (Retno et al. 2024) adopted a multi-building or cluster-scale framework, their study centered on energy and water sustainability rather than outdoor thermal conditions. To date, no research has been identified that specifically analyzes the interaction between building configuration and massing form using multi-building simulations to evaluate outdoor thermal performance in Indonesian subsidized housing environments. This knowledge gap highlights a significant research opportunity that requires further exploration.

Methodologically, this study employs a quantitative research design using simulation tools in Rhinoceros and Grasshopper. Its primary aim is to investigate how variations in building configuration and massing form influence outdoor thermal comfort within subsidized housing environments. The analysis utilizes a hypothetical case study that simplifies building massing conditions and situates the scenario in Balikpapan. The contribution of this research lies in applying configuration and massing principles typically studied at urban or district scales to the much smaller spatial context of subsidized housing clusters. The study's central hypothesis posits that even at this reduced scale, modifications to building configuration and massing form will continue to generate measurable effects on outdoor thermal conditions. The findings are expected to provide conceptual guidance for architects and subsidized housing developers, contributing to the creation of affordable housing environments that also deliver adequate environmental and thermal performance.

Methods

This study employs a quantitative methodology that integrates experimental and simulation-based strategies using the Rhinoceros–Grasshopper–Ladybug software suite. Ladybug functions as a plugin within Grasshopper, while Grasshopper itself operates as a plugin embedded in Rhinoceros. The research process consists of three principal stages: model development, simulation execution, and data analysis (figure 1). A three-dimensional model is constructed in Rhinoceros and subsequently imported into a Brep component in Grasshopper, where simulations of outdoor thermal comfort are conducted using the Universal Thermal Climate Index (UTCI).

UTCI is a one-dimensional index used to characterize the human physiological response to various outdoor environmental parameters, including wind speed, humidity, radiation, and air temperature (Bröde et al. 2012). The equivalent UTCI temperature categories are presented in (table 1). UTCI is defined as the air temperature of a standardized reference environment, where air temperature equals mean radiant temperature (MRT), wind speed is 0.5 m/s at a height of 10 m, relative humidity is 50% or vapor pressure is maintained at 20 hPa, and metabolic rate is 135 W/m², that produces the same level of thermal stress experienced in real environmental conditions (Ji, Song, and Shen 2022) (Zare et al. 2018). Developed as a unified metric for evaluating outdoor thermal environments across multiple climates, seasons, timescales, and spatial contexts, UTCI is fundamentally based on the concept of thermal stress (Schrijvers et al. 2016) (Thapa, Rijal, and Zaki 2024).

A growing body of literature has applied UTCI as the primary indicator for assessing outdoor thermal comfort across diverse climatic regions. For example, (Ibrahim et al. 2021) examined the relationship between geometric design and outdoor thermal comfort in Cairo's hot, arid climate, revealing a negative correlation between H/W ratios and UTCI values, with reductions of up to 6 °C observed through alterations to building height-to-width ratios and orientation. In a tropical setting, (Krishna Bhakta and Syafii 2024) investigated the influence of urban morphology on outdoor thermal conditions in Jakarta and found that greater Building Site Coverage corresponds to improved UTCI performance. (Sun et al. 2023) optimized outdoor spaces for kindergartens in Tianjin (temperate continental monsoon climate) and Shanghai (humid subtropical monsoon climate), demonstrating that their proposed design interventions effectively decrease overall thermal stress.

Table 1. UTCI equivalent temperature based on thermal stress category

UTCI (oC)	Thermal stress category
Above +46	Extreme heat stress
+38 until +46	Very strong heat stress
+32 until +38	Strong heat stress
+26 until +32	Moderate heat stress
+9 until +26	No thermal stress
+9 until 0	Slight cold stress
0 until −13	Moderate cold stress
−13 until −27	Strong cold stress
−27 until −40	Very strong cold stress
Below −40	Extreme cold stress

Source: (Bröde et al. 2012)

The simulation process is carried out through the Ladybug plugin. Before running simulations, meteorological data for the study area must be prepared in the form of an EnergyPlus Weather (EPW) file. This study utilizes EPW data from the Sultan Aji Muhammad Sulaiman Sepinggan International Airport weather station in Balikpapan, East Kalimantan. Balikpapan was selected due to its representativeness for cities located near the equator and sharing similar geographic and climatic characteristics.

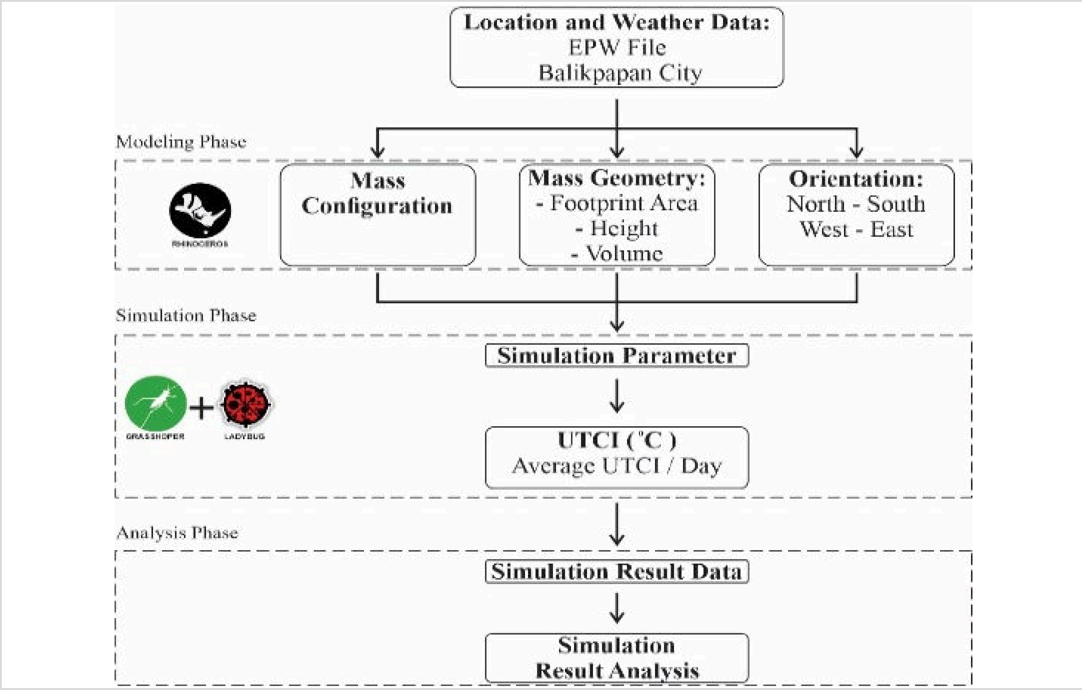


Figure 1. Research framework

Research object

According to the Indonesian KepmenPUPR (2023), the allowable land area and floor area for landed public housing (subsidized housing) are defined as follows:

Table 2. Land area and building area specifications of subsidized housing

Type of House	House Floor Area (m2)		Land Area (m2)	
Landed House	Lowest	Highest	Lowest	Highest
	21	36	60	200

Source: (KepmenPUPR 2023)

Based on the floor area and land area listed in (table 2), this study simulates a subsidized housing unit consisting of a 36 m² floor area situated on a 72 m² plot (Type 36/72). The site comprises eight land parcels and their corresponding building masses arranged within an overall area of 28.8 m × 26 m. A central roadway bisects the site into two opposing rows of four plots each. The building footprint maintains 50% coverage of each plot, while three different massing geometries are tested. All building masses have a uniform height of 5 m, ensuring identical footprint areas, heights, and volumes, with variations limited only to footprint configuration. Four mass-configuration case groups are analyzed. Group 1 features a mass width of 7.2 m with no separation between adjacent masses. Groups 2–4 incorporate separation distances of varying widths: 6 m in Group 2, 5 m in Group 3, and 4 m in Group 4. Group 1 serves as the base case, reflecting typical configurations in existing subsidized housing developments, while Groups 2–4 act as comparative cases with modified massing arrangements. A visual overview of the four case study groups is shown in (figure 2).

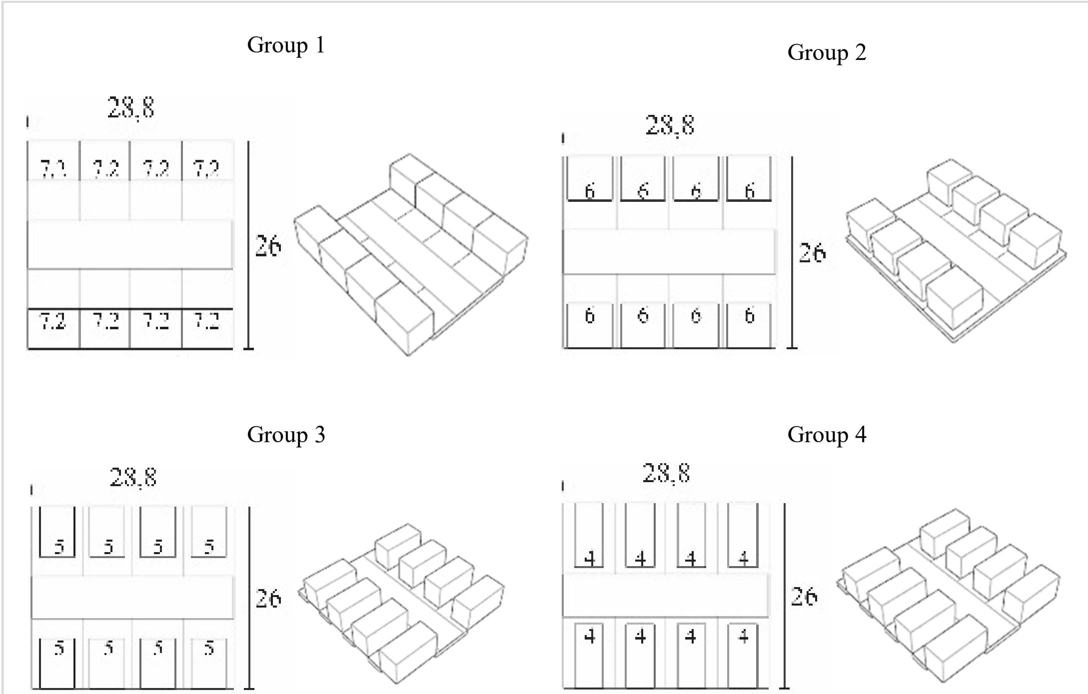


Figure 2. Four case study groups' plans and perspectives

For each of the four case groups, the building mass is further modified into three different forms, resulting in a total of nine simulation scenarios. These mass form variations are derived from existing built examples (figure 3) and transformed into simplified three-dimensional geometries for simulation.

Figure 3. Types of building mass forms
Source: Google Map and Google Image 2025

Modifications to building mass form are applied exclusively to the street-facing façade; all other sides remain unchanged. Form A functions as the base case, representing the unmodified massing condition. The three mass form variants are illustrated in (figure 4).

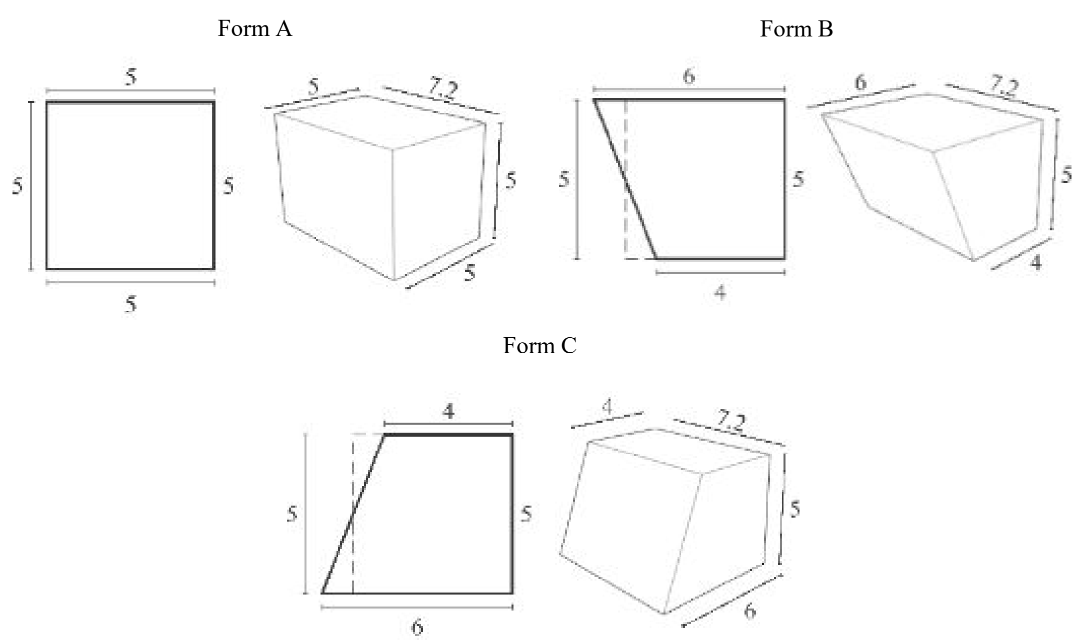


Figure 4. Side view and perspective of three variants of 3d models of building mass forms

Simulation parameters

Several input parameters were defined prior to conducting the simulations. The UTCI simulation period corresponds to the hottest day of the year (October 7), based on the Balikpapan EPW file, and spans a full 24-hour cycle from 00:00 to 23:00. The simulations also incorporate different surface-cover materials according to their albedo values (table 3). Material albedo is known to influence UTCI results, as demonstrated in (Schrijvers et al. 2016), (Krishna Bhakta and Syafii 2024), and (Mohammad et al. 2021).

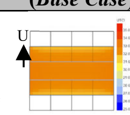
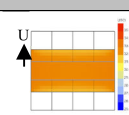
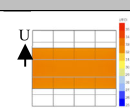
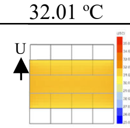
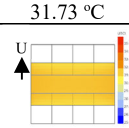
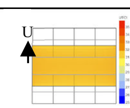
Tabel 3. UTCI simulation parameter

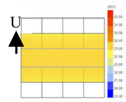
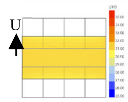
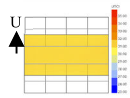
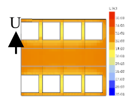
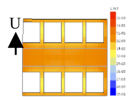
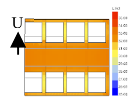
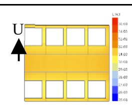
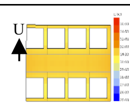
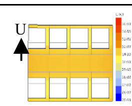
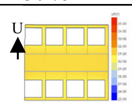
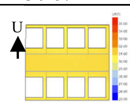
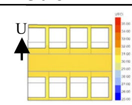
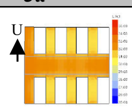
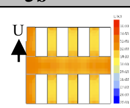
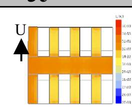
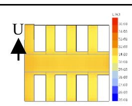
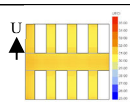
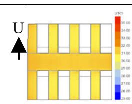
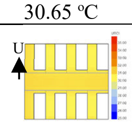
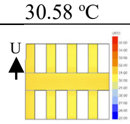
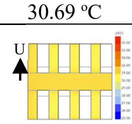
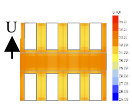
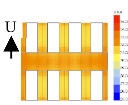
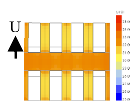
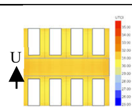
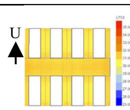
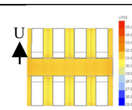
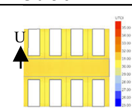
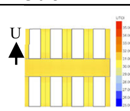
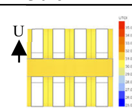
Parameter		**Value**
Simulasi UTCI	Time Periode	Date 7, Oktober Month, Time 00.00 – 23.00
	Grid size	1
	Measuring Height	1.2 m
	Material Albedo	white portland cement concrete (0.7) grass / dry bare soil (0.25)
		aspalt (0.05)

Results and discussion

Twelve case studies were examined using three types of site surface materials white Portland cement concrete, grass or dry bare soil, and asphalt. The first simulation was carried out on a site with a West–East orientation, and the results are summarized in (table 4) as follows:

Table 4. Average UTCI values at sites with west – east orientation

	Case Study 1a (*Base Case*)	**Case Study 1b**	**Case Study 1c**
White portland cement concrete	 32.01 ºC	 31.73 ºC	 32.27 ºC
Grass / dry bare soil	 31.02 ºC	 30.85 ºC	 31.16 ºC

Aspalt	 30.58 ºC	 30.46 ºC	 30.67 ºC
	Case Study 2a	**Case Study 2b**	**Case Study 2c**
White portland cement concrete	 31.58 ºC	 31.44 ºC	 31.74 ºC
Grass / dry bare soil	 30.75 ºC	 30.67 ºC	 30.84 ºC
Aspalt	 30.39 ºC	 30.33 ºC	 30.45 ºC
	Case Study 3a	**Case Study 3b**	**Case Study 3c**
White portland cement concrete	 31.41 ºC	 31.29 ºC	 31.49 ºC
Grass / dry bare soil	 30.65 ºC	 30.58 ºC	 30.69 ºC
Aspalt	 30.31 ºC	 30.26 ºC	 30.34 ºC
	Case Study 4a	**Case Study 4b**	**Case Study 4c**
White portland cement concrete	 31.27 ºC	 31.19 ºC	 31.36 ºC
Grass / dry bare soil	 30.56 ºC	 30.51 ºC	 30.61 ºC
Aspalt	 30.25 ºC	 30.21 ºC	 30.28 ºC

Across the twelve simulations, the findings show that the change in UTCI values from Case 1A, which serves as the base case, to the scenario with the most optimal UTCI performance (Case 4B) is relatively modest. The difference between the base case and this best-performing configuration is approximately 0.8 °C for white Portland cement concrete, 0.5 °C for grass or dry bare soil, and 0.4 °C for asphalt (figure 5). Nevertheless, Case 4B, which achieves a UTCI of 30.21 °C using asphalt as the site surface, produces the overall lowest UTCI and delivers a 1.8 °C reduction when compared with Case 1A, which records a UTCI of 32.01 °C and employs white Portland cement concrete.

The UTCI classification also remains largely consistent, as nearly all case studies fall within the same category, namely *moderate heat stress* (26–32 °C). Only Case 1C, which uses white Portland cement concrete, falls into the *strong heat stress* category (32–38 °C). Even so, a steady decrease in UTCI values is observed from Group 1 to Group 4, indicating that variations in mass configuration and form do exert a measurable influence on outdoor thermal conditions.

The results also demonstrate that Case Group 4 (4A, 4B, 4C) exhibits the most favorable UTCI values across all site surface types white Portland cement concrete, grass or dry bare soil, and asphalt (figure 6). This group features a slender, elongated mass oriented along the north–south axis, which generates a larger shaded footprint than the other case groups. The increase in shaded area reduces solar exposure on site surfaces, thereby lowering insolation and exerting a positive influence on UTCI. As noted by Achour-Younsi and Kharrat (2016), shading produced by building mass configurations diminishes the level of solar radiation received by the ground surface and consequently reduces surrounding environmental temperatures. The simulation results also reveal that the three site surface materials contribute differently to UTCI reduction. This influence corresponds closely with their albedo characteristics: lower albedo materials tend to produce lower UTCI values, whereas higher albedo surfaces correspond to higher UTCI. Several previous studies support these findings. Krishna Bhakta and Syafii (2024) observed that asphalt having the lowest albedo generated the most favorable mean UTCI values when compared with concrete and grass. Likewise, Mohammad et al. (2021) noted that low-albedo surfaces reduce mean radiant temperature, thereby improving outdoor thermal conditions. Schrijvers et al. (2016) investigated albedo adaptation strategies in an idealized two-dimensional street canyon and found that although high-albedo surfaces can reduce air temperature, they substantially increase mean radiant temperature, leading to higher UTCI. These studies collectively highlight that increasing albedo generally elevates mean radiant temperature and consequently raises UTCI, and vice versa.

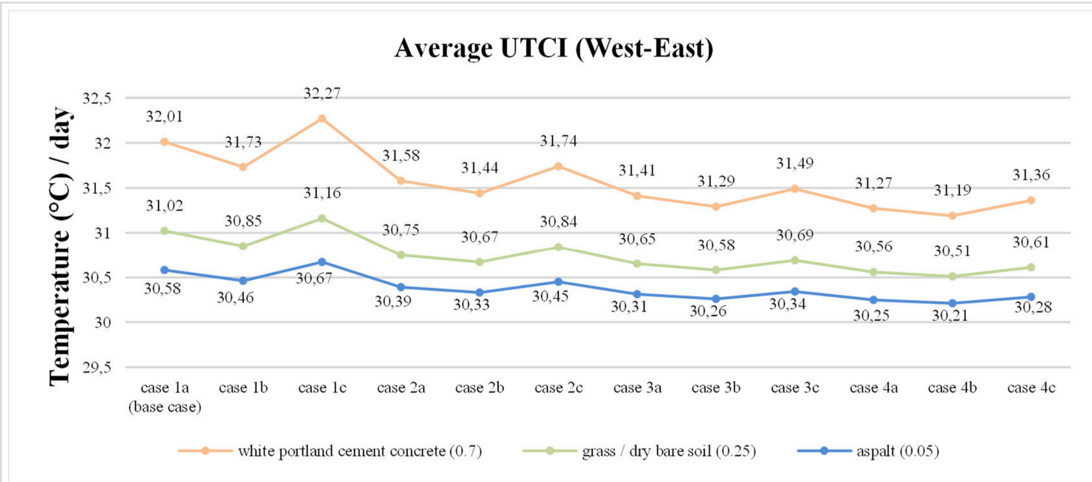
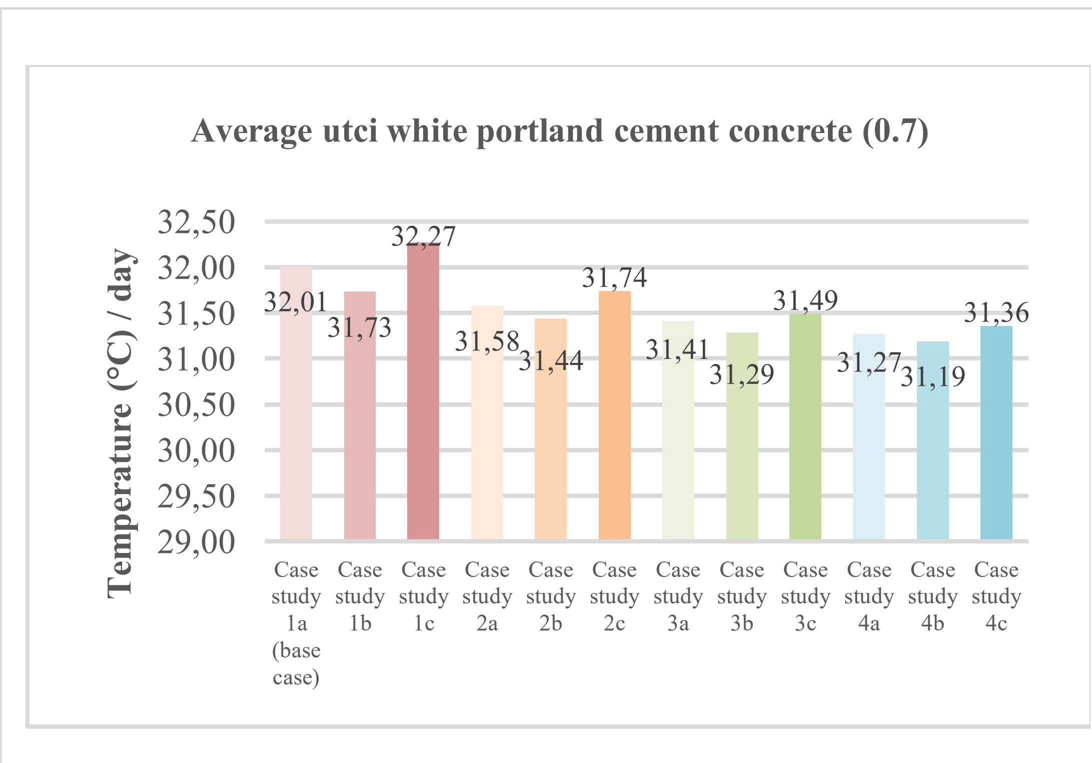


Figure 5. UTCI values based on site surface material types on west – east oriented sites



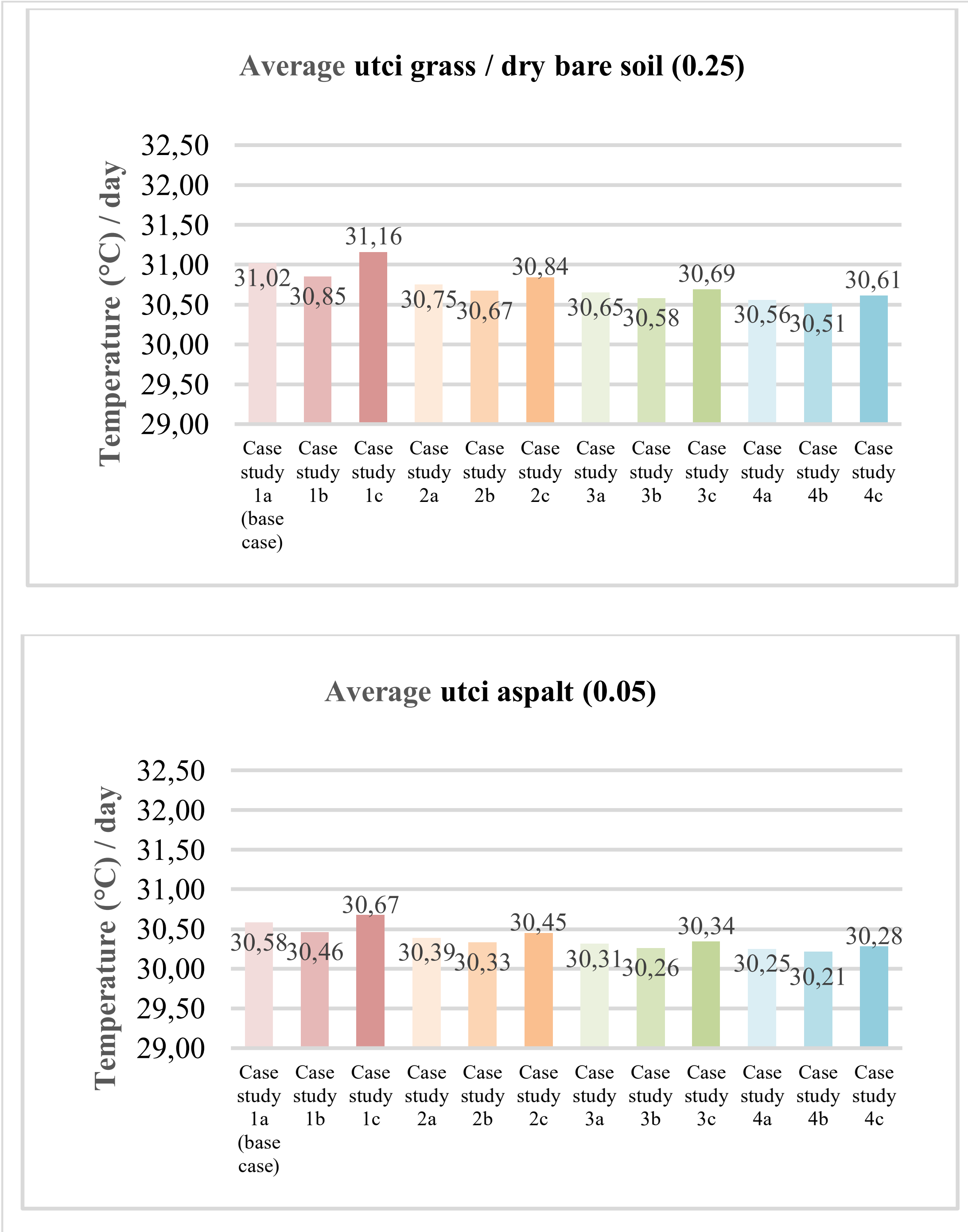


Figure 6. UTCI values based on site surface material type at sites with west-east orientation

In addition to the material's albedo value, changes in the building mass form in each case study group also show different average UTCI values. On the site with a West–East orientation, mass form B has the lowest average UTCI compared to mass forms A and C (figure 7). This occurs because Mass Form B produces a greater shaded area relative to the base case (A) and Form C, the latter of which actually reduces shading. Consequently, variations in the extent of shading significantly influence average UTCI across the site.

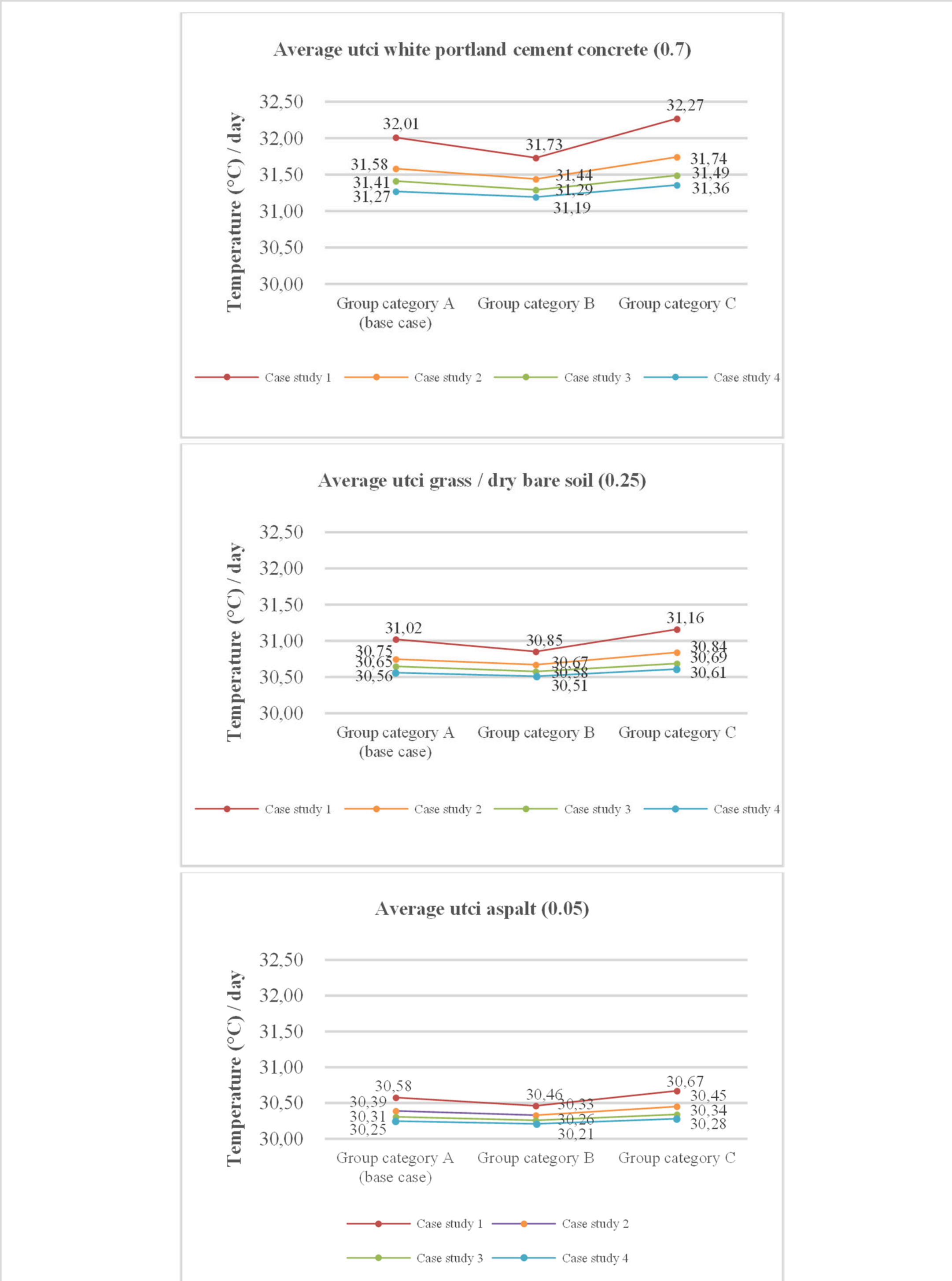


Figure 7. UTCI Values based on the categories of mass form groups and types of site surface materials at sites with a west-east orientation

Comparable findings were reported by Sun et al. (Sun et al. 2023) whose research demonstrated that optimizing building mass form can reduce thermal stress in outdoor spaces. Their study confirmed that configurations generating the greatest shaded area were most effective in lowering outdoor temperatures. Similarly, Lee, Voogt, and Gillespie (2018) showed that building shadows were the most effective mechanism for reducing ambient temperature, followed by tree shading and artificial shading devices such as umbrellas.

Among all scenarios, Case 4B, using asphalt as the surface material, achieves the lowest average UTCI of 30.21 °C. The group features a flat, north–south-oriented mass that increases shading, while Mass Form B further enhances shaded coverage. The asphalt surface, with its relatively low albedo value of 0.05, contributes additional cooling effects, reinforcing the reduction in average UTCI.

The simulation results for the West–East orientation were subsequently compared with those of the North–South orientation (figure 8), given that earlier studies highlight orientation as a critical factor influencing outdoor thermal comfort. Abdollahzadeh and Biloria (2021), for instance, demonstrated that street canyon orientation accounted for the greatest impact (46.42%) on thermal performance, followed by aspect ratio (30.59%).

Upon comparison, the North–South–oriented site shows slightly better UTCI performance than the East–West site, though the difference remains relatively small. Both orientations reveal similar patterns: Case Group 1 (1A, 1B, 1C) consistently presents the highest UTCI values, while Case Group 4 (4A, 4B, 4C) generates the lowest. Among the building mass types, Mass Type B produces the lowest UTCI, whereas Mass Type C yields the highest. Overall, the North–South orientation is more advisable for site planning because it delivers improved outdoor thermal comfort compared with the East–West orientation (Deng and Wong 2020) (Srivanit and Jareemit 2020) (Acero et al. 2021).

This study sought to determine the influence of building mass configuration and form variations on outdoor thermal comfort in subsidized housing environments. The simulations demonstrate that although the influence on UTCI values is not highly significant, variations in building configuration and volume form nonetheless present considerable potential as cost-effective passive design strategies for improving thermal comfort. Building forms that generate broader shaded areas reduce solar radiation on site surfaces and consequently lower UTCI. This is consistent with the findings of Achour-Younsi and Kharrat (2016), who observed that shading from building masses decreases solar exposure and ambient temperatures. Research by Mousaeipour et al. (2025) further supports this, showing that urban block configurations significantly affect outdoor thermal comfort, with block spacing emerging as a key parameter influencing MRT and UTCI.

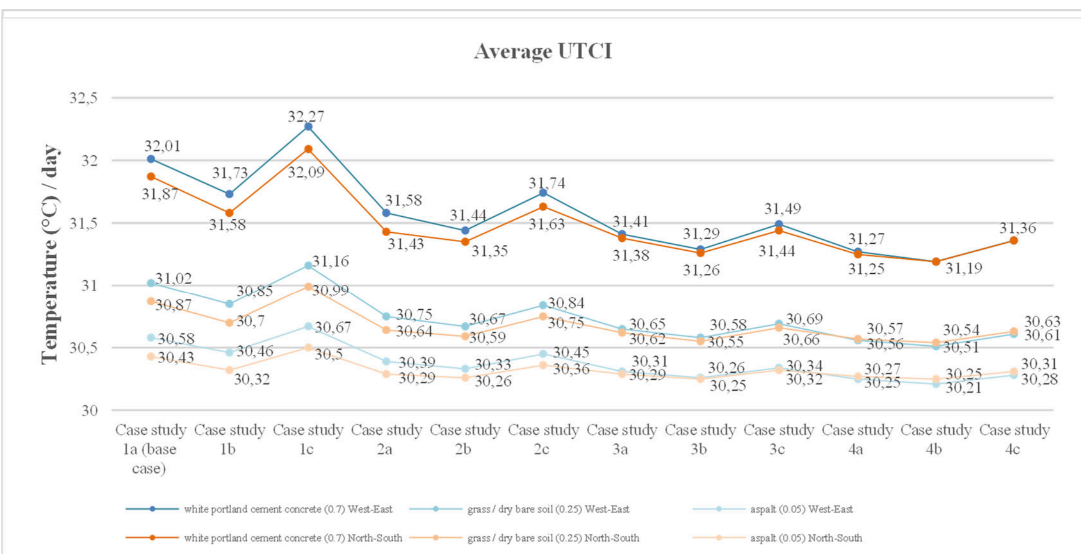


Figure 8. Comparison of UTCI value simulation results based on site surface material type at sites with west-east and north-south orientations

Conclusions

Based on the preceding analysis and discussion, the results demonstrate that variations in building mass configuration and form do influence UTCI values in outdoor settings and can contribute to lowering them, although the extent of this reduction remains relatively modest. The decrease in UTCI is closely linked to the enlargement of shaded areas produced by the building masses. As the proportion of shaded surfaces increases, the corresponding UTCI values generally decline.

In addition, regarding the site surface covering materials, asphalt exhibits the most beneficial effect in lowering UTCI when compared with the other materials. A lower surface albedo leads to a reduction in mean radiant temperature, which in turn contributes to lower UTCI values. Case 4B emerges as the scenario with the most favorable UTCI performance in both orientations. In the West–East orientation, Case 4B (30.21 °C), which utilizes asphalt as the surface covering, records the lowest UTCI value compared with Case 1A (32.01 °C) the base case that employs white Portland cement concrete resulting in a reduction of 1.8 °C. Similarly, in the North–South orientation, Case 4B (30.25 °C) with asphalt reduces UTCI by 1.6 °C when compared with Case 1A (31.87 °C), which also uses white Portland cement concrete.

Site orientation likewise plays a role in reducing UTCI. When building masses adopt relatively compact or box-shaped configurations, as seen in Case Groups 1 through 3, North–South–oriented sites tend to produce lower UTCI values than West–East orientations (WE > NS). However, when the building masses transition to more elongated and slender geometries, the West–East–oriented sites produce lower UTCI values than the North–South orientation (WE < NS).

These findings are expected to provide an initial reference for architects and practitioners involved in the planning and design of residential environments, particularly subsidized housing. In this context, modifying building mass configurations and geometric forms presents a cost-effective passive design strategy that has the potential to reduce outdoor temperatures and enhance thermal comfort within residential developments.

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Nedyomukti Imam Syafii contribute to the research concepts preparation and literature reviews, data analysis, of article drafts preparation and validation.