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# Effect of high-rise buildings on the surrounding thermal environment

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ABSTRACT

High-rise buildings degrade the thermal environment of their surroundings through wind turbulence, cooling, and excessive heating. This study identifies the role and relationship of geometric (form, orientation, dimension) and material (type, volume) parameters in conditioning the thermal environment around high-rise buildings. We performed the field measurements at four widely separated high-rise apartment buildings at different elevations (675–1050 m above sea level) in Bandung, Indonesia. Temperature, air velocity, and humidity were measured within a 150 m radius around each building three times daily (08–10 a.m., 12–04 p.m., and 06–08 p.m.) for three days in February. Airflow and shading patterns were analysed with Ansys-Fluent CFD and SketchUp software, respectively. Both direct observation and simulations showed that different orientations of buildings relative to the sun and wind can heat or cool the surrounding areas. The sail effect of a high-rise building exposed to direct sunlight can cause hot spots behind the building; choice of building material and use of shadowing can reduce this effect. The wind-tunnel effect can cause cold paths, especially if the area is shaded. Air turbulence and high-velocity airflow can result in uncomfortable conditions in the surroundings, based on the building height. Thus, high-rise buildings profoundly affect local thermal conditions. The results of this study are therefore essential for designing new buildings (and mitigating environmental quality around existing ones) in tropical cities.

## 1. Introduction

High-rise apartment buildings are ubiquitous in developing countries, where they are associated with economic growth and urbanisation. The construction of high-rise buildings in many parts of a city greatly alters the cityscape. For example, in the large Indonesian city of Bandung, rapid physical development has resulted in an increase in the air temperature [1]. One of the causes of urban heat island (UHI) effect is the extensive use of heavy building materials such as bricks and concrete on sidewalks and buildings in urban areas [2]. Other causes include thermal mass [3], land topography and water bodies [4], transportation and pollution [5], and vegetation [6].

The intensity of the UHI effect increases in areas where hot air is entrapped in urban canyons [7] or where heavyweight building materials store a great deal of energy from solar radiation, which is then released back to the environment in the long-wave infrared band [8]. Urban canyons can prevent the wind from sweeping warmer air away from building surroundings [9]. The building height, street orientation, and compactness of construction in an area also play important roles in urban ventilation performance on the precinct scale [10]. The canyon effect typically occurs in the low-wind-speed area surrounding the canyon [11], or where the geometry of the canyon causes a wind-shadowing effect [12]. The shadowing effect can be reduced by manipulating the canyon form [13], e.g. by providing the wind-scoop effect of taller buildings in the canyon [14] or changing building configuration, layout, or vertical components [15]. Different canyon orientations will cause different canyon air-temperature intensities [16]. The orientation of urban roads affects the solar heat gain on the wall surface of the canyon [17]. The material and albedo of streets and walls in a canyon store and release considerable heat energy from solar radiation [18]. The release of thermal energy from the canyon floor and wall results in an increase in the canyon air temperature [19].

In general, urban geometry strongly influences the cooling process, local warming control, and humidity; therefore, it must be considered in urban planning regulations [20]. The microclimate is a crucial factor that needs to be considered in the development strategy of an urban area [21,22]. Passive design, the most popular strategy for managing thermal environments such as those of UHIs and urban canyons and corridors, aims to maintain the quality of the natural microclimate and minimise uncomfortable conditions in an area without using artificial

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air-conditioning systems that consume large quantities of energy.

### 1.1. Geometric and material aspects of building design

An apartment building has a unique typology that can be used to determine its indoor thermal performance [23,24]. However, studies on the effect of large buildings on surrounding areas are very limited and generally focus on the UHI effect. Mavrogianni et al. [25] stated that the form of an apartment building has a considerably stronger effect on the variation in indoor air temperature than does its site. However, Soemarno [26] stated that outdoor design influences indoor thermal comfort, although form geometry aspect playing a significant role. In this study, formal/geometric building characteristics are considered alongside other aspects of design.

The form of a building mass affects the thermal environment and microclimate of the surrounding region. For example, cuts, recesses, and roundness modifications at the corners of tall buildings reduce aeroelastic instability. The effectiveness of these measures depends on their depths and the shape of the building. For example, corner modification results in a different performance when applied to a large building with a square plan than to a building of similar size with a rectangular plan [27]. Thus, the effects of a tall building on the microclimate/regional temperature may vary with its shape. Similarly, studies on several horizontal series of settlements with or without front yards show differences in thermal conditions [28]. Further, massing order and surrounding space affect ventilation [29], and dense high-rise buildings increase wind speed [30,31].

Not only the forms of buildings, but also their bulk and surface properties affect heat gain and release in an urban area. The wall material of buildings contains heavyweight materials such as concrete and brick, which store the heat energy from solar radiation. The wall orientations influence how solar energy is absorbed and re-radiated [32]. For example, heavyweight building material absorbs considerable heat energy; if a heavyweight wall or plate directly faces the sun, it acts as a major thermal reservoir [33]. Like the wall type, the bulk and surface properties of the building material [34] also play an important role in the absorption and release of heat energy [35].

Shadowing the wall and street, especially with vegetation, can also reduce heat gain and release, significantly affecting UHI intensity [36,37].

The roof of a building also contributes to heat island intensity. In tropical regions, the high solar altitude increases the radiation on the roof surface [38]. A horizontal concrete roof absorbs solar radiation during the day [39]. The heat released from a flat roof could be more significant than that released from the walls of low-rise buildings, but the same is not true for tall buildings [40,41].

The effect of air conditioning on the canyon air temperature is also significant [42]. High-thermal conductivity wall-material and insufficient thermal insulation cause an increase in the indoor air temperature [43]. Installing glass windows or walls on the east or west walls causes heating inside the rooms of buildings in tropical areas. The reflective glass helps reduce indoor cooling load, but it increases the air temperature in the surrounding microclimate [44]. The air conditioner releases the warmer air outside, which causes an increase in the canyon temperature.

We can conclude that the effect of building massing is attributable to many intercorrelated factors. The main factors are the thermal properties and volume of the building material, as well as the building geometry. Heavyweight materials such as concrete, brick, and asphalt can store and release much heat, but light materials such as glass, and metal panels do not. The impact of the material on the microclimate may be significant if its volume is large or if it is widely used in the built environment. Geometric factors related to the building's shape, orientation, and dimensions affect the microclimate by determining exposure and shading of sunlight and wind.

### 1.2. Objective

The objective of this study was to identify the material and geometric factors describing the apartment-building massing in the city of Bandung, Indonesia, that influence the environmental quality, as reflected in the air temperature, globe temperature, air velocity, and relative humidity. The material factors are the type and volume of building materials used in the façade, the pavement around the building, and other components. The geometric factors are the form, orientation, and dimensions of the apartment building. The effects of building massing can depend on the solar position over the course of the day, wind orientation, building shape, topography, and elevation of the area above mean sea level [1].

### 1.3. Research significance

According to existing research, the massive construction of high-rise buildings in urban areas contributes to climate change. To reduce a city's adverse thermal impact requires understanding of the physical characteristics of the urban environment, including geometric and material factors. In addition to looking at the urban environment on a large scale, it is important to consider the scale of individual buildings: the effect on the surroundings is larger for a larger and higher building, e.g., a high-rise apartment building.

In this paper, we discuss the influence of high-rise apartment buildings on the thermal conditions of their surroundings in a highland urban setting in the tropics. This discussion emphasises how the geometry and form of an urban apartment building on the one hand, and the characteristics of materials on the other, affect the micro-climate and thermal environmental conditions of the adjacent area. (Fig. 1).

In this study, the relevant parameters include the geographic elevation and distance from the large building. We seek to describe which aspects of big buildings do or do not significantly affect the thermal conditions of the surrounding area. This knowledge is essential for architects, planners, and regulators who establish development policies and thermal-environment requirements for urban areas. In addition to helping mitigate thermal environmental conditions around high-rise buildings already standing in urban areas, this information will allow architects to be creative in combining the effects of materials and geometry to produce comfortable, or at least acceptable, conditions in the areas around large buildings.

## 2. Methodology

### 2.1. Case study

Bandung is a highland city located 675–1050 m above mean sea level with a very comfortable air temperature of 16–25 °C. It lies in the basin of a mountainous area, making it a high-humidity environment. The comfortable environment in this area has led to the rapid growth of many high-density built-up areas and urban kampongs, with high-rise and low-rise buildings present in the same areas. Thus, building planning and design strategies are required to ensure a suitable environment in the areas surrounding big buildings. This study discusses four high-rise apartment buildings in the city of Bandung with various typologies and settings (Fig. 2).

### 2.2. Field measurement and simulation study

Field observations and measurements were conducted to determine the thermal conditions around each apartment building at pedestrian level (150 cm above the ground). To observe the phenomenon of wind deflection and shadowing by the high-rise building in its entirety, we added a computational fluid dynamic (CFD) simulation using Ansys Fluent v.16.0 multiphysics software. This simulator provides an accurate and visually clear picture of airflow for high-rise buildings. Using a

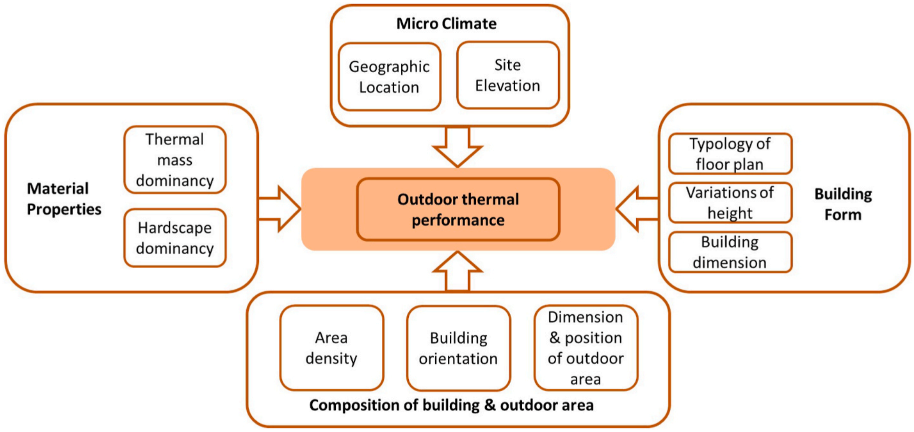



**Fig. 1.** Physical factors that affect the thermal performance of the apartment-building environment.

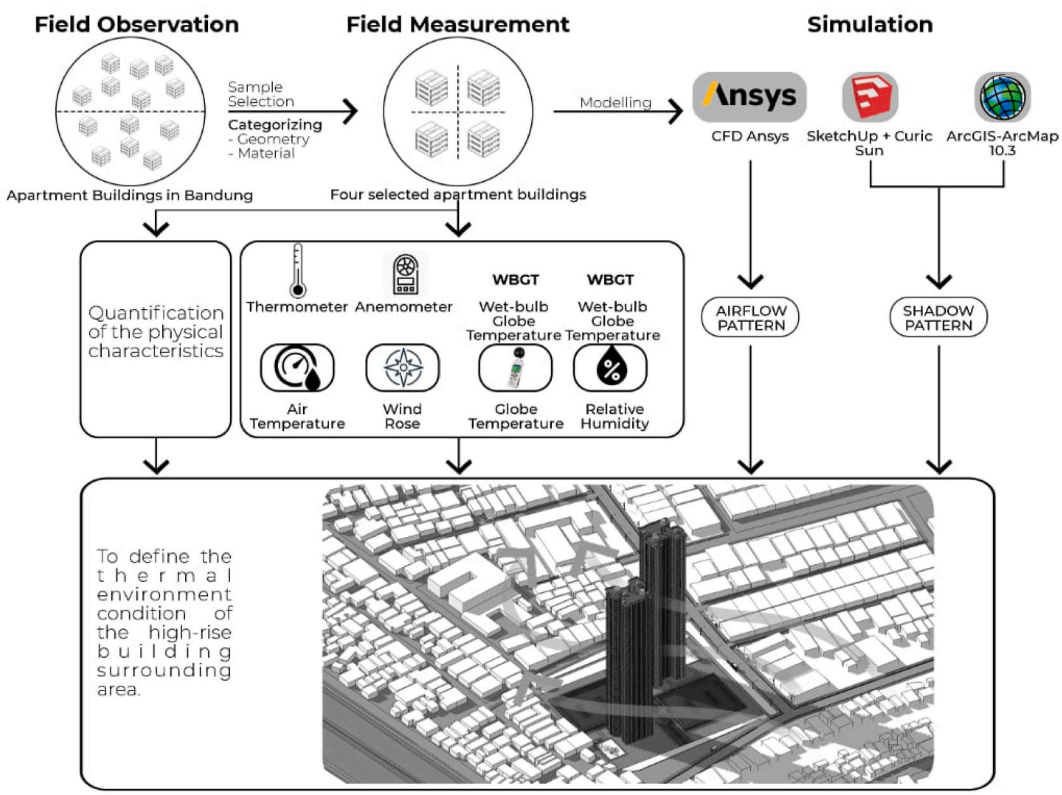



**Fig. 2.** Research method.

simulation can confirm the results of field measurements and help in the analysis.

Field observation was divided into two stages: mapping the profile of apartment buildings in Bandung and measuring the thermal environmental conditions in the four buildings selected in the first stage. The target object was determined using purposive sampling based on the general characteristics of apartments in Bandung with the following considerations: 1) the target object included buildings in the high zone in the North Bandung Region and the low zone in the south of Bandung; 2) in each zone, samples were selected that met the typological criteria of certain forms, so that a comparative analysis between zones could be conducted; 3) the unit of analysis was the subject building and its surrounding area within a radius of 150 m (not individual apartment units). (See Fig. 3).

### 2.2.1. *Sample selection*

As shown in Fig. 3, apartments in Bandung are typically double loaded, with medium- and high-rise circulations, precast-concrete panelled façades, and flat concrete roofs. This study discusses four apartment buildings in Bandung: two located in Bandung highland (HL) (above 750 m above mean sea level) and two in Bandung lowland (LL) (below 750 m above mean sea level) (Fig. 3).

Based on the field survey, we classified the apartment buildings by corridor types, number of floors (building height), façade materials, and roof materials. The corridor types and building height can be categorised as geometric factors, while façade and roof material can be categorised as material factors. Both aspects are studied for the cases of apartment buildings located in the HL and LL of Bandung. In the field survey, we recognised an important aspect of geometry: massing, which could be cluster-parallel or cluster-unparallel (Fig. 4).

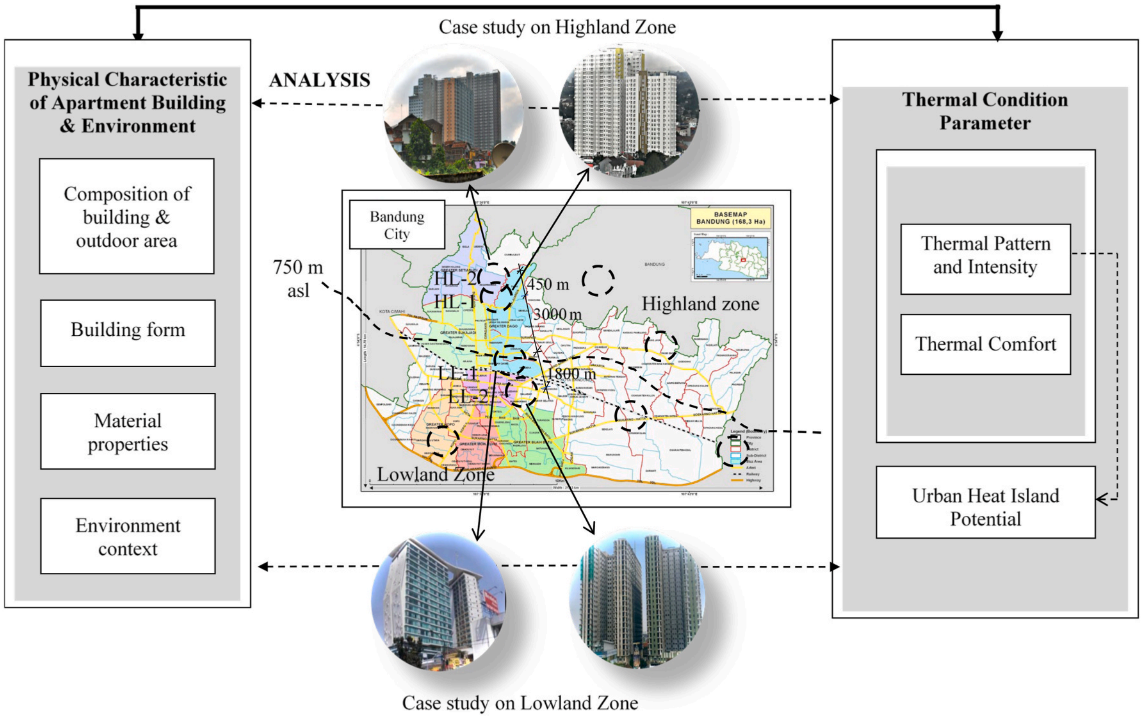



**Fig. 3.** Categorising apartments in highland and lowland zones of Bandung.

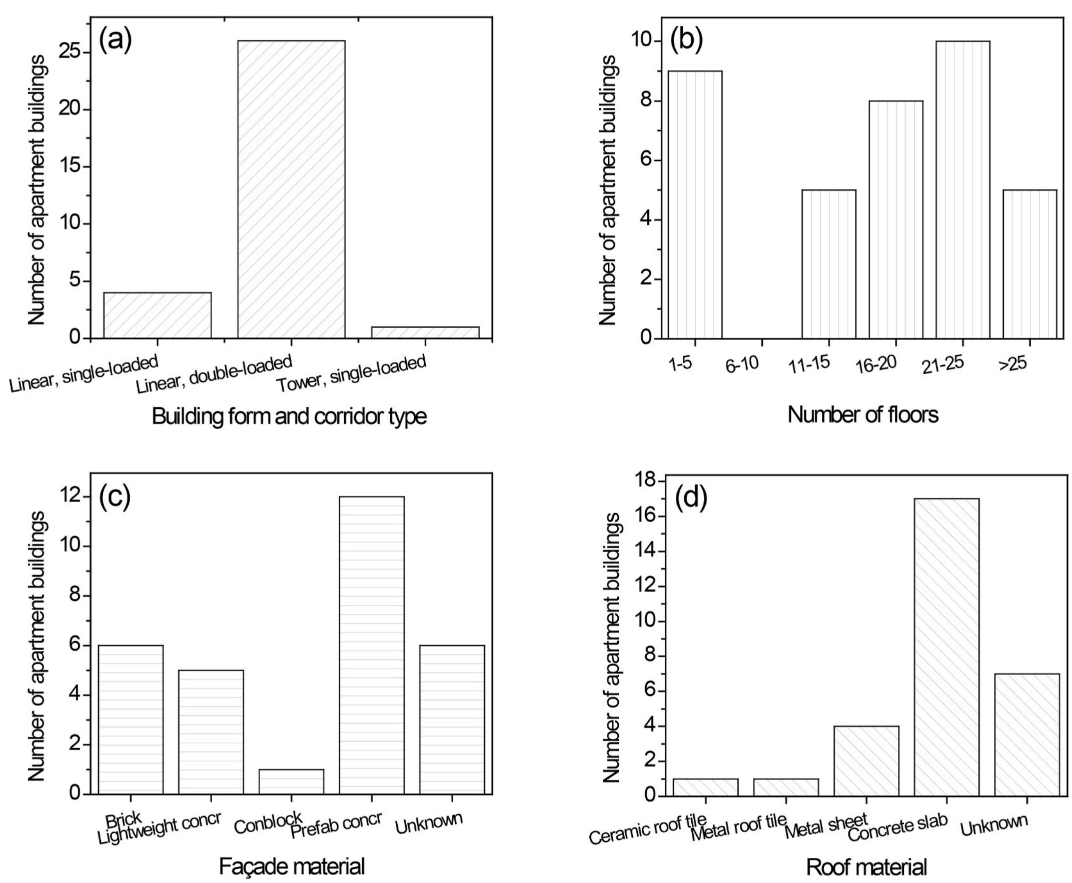



**Fig. 4.** Characterisation of apartment buildings in Bandung based on (a) building form and corridor types, (b) number of floors, (c) façade material, and (d) roof material.

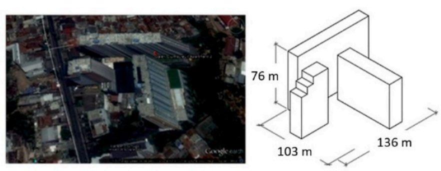
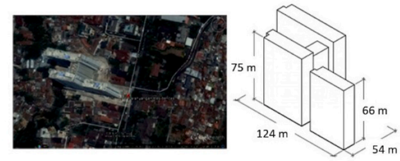
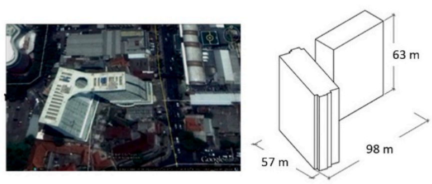
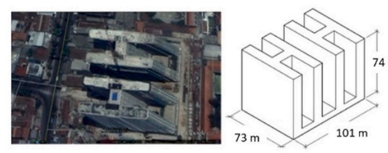
| **Type 1** | **Type 2** |
|---|---|
|  |  |
| HL-1 (34 floors – 794 m a.m.s.l.<br>Type: linear<br>Massing composition: cluster-unparallel | HL-2 (24 & 38 floors – 812 m a.m.s.l.)<br>Type: linear-courtyard<br>Massing composition: cluster-parallel |
|  |  |
| LL-1 (20 floors – 729 m a.m.s.l.)<br>Type: linear<br>Massing composition: cluster-unparallel | LL-2 (24 floors– 701 m a.m.s.l.)<br>Type: linear-courtyard<br>Massing composition: cluster-parallel |

**Fig. 5.** Aerial photographs and schematic drawings of the four selected apartment buildings. The a.m.s.l stand for above mean sea level.

In this research, we selected four apartment buildings: two in the HL zone and two in the LL zone, as presented in Fig. 5. The average height of the surrounding buildings was two stories, or about 10 m. The selected apartment buildings, which ranged from 20 stories up to 38 stories, corresponding to heights of 63 m–76 m, were therefore 10–20 times higher than the nearby buildings. The lengths and widths of the buildings were 54 m–124 m. Thus, the aspect ratios of the building configurations (significant for solar and wind shadowing) were 1.37–4.2 (Table 1). The apartment buildings represented two typologies: type 1 (linear, with cluster-unparallel massing) and type 2 (linear-courtyard, with cluster-parallel massing). The observation, field measurement, and digital simulations were performed at these buildings.

ArcGIS-ArcMap 10.3 and SketchUp were employed to obtain the physical characteristics of the apartment buildings in terms of wall areas and openings facing east, west, north, and south; footprint area; building coverage ratio (BCR); floor area ratio (FAR); aspect ratio (AR); slenderness ratio (SR); building volume; pavement area; and vegetation index. The wall areas facing east, west, north, and south were calculated using a projection perpendicular to each direction. The simulation indicated that the building configurations acted as wind tunnels; the data are summarised in Table 1.

**Table 1**
Quantification of the physical characteristics of the four observed apartments.

| | | Highland Zone | | Lowland Zone | |
|---|---|---|---|---|---|
| | Unit | HL-1 | HL-2 | LL-1 | LL-2 |
| East wall area | $m^2$ | 6.020 | 5.253 | 4.077 | 7.119 |
| East wall openings area | $m^2$ | 1.860 | 732 | 1.380 | 814 |
| West wall area | $m^2$ | 6.020 | 5.253 | 4.077 | 7.119 |
| West wall openings area | $m^2$ | 1.573 | 660 | 2.162 | 814 |
| North wall area | $m^2$ | 8.992 | 7.856 | 5.794 | 6.073 |
| North wall openings area | $m^2$ | 2.360 | 1.650 | 2.587 | 668 |
| South wall area | $m^2$ | 8.992 | 7.856 | 5.794 | 6.073 |
| South wall openings area | $m^2$ | 2.083 | 1.369 | 1.873 | 668 |
| Site area | $m^2$ | 16.004 | 9.546 | 5.249 | 13.556 |
| Building coverage area | $m^2$ | 3.712 | 2.746 | 2.053 | 8.196 |
| Building coverage ratio (BCR) | % | 23 | 29 | 39 | 60 |
| Floor area ratio (FAR) | Coef. | 5,05 | 6,54 | 7,87 | 8 |
| Aspect ratio (AR) | Coef. | 4,2 | 2,2 | 2,9 | 1,37 |
| Slenderness ratio (SR) | Coef. | 3,6 | 2,2 | 3,36 | 0,74 |
| Volume | $m^3$ | 242.262 | 187.315 | 123.868 | 335.976 |
| Pavement area | $m^2$ | 6.269 | 4.760 | 2.237 | 12.434 |
| Vegetation area | $m^2$ | 6.023 | 2.040 | 959 | 1.084 |

### 2.2.2. Instrumentation

The thermal environment was quantified via air temperature, radiation temperature, and relative humidity measurements obtained using a wet bulb globe temperature (WBGT) meter; the rate and direction of the airflow were measured using an anemometer (Table 2). Data were collected at an elevation of 150 cm above ground level; the WBGT device was shadowed (not exposed to direct sunlight). These measurements were conducted three times a day (morning, afternoon, and evening) over three days; weather conditions during the measurements were also recorded.

Thermal data related to the orientation of buildings to the sun and wind were collected at measuring points 50 m, 100 m, and 150 m away from the centre point of the apartment building that was the main object of study, for all eight orientations of the compass (Fig. 6). The measurements collected 150 m away from the target building constituted the limit of the spatial analysis conducted in this study. This limitation was based on the study by Du et al. [45], who found that the physical aspect of a building had a significant impact on the nearby surrounding environment.

A comparative analysis of apartment-building conditions was used to explain the thermal characteristics of the surrounding areas during the

**Table 2**
Sensor types and specifications.

| Sensor | Model/Type | Range | Accuracy | Resolution |
|---|---|---|---|---|
| WBGT meter | WBGT2010SD | Air temp. (TA): 0–50 °C<br>Black globe temp. (TG): 0–80 °C<br>Humidity: 5–95% RH<br>Wet bulb temp.: −21.6 to 50.0 °C | Air temp. (TA): ±0.8 °C<br>Black globe temp. (TG): ±0.8 °C<br>Humidity: ≧70% RH, ± (3% reading + 1% RH); <70% RH, ± 3% RH. | Air temp. (TA): 0.1 °C<br>Black globe temp. (TG): 0.1 °C<br>Humidity: 0.1% R.H.<br>Wet bulb temp.: 0.1 °C |
| 4 in 1 environment tester | 45170 | Air velocity: 0.4–30 m/s<br>Relative humidity: 10–95% RH<br>Temperature (Thermistor): 0–50 °C | Air velocity: ±3% F.S.<br>Relative humidity: ±4% RH<br>Temperature (Thermistor): 1.2 °C | Air velocity: 0.1 m/s<br>Relative humidity: 0.1% RH<br>Temperature (Thermistor): 0.1 °C |

WBGT is wet bulb globe temperature, and RH is relative humidity.

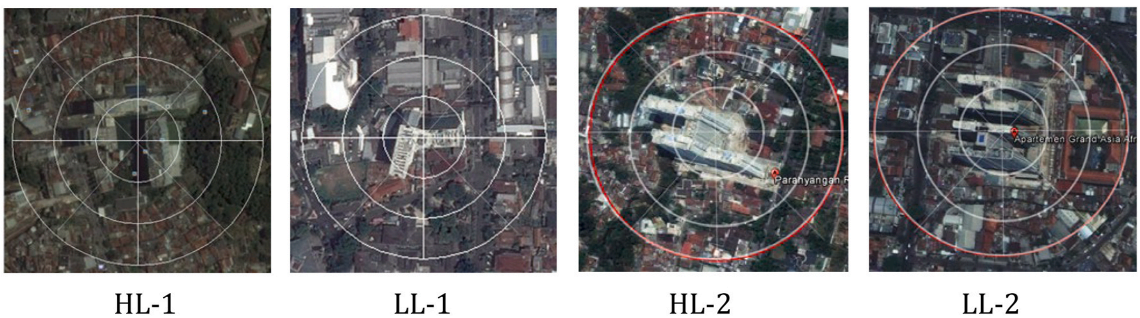



**Fig. 6.** Zones and points of measurement around the four apartment buildings.

day and night. Temporal analysis was conducted over three periods: morning, 8–10 a.m.; afternoon, 12–4 PM; and night, 6–8 PM.

To confirm the results of measurements in the field, simulations of airflow characteristics and air temperature were conducted using CFD Ansys Fluent v.16.0 software. SketchUp with the Curic Sun extension was used to illustrate the shadowing effect. The setup for the simulation included setting the boundary to 6 × H in the front, right, and left sides of the apartment-building model (where H = height of the building model), and 16 × H at the back side of the building (Fig. 7). The mesh (grid) around the building was set to 5 m for a sufficiently accurate result. Digital simulations were conducted to obtain more detailed data and insight into phenomena that could not be observed in the field, e.g. airflow patterns at various heights around the apartment buildings. The simulation was validated by matching the trend of the results of the field measurements with that of the simulation results.

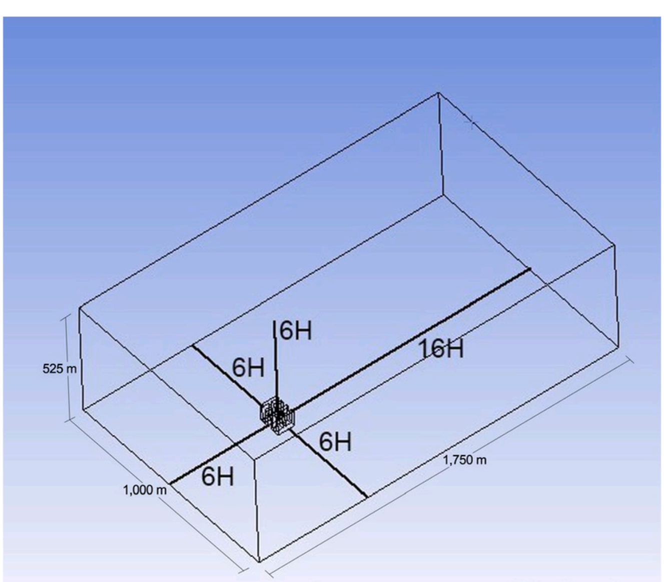



**Fig. 7.** Model of apartment building and wind tunnel dimensions in computational fluid dynamics experiments. H is the height of the model building.

The first step of simulation was the creation of a digital model of an apartment building using AutoCAD software, which was then imported into Ansys Fluent as geometric data. These data already included the wind tunnel geometry, with dimensions as shown in Fig. 7 (mean wind-tunnel size: length $p = 1750$ m, width $l = 1000$ m, height $t = 525$ m). Next, the mesh/grid was adjusted to a value ranging from 0.3 m in the area closest to the building up to 10 m in the farthest area (at the edge of the wind tunnel). All wind-tunnel faces were set as solid planes, except for the inlet and outlet, which were set according to the velocity inlet and outlet boundary conditions, respectively. The simulation carried out in this study was limited to observations of air movement, with turbulence models using viscous–laminar conditions. The calculations were conducted to reach a minimum of 1000 iterations.

## 3. Results and analysis of field measurements and simulations

The effect of apartment buildings on the thermal conditions around the building was analysed in terms of the orientation of the sun and wind. The wind factors affecting each building setting were analysed. The simulation results of the effect of the shadow pattern of the building on wind flow and solar radiation during the days of measurement were analysed for verification.

### 3.1. Thermal measurement and simulation of air velocity

At various times of day, we collected average thermal data at points outside the building at 50 m, 100 m, and 150 m, to determine the effects of wind and received solar radiation.

The air temperature around a given building varied according to the shading of the sun and wind. The air temperature near the building—within a radius of 50 m—tended to be lower due to the influence of the building wall materials. However, the globe temperature at a given distance tended to be higher when the sun shone on the east side of the building (from morning to noon), and lower when it shone on the west side. At a radius of 150 m, the globe temperature on the west side of the building tended to be particularly high from morning to noon because there was no shadowing effect at this distance.

The massed buildings served as a barrier to horizontal air movement, with the narrow gap between buildings causing the airflow speed to increase. Furthermore, the high mass of the building blocked the air movement like a sail and forced the airflow upwards, creating a wind shadow behind the building. As the effect of the building shape on the movement of air occurred along the full height of the building, all apartment units were affected by the resulting airflow (Fig. 8).

The airflow speed during the afternoon was found to be faster than that during morning and evening; it was considerably influenced by the shape of the building mass. The effect of building shape can extend to a distance of 1–1.5 times the building height, according to the simulation results shown in Fig. 9. The simulation results of airflow at an altitude of 1.5–70 m show the effect of wind shadows due to the mass of large buildings (Fig. 9).

The simulation results (Fig. 9) show that the effect of building shape on airflow was more significant in bigger buildings. In the case of LL-2,

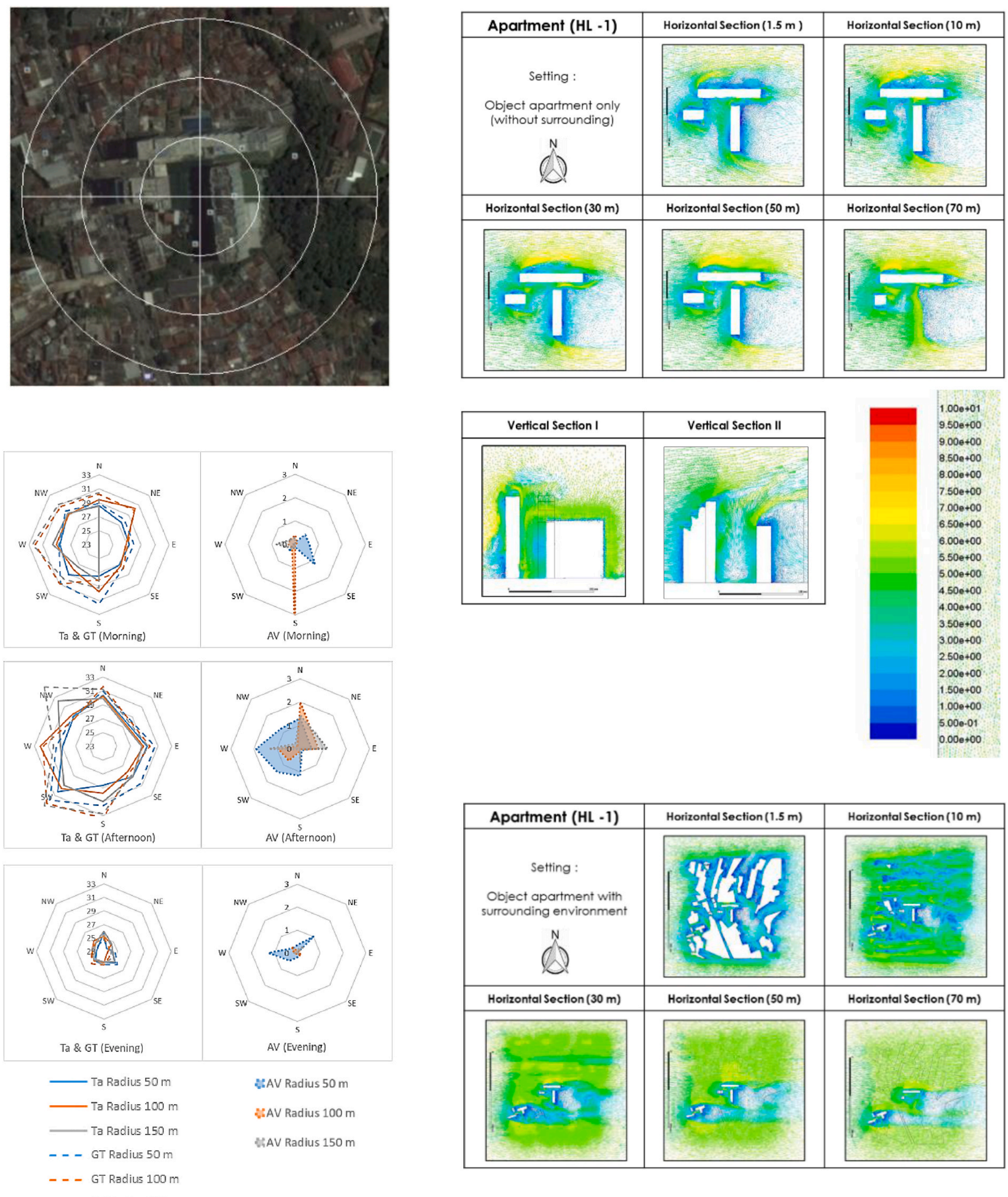



**Fig. 8.** Effect of HL-1 apartment building: (Left) Field measurements of air temperature (Ta), globe temperature (GT), and air velocity (AV); (Right) Airflow pattern with and without surrounding environment, simulated using Ansys Fluent.

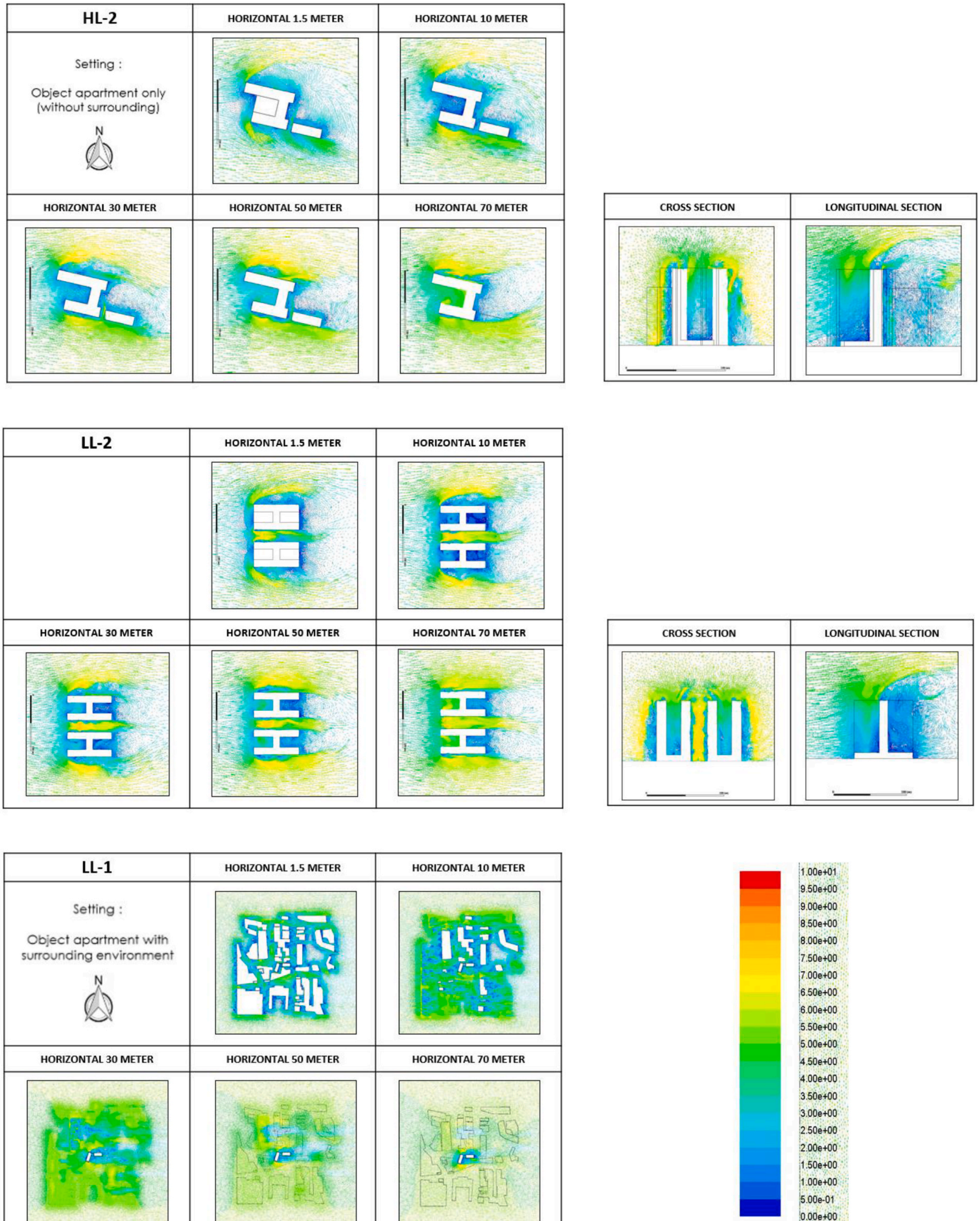



**Fig. 9.** Effect of building shape on the surrounding airflow patterns at various levels of elevation.

extreme differences were observed in the airflow rates around the building, as the shape of the niche created regions of turbulent and/or motionless air, and the form of the narrow alley generated a strong airflow.

### *3.2. Shadow simulations*

The city of Bandung is located at 6°54′ S; therefore, the apparent position of the sun is toward the north from late February to late October, and to the south otherwise. These positions lead to different shading patterns and affect thermal conditions around the apartment buildings. Therefore, shadow simulations were conducted for the same days that the field data were measured to ensure that the shadow data could be compared with thermal data obtained by measurement. In addition, simulations were conducted for several months with markedly different sun positions (June 21, when the sun was in the 23.5° U position; September 23 when the sun was above the equator; and December 22, when the sun was in the 23.5° LS position). The simulation results are listed in Table 3.

Shading has a positive effect in terms of blocking heat radiation; however, it simultaneously increases air humidity. The effects of shading are felt mainly in the morning and afternoon. Shading reduces the amount of morning sun available in shaded residential areas; this is particularly detrimental in the rainy season. However, shading on an asphalt road has a positive effect on the local air temperature.

The shadow of a building depends on the building's shape and dimensions. Buildings with a small aspect ratio cast only a small sun shadow compared to those with large aspect ratio.

### *3.3. Effect of building massing on air temperature*

Because a large apartment building casts a large shadow, light and solar thermal radiation are partly prevented from hitting certain nearby areas. To observe the effect of the shadow caused by the mass of the building, a morning-to-evening (08:00–17:00) shadowing simulation was conducted on the environment around each apartment building (Fig. 10).

The results of the field measurements in the neighbourhood around the HL-1 apartment building indicated a significantly lower average air temperature (Ta) on the northeast side at radii of 50 m and 150 m and on the east side at a radius of 50 m. The highest Ta did not appear to move in a specific direction (Fig. 10).

The Ta in the neighbourhood around the HL-2 type apartment building showed an area with the highest air temperature on the southwest side, at radii of 50 and 150 m; the lowest Ta was on the northwest side, at a radius of 50 m from the building. Around the LL-1 apartment building, the areas with the lowest air temperatures were in the north, northeast, east, and southeast, at radii of 50 and 100 m. The Ta in the radius of 100 m around the apartment was the lowest in almost all directions of the compass. In the environment around the LL-2 apartment, the lowest air temperature was at a radius of 50 m, independent of direction.

The apartment buildings, as mentioned, were of two types: linear (type 1) and linear-courtyard (type 2). Those of type 2 showed a lower daily average temperature at a given radius. Thus, in the environment around apartment building LL-1, lower temperatures occurred at a radius of 100 m; around LL-2, lower temperatures occurred at a radius of 50 m. For both types, Ta was highest at a radius of 150 m.

The 150 m radius measurement point in the LL-2 type environment was close to an asphalt highway; those in the LL-1 type environment were in various surroundings (highways, footpaths, green spaces, and riverbanks). Points at a radius of 150 m were far from high-rise apartment buildings, and therefore, the effect, if any, of the large building's shadow was of very short duration and could be neglected. Thus, it did not have a significant effect in holding sun exposure around the measuring point.

### *3.4. Effect of building massing on mean radiant temperature*

Globe temperature (GT) measurement results show that GT reaches its maximum value at a radius of 150 m. By contrast, the air-flow rate (AV) at the same radius is at a minimum. At 50 m and 100 m, however, the AV is larger than in the surrounding environment. Points at a radius of 150 m are far away from the mass of apartment buildings, and therefore, changes in the pattern and rate of airflow caused by the presence of the apartment buildings are relatively small (Fig. 11).

### *3.5. Effect of building massing on air velocity and humidity*

The role of the wind was analysed to observe its effects on cooling of the area around the building. Several phenomena such as turbulence, increasing wind velocity, and reverse effect (no cooling) might be expected in areas sheltered from the wind (Fig. 12).

The two type-2 buildings were both orientated parallel to the direction of the wind. Digital simulations of airflow around these buildings showed significant changes in air-flow characteristics due to the apartment building, especially at high elevations. Airflow close to the ground surface was not only affected by the high mass of apartment buildings but also by physical objects at the ground level (other buildings, road corridors, land contours, and vegetation). The airflow rate appeared to increase significantly close to the apartment building, especially in the open area of the apartment site. In this area, the results of airflow measurements seemed to depend on the mass of the apartment building alone. By contrast, the airflow in a radius far from the apartment was greatly influenced by nearby buildings.

The shading of wind and sun by the building increased the humidity of the air around the building. The area where the humidity increased depends on the shape of the building and the weather conditions. On a clear morning, the east side of the building was dry; however, the west side was shaded and tended to be humid, especially if the wind speed was very slow at that time (Fig. 13). The mass of a building casts a broad shadow when the sun is low on the horizon in the east or west; this may cause uncomfortably high humidity in the outdoor space.

### *3.6. Effect of building material*

The building material also affects the thermal conditions around the building. For example, heavy building materials, such as bricks and concrete, have the potential to store large amounts of heat, thereby providing a warming effect on the environment due to the heat released into the air over a long period of time (up to 16 h). In contrast, light building materials, when exposed to sunlight, immediately increase in temperature and heat the surrounding environment with high intensity. In addition, light materials tend to transmit heat into buildings, increasing the energy consumption for air conditioning. Fig. 14 shows the composition of the building-material types used in the four apartment buildings in this study.

Apartment building LL-2 had the largest percentage of heavy materials. Most of the heavy material faced north and south and therefore had a low impact on the air temperature. Thus, even though the building is located on low land, its environment did not become hotter than that of HL-1, which is located on higher land (Figs. 10 and 11). The type-2 apartment building has a wing unit that faces the east and west, and therefore, it receives higher and longer solar radiation (Table 3). Thus, it can be concluded that the shape of a big building has a dominant effect on the air temperature of the surrounding environment.

## 4. Discussion

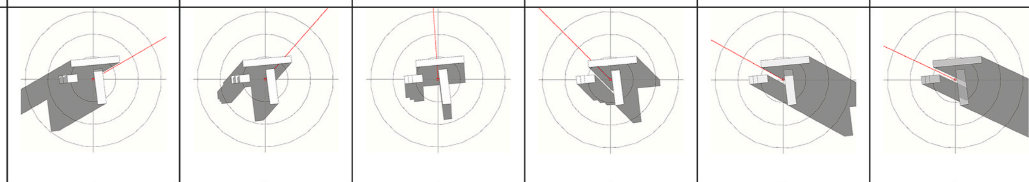
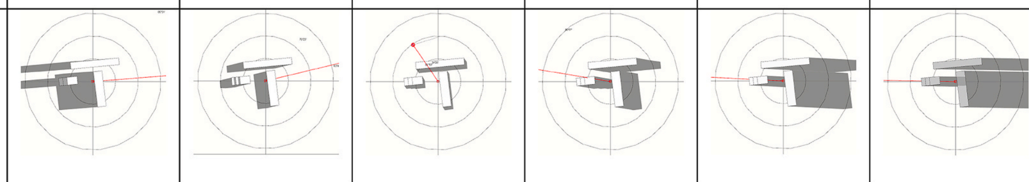
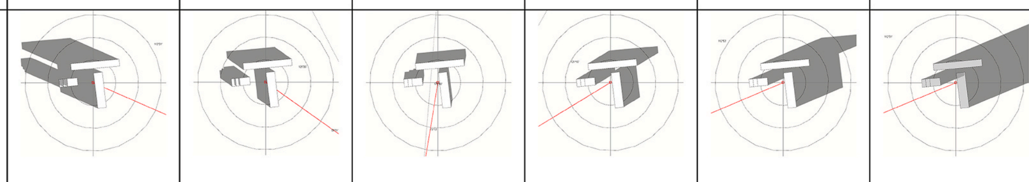
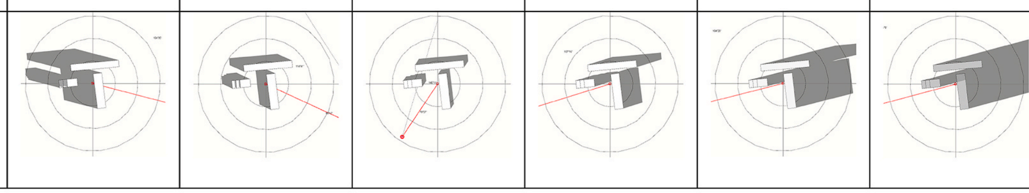
### *4.1. Effect of distance from high-rise building*

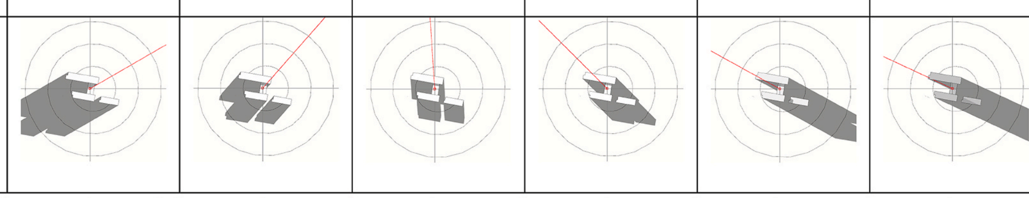
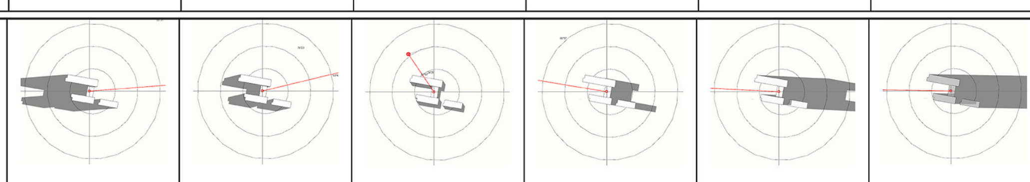
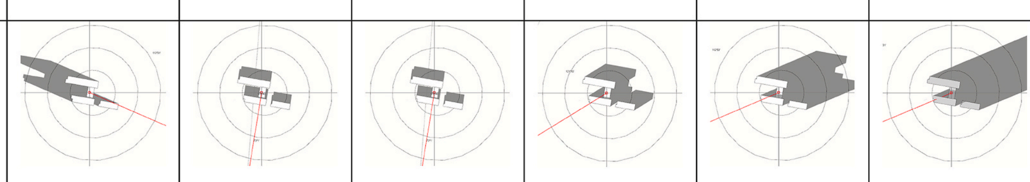
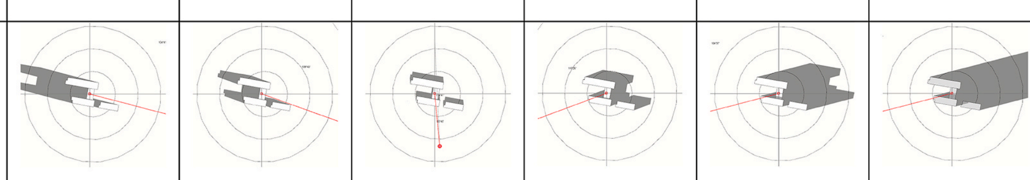
The general pattern of the building massing effect is shown in Figs. 15 and 16. In Fig. 14, N1, N2, and N3 are the measurements at the north side of the building within a radius of 50, 100, and 150 m, respectively; measurements in the other seven compass directions are labelled similarly.

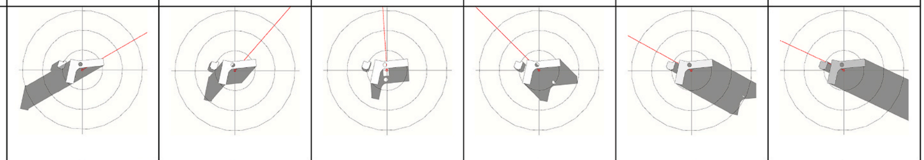
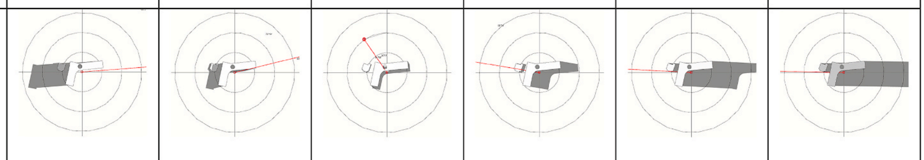
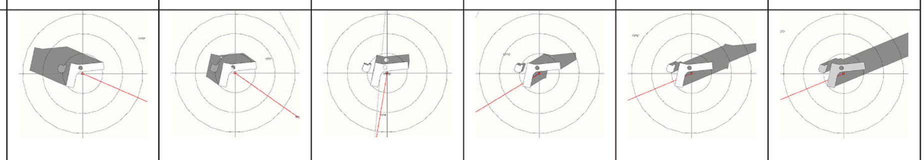
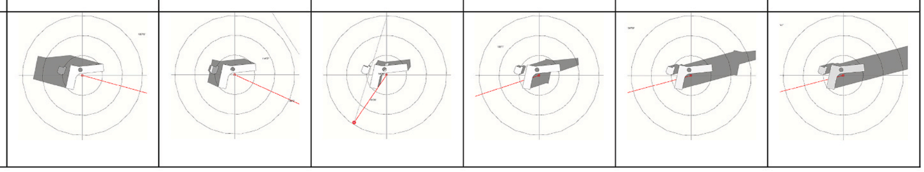
In Figs. 15 and 16, the secondary Y axis shows the volume of the buildings ($m^3$). Morning, afternoon, and night temperatures were recorded in eight directions around the building at distances of 50 m, 100 m, and 150 m from the centre point of the building. Farther away from the building, the morning and afternoon air temperatures tended to increase.

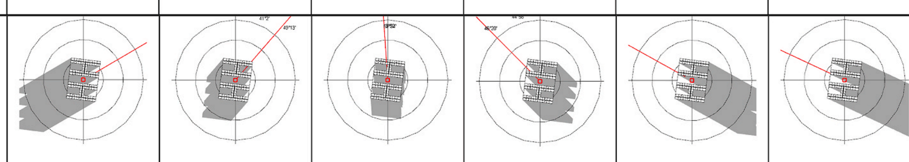
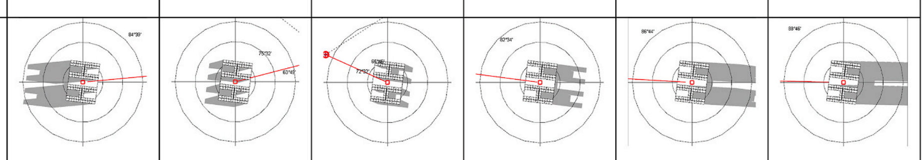
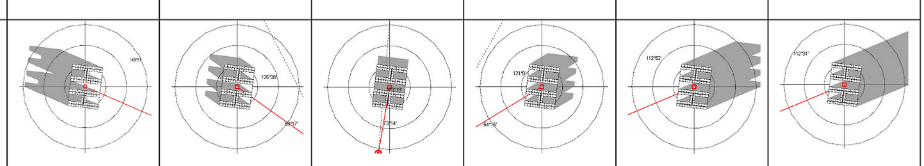
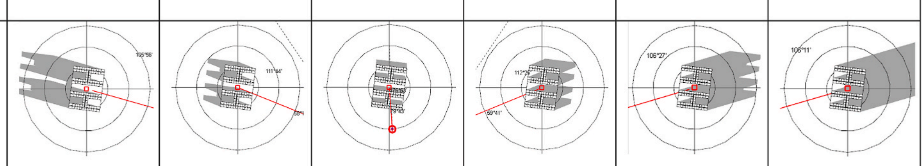
In general, the farther away the measurement point was from the

**Table 3**
Simulation of sun shadow around the apartment buildings.

| Apartment Building HL-1 | | | | | | |
|---|---|---|---|---|---|---|
| Date | 08.00 am | 10.00 am | 12.00 pm | 2.00 pm | 4.00 pm | 5.00 pm |
| June 21 |  | | | | | |
| September 23 |  | | | | | |
| December 22 |  | | | | | |
| November 5 |  | | | | | |

| Apartment Building HL-2 | | | | | | |
|---|---|---|---|---|---|---|
| Date of measurement | 08.00 am | 10.00 am | 12.00 pm | 2.00 pm | 4.00 pm | 5.00 pm |
| June 21 |  | | | | | |
| September 23 |  | | | | | |
| December 22 |  | | | | | |
| February 6 |  | | | | | |

| Apartment Building LL-1 | | | | | | |
|---|---|---|---|---|---|---|
| Date of measurement | 08.00 am | 10.00 am | 12.00 pm | 2.00 pm | 4.00 pm | 5.00 pm |
| June 21 |  | | | | | |
| September 23 |  | | | | | |
| December 22 |  | | | | | |
| November 7 |  | | | | | |

| Apartment Building LL-2 | | | | | | |
|---|---|---|---|---|---|---|
| Date of measurement | 08.00 am | 10.00 am | 12.00 pm | 2.00 pm | 4.00 pm | 5.00 pm |
| June 21 |  | | | | | |
| September 23 |  | | | | | |
| December 22 |  | | | | | |
| February 5 |  | | | | | |

building, the higher was the temperature; this was especially true in the morning and the afternoon. Proximity to the building caused lower air temperatures owing to the shadowing effect of the mass of the apartment building in the morning and evening; walls, roofs, and pavement did not receive continuous direct radiation from the sun, but were periodically overshadowed. Some parts only warmed up in the morning, but not in the afternoon, or vice versa. Owing to noncontinuous heating, the east and west sides took turns receiving sunlight, and this affected air temperatures in various directions (Fig. 16).

Fig. 17 shows that air temperatures on the south side tended to be higher in the morning. This was because the south side received morning sunlight in February (when the measurements were carried out); the south wall of the building faces slightly east, causing the morning air temperature to be higher.

### 4.2. Effect of form and orientation

The shape and orientation of buildings affect the thermal quality of residential spaces. In Bandung, rooms on the east and west sides of buildings receive sun and morning radiation exposure; they are also exposed to west winds in the wet months (September–February) and east winds in the dry months (May–August). Thus, the west and east faces of the buildings are prone to rainwater leakage through the walls and to unwanted light, rain, or airflow through openings. For these reasons, building planners generally minimise spaces and openings facing east or west.

From the perspective of urban space, the phenomenon of UHI occurs because of heating of the sides of buildings facing east and west. This effect is made worse if the east and west walls are composed of heavy building materials that absorb and release heat in large quantities. Therefore, buildings should not have extensive east and west walls.

The shape of a large building influences the surrounding environment in two ways:

(a) In planning outdoor activities around buildings, it is necessary to consider shading. The building may block the sun in certain directions, lowering the ambient air temperature (which is considered a positive effect in a tropical environment). A large building massing in the middle of a city acts like an urban umbrella, which, if well planned, will benefit the surrounding environment. However, there are also negative effects such as increased humidity or formation of puddles on the west side of the building, especially in the wet season. The burden of maintenance caused by this can be very large; e.g. rainwater on brick and concrete walls may causes salting. In addition, leakage also damages other building components, ranging from ceilings to furniture. The maintenance of buildings with this orientation must be conducted routinely; waterproofing and painting must be conducted seasonally. This leads to an increase in maintenance and life cycle costs over the lifetime of the building. In planning a building's figure, investment costs for the owner must be considered.

(b) The wind shadows on the surrounding buildings have several positive and negative effects. Wind turbulence around the building occurs because of the height of the building's mass, which acts like a wind catcher (wind scoop); this cools the environment, lowers air temperatures, and repels humidity and pollution. This positive effect was identified in a number of apartment areas in Bandung. However, air turbulence has an adverse effect on the surrounding buildings as well; it interferes with light building components (roofs, canopies, openings), generates noise, and causes considerable damage. Other negative effects are felt when air turbulence directly affects people moving around the building, such as pedestrians or those who operate outside the building. On the other side of the building, the wind shadows provide negative or neutral air pressure that can cause negative effects such as humidity, pollution, and higher air temperatures; this results in an especially uncomfortable environment in cloudy weather. These negative effects are associated with the wet season; in the dry season, the wind shadow has a positive effect on outdoor users because they are protected from strong winds. Nevertheless, the effect of wind shadows on the east and west side of the building cannot have a positive effect throughout the year. Therefore, building configurations with large east-west fields should be avoided.

Changes in the microclimate quality will occur when the walls of large buildings are constructed using heavy materials that increase the ambient air temperature. Applying the energy balance concept to building components can therefore serve as a potential UHI-mitigation technique. The use of smart walls that manage heat, e.g. green walls that absorb heat to power photosynthesis, can realise zero-UHI-impact buildings [46].

### 4.3. Effect of urban ventilation

The air temperature around a building depends on the distance to the building and the shape of the building. The distance of a measuring point from the building influences both solar and wind shading. The shading of the sun causes lower air temperatures, but, in some places, wind shadows eliminate the cooling effect; therefore, the air temperature tends to be high. Other places, however, may not get sunlight because they are overshadowed by the building but are not in its wind shadow; hence, cooling occurs. In general, air temperature at a measuring point depends on the equilibrium between the heating and cooling processes.

The shape and orientation to the sun and wind of big buildings in the middle of a city thus have a significant influence on the temperature of the adjacent environment. A vertical plane parallel to the wind direction only has a small wind shadowing effect, thereby allowing the cooling of the surroundings by the wind. Conversely, a vertical plane perpendicular to the direction of the wind acts like a screen that blocks the cooling process behind the building; the ambient temperature behind the screen tends to be high, especially when the building faces east–west. The phenomenon of negative air pressure in the wind-shadow area causes a suction effect on the façade that can force doors or windows to open or be separated from the wall. Vice versa, there is an effect on the façade facing the wind effect of the pressure on the surface of the façade. Thus, the mass of large buildings in the middle of the city should not be oriented such that they face the direction of the wind or the rising or setting sun.

The figure of a large building in the middle of the city is very sensitive to its shape and orientation; therefore, designers of such structures must consider surrounding buildings and include the masses of the surrounding buildings in a complete thermal environment plan, e.g. by addressing the role of ventilation mass (elevated buildings, solid-void concepts on building masses, or aerodynamic forms of buildings). Urban ventilation has a considerable influence on the quality of the microclimate surrounding a building in terms of local warming control and UHI mitigation. Indeed, the microclimate quality is shaped by three crucial urban ventilation factors: compactness, building height, and street structure [47].

Designers also need to consider the shape and orientation of the opening components of buildings, such as sills, shutters, doors, glass, and aluminium panels, which can cause casualties to the surrounding community.

### 4.4. Big buildings, topography, and city climate

Building-mass configurations also play a role in wind shading. The configuration of two building masses to form a corridor parallel to the direction of the global wind results in a strong wind-tunnel effect that cools but has the potential to disturb the surrounding buildings. The

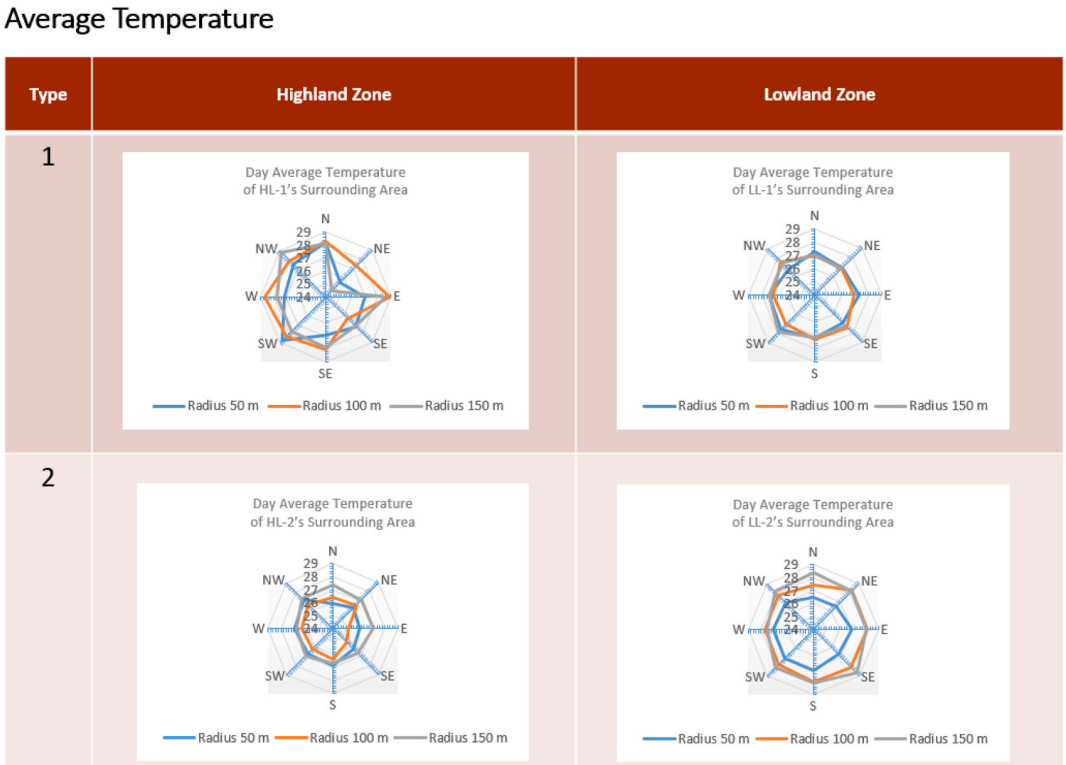



**Fig. 10.** Average air temperature in areas surrounding apartment buildings in study.

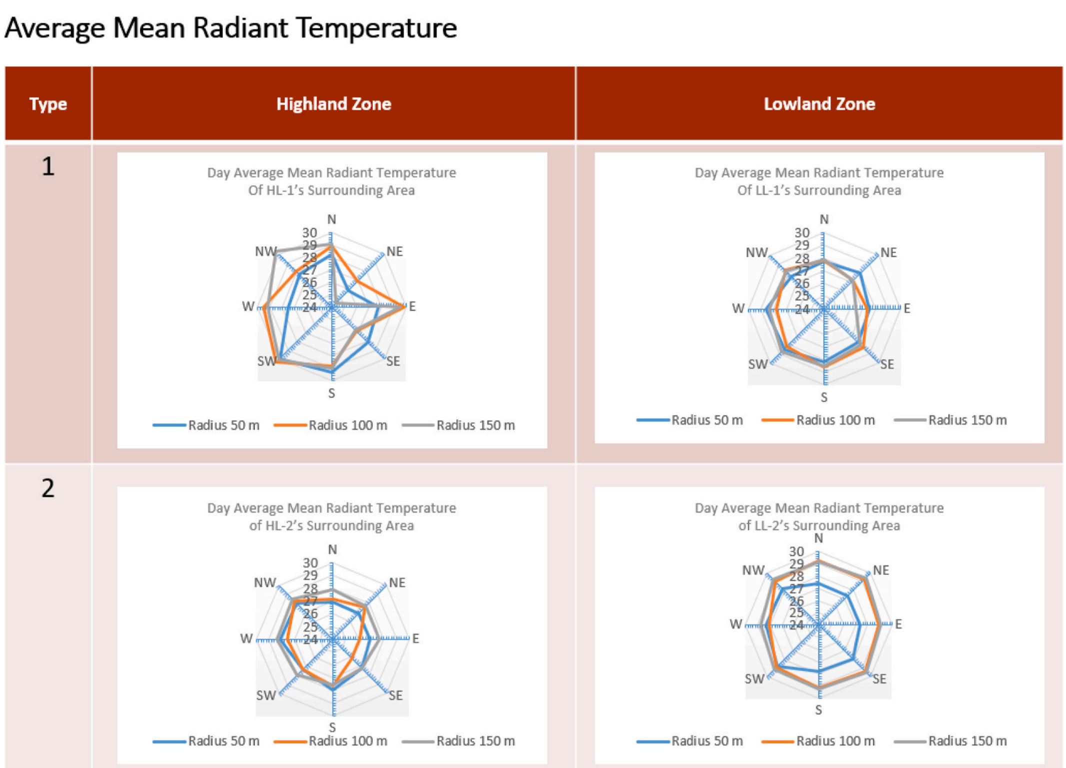



**Fig. 11.** Globe temperature at various distances from apartment buildings.

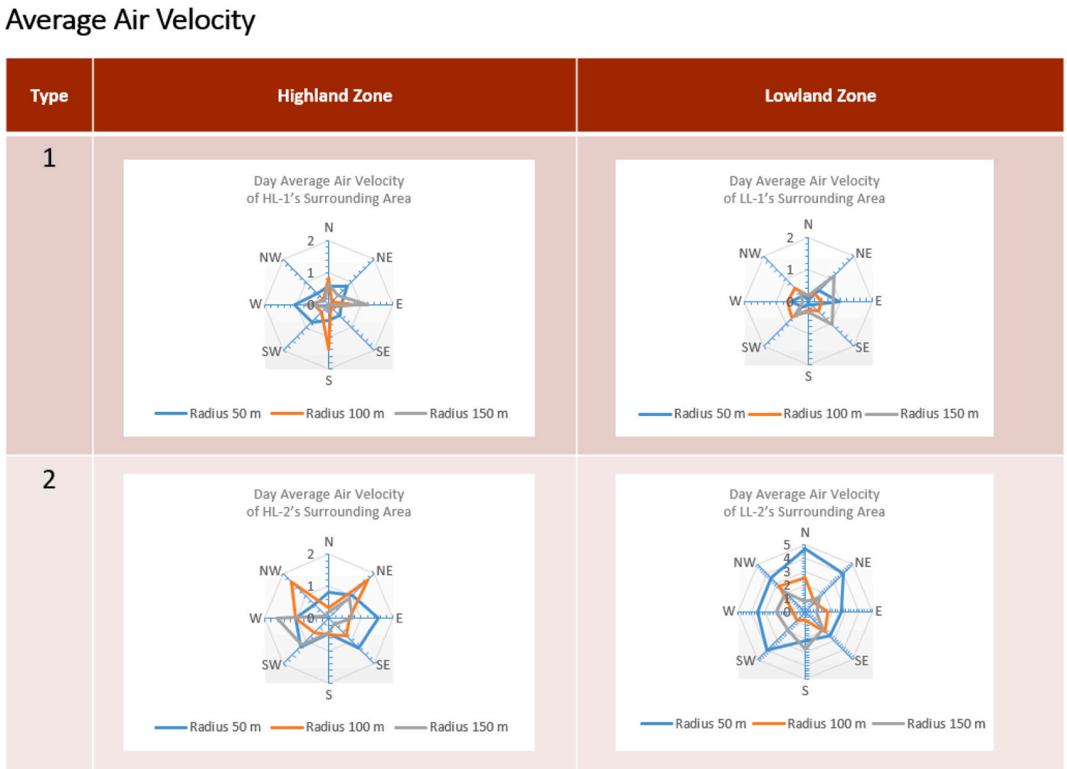



**Fig. 12.** Average air speed at various distances from apartment buildings.

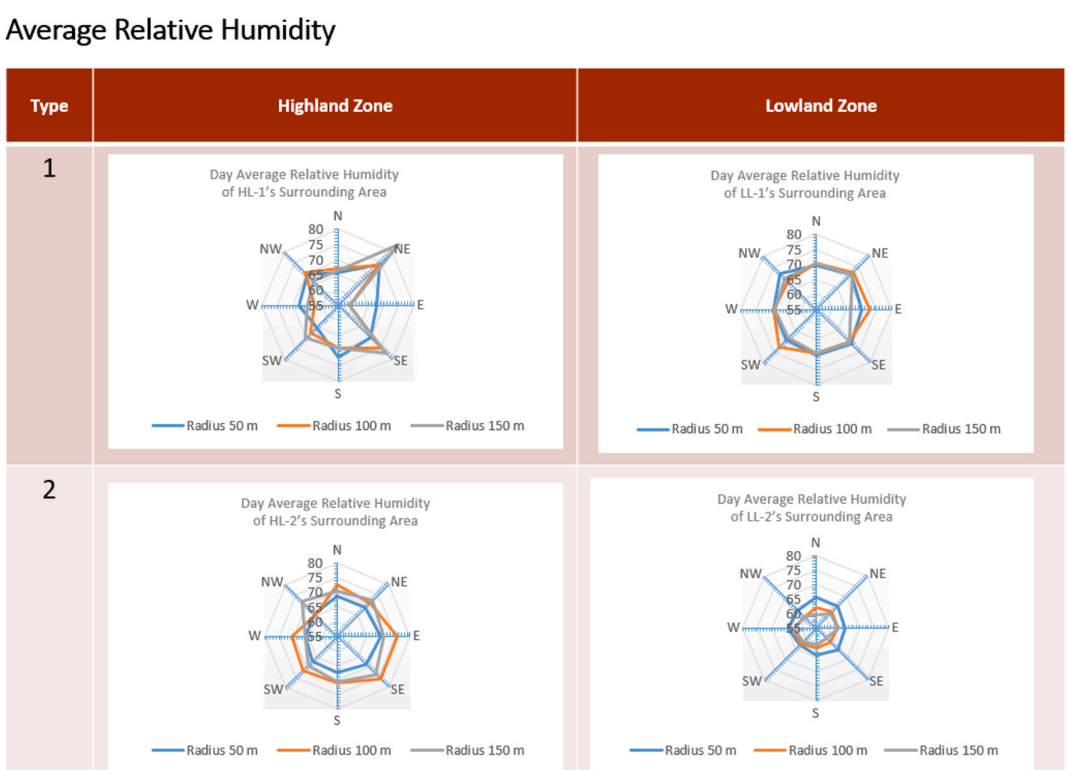



**Fig. 13.** Humidity of the air around a building is influenced by wind speed and the shape of the building.

wind may even dislodge roof coverings and clotheslines and cause serious problems for people in the surrounding area. The height of the building massing and the length of the building determine the extent of the wind and sun shadows. The wider the plane of the shadow is, the greater is the difference in air pressure and air temperature. Therefore, it is necessary to study the permissible mass of buildings in the middle of

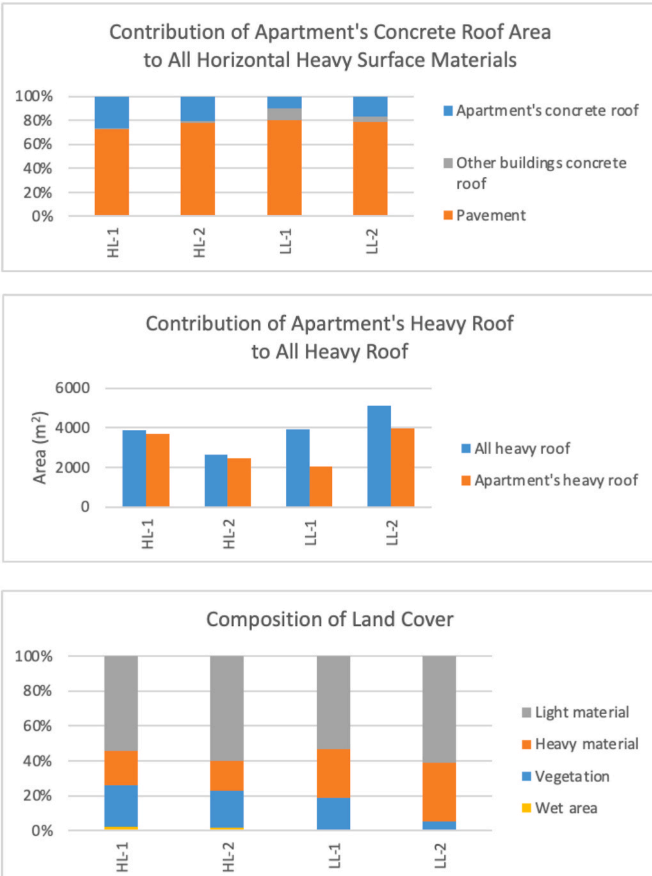



**Fig. 14.** Composition of types of building materials in each apartment building.

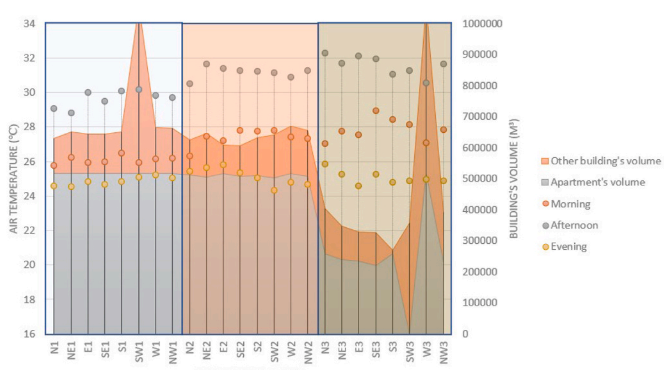



**Fig. 15.** Morning, noon, and night temperatures in various directions around an apartment building. The three segments of the X axis correspond to measurements in eight directions at 50, 100, and 150 m.

the city further.

Bandung is located on a plateau. This provides a thermal advantage; the temperature of the city is lower than the temperature of large cities located in the lowlands, such as Jakarta, Semarang, and Surabaya. The tread elevation range of the city of Bandung is considerable, between 675 and 1050 m. In addition to influencing air temperature, the elevation range is related to regional characteristics (flat and slope) and city regulations that limit the density of buildings in the high zone. Thus, different thermal phenomena emerge in the low and high elevation zones studied.

Airflow around a building is affected by macro-scale and micro-scale winds. The micro-scale winds in the environment around the apartment

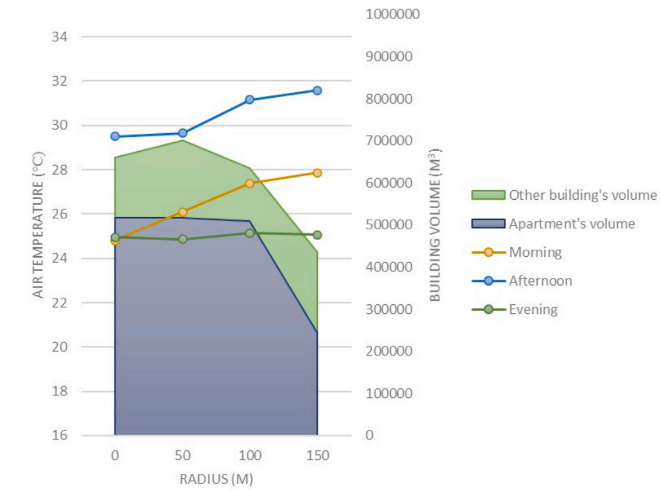



**Fig. 16.** Air temperature as a function of distance from an apartment building, averaged over all cardinal directions.

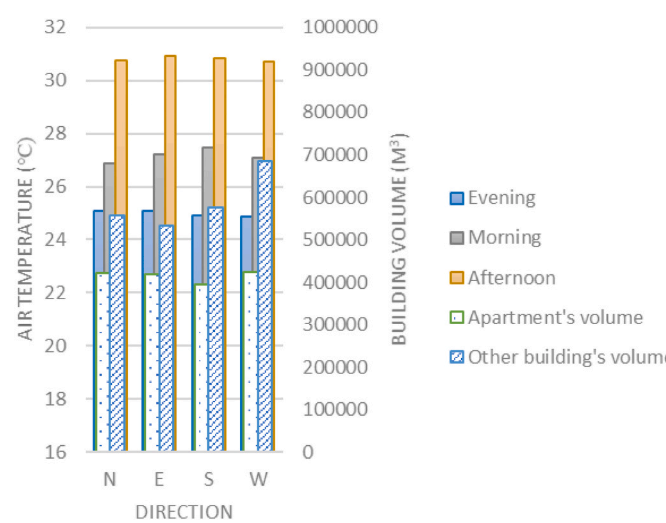



**Fig. 17.** Average air temperature at 0–150 m, sorted according to the direction of the wind around the building.

buildings under study were influenced by the design of the building (shape, dimensions, orientation, height, façade articulation, and material) and the surrounding environment. The environment around the apartment building in the high zone was dominated by low-rise buildings and many big trees. In addition, the site was located beside a river and had the topographic character of a valley. Rivers in the high zone are still quite natural, with a considerable number of trees and other types of vegetation along the river channel.

The existence of river valleys around the site caused wind corridors to have a major influence on the thermal environment. If the wind blew harder, the building massing caused a wider wind shadow area, greater turbulence, and greater airflow rates in the surrounding environment due to wind acceleration. Strong winds can cool the environment; however, if the wind is too strong and is accompanied by turbulence, it will cause disturbances. Strong winds in the tread area of the apartment building can disrupt activities in the drop-off area of the building entrance, as well as in the playground, lounging areas in the park, sports facilities (sports fields, jogging tracks, and swimming pools), and along the pedestrian paths to and from buildings.

The environment around apartment buildings located in the low zone, especially in the city centre and those that have many other large-scale buildings, is influenced by the mass of many buildings and the corridors between them, which may cause micro-scale winds. The gradation of the height of the surrounding buildings, especially those in the wind-direction area, significantly influences wind characteristics around the apartment building, for example, in the outdoor area and apartment podium pool. The wind tunnel formed by the compound mass of the apartment building and the deflection of airflow by the building mass change the characteristics of airflow and thermal conditions and disturb the surrounding community. Air temperature and flow are influenced by the shadowing and mass of the high-rise apartment building itself and the other large buildings nearby. The composition of the mass of apartment buildings together with the mass of the surrounding big buildings significantly changes the characteristics of the environment airflow. The number of big buildings in the city centre causes changes in the areas exposed to sunlight or overshadowed by the buildings. This affects the air temperature, radiation temperature, humidity, and even airflow.

The lack of green land and vegetation in much of the city centre, compared to the environment around apartments in the high zone, affects evaporation and evapotranspiration, and thereby the humidity in the area.

### *4.5. Research limitations and recommendations*

The scope of research, measurement, and simulation in this study was limited to the effect of the physical characteristics of an apartment building on the surrounding thermal environment that it dominates. Several limitations on the results and methodology of the present work should be noted:

This study of the characteristics of the thermal environment around various apartment buildings was carried out at particular times of year and not throughout the year. Thus, the influence of seasonal climate was not considered. Also, the measurements were obtained only during the day, from morning to evening, when the sun was shining. Moreover, data were not simultaneously collected at all measuring points, but rather obtained over a 2-h period due to the limitations of the instruments.

Based on the analysis of the physical aspects of various apartment buildings and the thermal conditions of their surrounding environments, we formulated several strategic recommendations for improving the building environment. This strategy includes the control of sunlight exposure in buildings and their environs, control of shadowing by the mass of an apartment building, and control of airflow. Thus, we recommend:

1. Regulating the composition of the building mass to avoid the formation of long corridors and minimise capturing wind like a sail, so that wind disturbances do not interfere with functional spaces and surrounding settlements.
2. Reducing heat absorption on the east and west sides of the building by regulating the shape/orientation and material composition of these sides.

## 5. Conclusion

In general, the presence of big buildings in the city changes airflow patterns (rate and direction), solar penetration to urban spaces, air humidity, air temperature, and mean radiant temperature of the surrounding built up environment. These factors alter the urban climate significantly. This problem is in line with studies by He et al. on urban ventilation [47], Firdausah and Wonorahardjo on urban canyons [7], and Wonorahardjo et al. on the thermal behaviour of buildings [3]. The design of big buildings in dense urban environments is very risky as it can disrupt the thermal environment.

The North Bandung area has more vegetation, cooler temperatures, and more contoured ground than the lower elevation areas in South Bandung. These conditions will inevitably affect the thermal environment around an apartment building. Indeed, the analysis results for four large apartment buildings in Bandung show different thermal conditions according to elevation, but some common conditions were identified.

The temperature and relative humidity of the air around an apartment building were found to depend on the shape and distance from the building. Areas shaded from the wind tended to be more humid and warmer; areas shaded from the sun also tended to be more humid but were colder. This is not surprising, as sun exposure lowers humidity and raises air temperature, whereas wind exposure lowers them both.

If the flat east- or west-facing surface of an apartment building received sunlight without airflow, high air temperatures were observed. This condition became even more extreme when the sun-exposed regions were made of heavy materials such as concrete or brick. This can be considered a thermal-collector effect. Improved airflow can help lower the temperature and humidity of the air in this case. However, the building surface opposite the sun tended to be humid and cold. If the wind is predominantly from the east or west, a building with a flat surface facing these directions will act as a sail, potentially casting a shadow over the wind and producing humid air behind the building.

The tunnel effect was observed to occur between two apartment buildings whose opposing faces did not receive direct sunlight and were oriented parallel to the direction of the wind. This caused extreme cooling and strong winds. The airflow rate at certain points around such apartment buildings could reach 6 m/s, causing disturbance to the people in settlements around the buildings.

Engineering the forms and materials of big buildings has the potential to control environmental heating, cooling, and humidity levels. The unavoidable exposure to sunlight can be mitigated by providing shading vegetation and the use of non-heat-storing materials. The design of apartment buildings and outdoor elements to direct the wind for cooling would be particularly beneficial for these areas. The parallel mass configuration that produces the wind-tunnel effect can be reduced by providing wind barriers and wind directors such as vegetation or other outdoor elements.

Discussions on building shape and material used in high-rise buildings in accordance with the objectives of this study are very limited in academic and practical literature. Knowledge of big-building geometry and materials is very important, and it is still not issued in regulations for the development of new buildings. Geometric and material aspects of buildings ought to be considered jointly, as they are not independent'. The evaluation of the thermal performance quality of the built environment should be done in multiple temporal settings (morning and afternoon, day and night, and dry and wet seasons) for a complete perspective and clearer picture of the problems.

This research has practical implications and is expected to contribute to the regulation of form, building composition, and use of materials in new-building construction. Future studies could focus on mitigating the negative impact of existing buildings through form-performance interventions associated with disruptive wind flow and choice of façade materials. The study of building material is not just limited to the strength of material, appearance, and durability, but it is also significant for balancing or reducing the negative impact of the geometry of the building, especially on thermal performance. In both new designs and mitigation projects, simulation plays an essential role in ensuring choices of geometry and materials that will optimise thermal effects on the environment.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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