



THESIS - DA185401

EFFECT GEOMETRY OF COURTYARD BUILDING ON COOLING ENERGY CASE OF HIGH-RISE APARTMENTS IN SURABAYA

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Architecture Department
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**PENGARUH GEOMETRI PADA BANGUNAN
COURTYARD TERHADAP ENERGI PENDINGIN
STUDI KASUS APARTEMEN BERTINGKAT
TINGGI DI SURABAYA**

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Dengan ini saya menyatakan, bahwa isi sebagian maupun keseluruhan tesis saya dengan judul:

Effect Geometry of Courtyard Building on Cooling Energy Case of High Rise Apartments in Surabaya

adalah benar-benar hasil karya intelektual mandiri, diselesaikan tanpa menggunakan bahan-bahan yang tidak diijinkan dan bukan merupakan karya pihak lain yang saya akui sebagai karya sendiri.

Semua referensi yang dikutip maupun dirujuk telah ditulis secara lengkap pada daftar pustaka.

Apabila ternyata pernyataan ini tidak benar, saya bersedia menerima sanksi sesuai peraturan yang berlaku.

Surabaya, 1 Agustus 2019

Yang membuat pernyataan;



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EFFECT GEOMETRY OF COURTYARD BUILDING ON COOLING ENERGY CASE OF HIGH RISE APARTMENTS IN SURABAYA

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ABSTRACT

Most of the electricity produced in Indonesia are consumed by residential sectors. Rapid development of high rise apartments, which rely heavily on mechanical cooling, are expected to increase the electricity consumption. Cooling energy can be reduced by minimizing solar heat gain generated by building envelope. Self-shading by building form is one of design strategy to reduce exposed area from direct solar radiation.

Nowadays, there are unlimited design of different building shape in tropical cities, such as Surabaya. High rise apartments with courtyard is one of dominant building geometry of multi storey residential building. These kind of apartment existed in different geometries, including H, U, Double U, Double L, and Quadruple L. These various building geometries create different shading area, and influence buildings thermal performance. The aim of this study is to identify the impact geometries on high rise apartment with courtyard towards cooling energy consumption.

Research methodology in this research are experimental research with simulation as tactic. Variable studied in this research are building geometries, courtyard aspect ratio, and building orientation. Design Builder by Energy Plus version 5.0 is the simulation tool used in this research.

The result of this study showed that the impact of building geometry with courtyard could reduce annual cooling energy up to 4.35%. Annual cooling energy reduction up to 6.46% is obtained as the impact of three different variables: building geometries, courtyard aspect ratio, and building orientation. Building geometries which generate the lowest annual cooling energy, is building geometries which has higher percentage of windows facing the courtyard area than windows located in the perimeter area, due to the result of layout arrangement. Among five different building geometries studied, Double L geometries generate the lowest annual cooling energy with courtyard aspect ratio of 1:1, and U geometries generate the lowest annual cooling energy with courtyard aspect ratio of 1:2.

Keywords : apartment, cooling energy, courtyard, high rise residential building, shape.

PENGARUH GEOMETRI PADA BANGUNAN *COURTYARD* TERHADAP ENERGI PENDINGIN STUDI KASUS APARTEMEN BERTINGKAT TINGGI DI SURABAYA

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ABSTRAK

Sebagian besar energi listrik diproduksi di Indonesia digunakan untuk konsumsi rumah tangga. Perkembangan pesat apartemen bertingkat tinggi, yang bergantung pada penghawaan buatan, akan meningkatkan pertumbuhan konsumsi listrik. Energi pendingin pada bangunan dapat diminimalisir dengan mengurangi paparan sinar matahari yang mengenai selubung bangunan. Pembayangan oleh bentuk bangunan itu sendiri adalah salah satu cara untuk mengurangi paparan radiasi matahari secara langsung.

Saat ini terdapat berbagai macam bentuk bangunan di kota-kota tropis, salah satunya Surabaya. Apartemen bertingkat tinggi dengan *courtyard* adalah salah satu bentuk bangunan yang sering ditemui pada hunian bertingkat. Terdapat berbagai macam bentuk apartemen dengan *courtyard*, yaitu H, U, Double U, Double L, dan Quadruple L. Berbagai macam bentuk apartemen ini, menciptakan pembayangan bangunan yang berbeda-beda. Tujuan dari studi ini adalah mengidentifikasi pengaruh berbagai macam geometri apartemen dengan *courtyard* terhadap konsumsi energi pendingin apartemen.

Metode yang digunakan pada riset ini adalah riset eksperimen menggunakan simulasi sebagai taktik. Variabel independen dalam studi ini adalah geometri bangunan, aspek rasio *courtyard*, dan orientasi bangunan. Design Builder oleh Energy Plus versi 5.0 adalah perangkat yang digunakan untuk simulasi pada riset ini.

Hasil dari studi menunjukkan pemilihan geometri bangunan dengan *courtyard* dapat menghemat konsumsi energi tahunan sebesar 4.35%. Reduksi energi pendingin tahunan sebesar 6.46% dapat didapatkan dengan mengkombinasikan efek dari geometri bangunan, aspek rasio *courtyard*, dan orientasi bangunan. Geometri bangunan yang menghasilkan konsumsi energi pendingin terendah adalah geometri yang mempunyai persentase luas jendela yang lebih tinggi menghadap *courtyard*, daripada luas jendela yang terletak pada sisi perimeter bangunan. Geometri Double L menghasilkan energi pendingin paling rendah ketika aspek rasio *courtyard* adalah 1:1, sedangkan Geometri U menghasilkan energi pendingin paling rendah ketika aspek rasio *courtyard* 1:2.

Kata kunci : apartemen, energi pendingin, courtyard, Gedung bertingkat tinggi, geometry.

PREFACE

First of all, author wants to express gratitude to Allah SWT, because of His blessing and grace, author can finish this thesis titled “Effect Geometry of Courtyard Building on Cooling Energy Case of High Rise Apartments in Surabaya” on time. Author also wants to express her deep and sincere gratitude for those who have been helpful in completing this thesis, as follows :

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The Author realizes that this thesis is not perfect. Hopefully this research can present new knowledge and insight for readers in the field of building science and cooling energy.

Surabaya, 1st August 2019

Author

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CHAPTER 1

INTRODUCTION

1.1 Background

1.1.1 Residential Energy Consumption in Indonesia

Ministry of Energy and Mineral Resources Indonesia reported that there was 5.9% increase of energy consumption in Indonesia. In the last twenty years, energy consumption in Indonesia has doubled, with the last five years have the highest rate of consumption. In 2015, 43.7% electricity produced by Indonesia national electricity company (PLN) was used in residential sector (djke.esdm.go.id, 2016). One of the main factor that contributes to the electricity consumption in residential sector is the energy for cooling.

In hot climate, building with respect to the local climate is able to generate lower indoor temperature, thus minimizing cooling energy. However, many buildings do not take into account environmental condition surrounding them. Therefore, it is important to consider building design in order to address issue on cooling energy consumption.

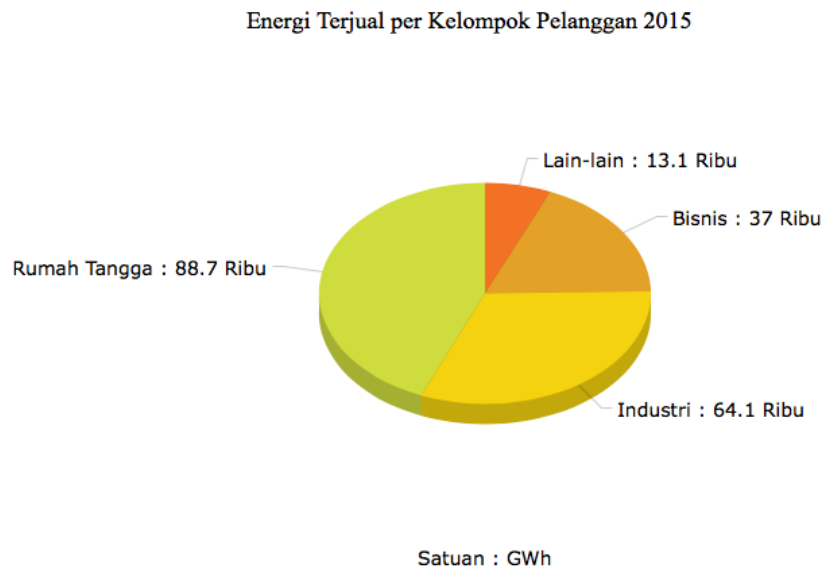


Figure 1.1 Indonesia Electricity Consumption (esdm.go.id)

1.1.2 Energy Consumption in High Rise Apartment

Surabaya is the second largest city in Indonesia with population over 3.4 million in 2015. With the high number of population, Surabaya has been a target of high rise residential building development. It is reported by Colliers International Survey (2017) a total of 33,414 new apartment units are expected to be completed in the next four years in Surabaya. Development of high rise apartment in Surabaya can be classified into two characteristics: apartments with a single tower block, and apartment with several tower blocks and internal courtyard. Apartments with single tower block are usually intended for middle to upper class segment, while apartments with internal courtyard target emerging middle class in Indonesia.

Surabaya is located in the equatorial region with warm humid climate and intense solar radiation. There are two different seasons occur in Surabaya, dry and rainy season. Seasonal difference in equatorial region is based on the amount of precipitation. However, the temperature in Surabaya is relatively constant with high humidity throughout the year. There is little temperature difference between daytime and night time. Thermal discomfort in the warm humid equatorial region could occur all the time because of the warm temperature, and high humidity.

A building creates a barrier between indoor environment and outdoor environment. In the warm humid climate such as Surabaya, a building should act as a climate modifier and be able to lower the outdoor temperature. Currently, in order to create thermal comfort inside a building, most buildings in Surabaya install Air Conditioner. A climate responsive building design enhances energy efficiency of mechanical cooling thus minimizing electricity consumption. Cases when the indoor temperature is lower than the outdoor, the Air Conditioner will require less energy in order to provide comfortable temperature.

The layout of high rise residential buildings in Surabaya is mostly arranged in double loaded corridors. Under the condition of natural ventilation, units in these apartments rely only on one sided ventilation. With high humidity and relatively high temperature, one sided natural ventilation is not sufficient to provide comfortable thermal environment all the time. Most apartment units install air conditioner to be able to maintain comfortable temperature under unideal condition.

According to the field survey of apartments in Surabaya, the average air

temperatures inside the unit of private apartments were generally higher than the outdoors under the condition of natural ventilation only (Alfata et al., 2015). Operating Air Conditioner in apartment units with higher temperature than surrounding environment will decrease energy efficiency of an AC thus increasing building energy consumption. In addition to that, a study conducted by Huda and Suheta (2017) about electricity usage in one of the high rise apartments in Surabaya mentioned that Air Conditioner usage accounts for 49.9% electricity consumption in the apartment.

These studies show that the apartment building did not take into account the warm-humid environmental condition of Surabaya. Instead of using passive design strategies to minimize temperatures inside the building, such as adding shading devices and thermal insulation, most apartment buildings rely solely on the air conditioner to provide thermal comfort inside the building. As a result, the operating air conditioner inside the building will require more energy, as the building is unable to minimize lower air temperature through its design strategies.

1.1.3 Courtyard as One of Passive Design Strategy

Among several high rise apartments in Surabaya, internal courtyard, or open space enclosed by surrounding walls, can be easily found. Lately courtyard has been a prominent design element in high rise apartments, as a result of the effective layout configuration and provision of open space for the building occupants. Courtyard in the high rise apartments of Surabaya are often functioned as open recreational area for occupants, with swimming pool and greenery.

Several researches show that courtyard can act as passive design strategy that will reduce energy consumption in building. Aldawould, A. (2008) revealed that building with courtyard is found to be energy efficient in all climates, especially in the hot arid and hot humid climates. However, in the case of Surabaya apartments the placement of courtyard in the building plan do not have intentional meaning of using courtyard as a passive design strategy. In addition, as courtyard is originally from hot and arid region, studies about courtyard in warm and humid equatorial region are still limited.

The thermal performance of a courtyard is highly influenced by the size of the courtyard, and design of the courtyard's enclosure (Hyde, 2000). Muhaisen

(2006) also mentioned that solar radiation received by courtyard surfaces is considered as the main factor affect thermal performance of courtyard building. Radiation received by building surfaces is determined by some factors such as location, climate, time of the year and shape of the courtyard.

Higher courtyards generally have better thermal performance than lower courtyard. However, there is no significant thermal performance improvement after certain height (Al-Masri and Abu-Hijleh (2012), and Martinelli and Matzarakis (2017)). Studies of courtyard aspect ratio mentioned that longer courtyard is more suitable for cooling purpose (Maniglou and Oral, 2015; Almhafdy et al., 2015). These studies support earlier study by Muhaisen and Gadi (2006) which stated that deeper and elongated courtyard is better than shallow rectangular one.

Although courtyard shape variables are widely investigated, most of studies about courtyard were conducted in temperate or hot and dry climate. Similar courtyard size located in different climate will receive different solar exposure, thus affecting its thermal performance. Studies about ideal courtyard height and aspect ratio in warm humid equatorial region are still limited.

In addition, most of studies about courtyard only examined rectangular shape courtyard. Little is known about courtyard performance with different shape. Nowadays, as a result of several factors, modern courtyard has various shape configuration such as U, L, T or Y as mentioned by Saeed (2007, cited in Almhafdy et al., 2013). Courtyard with different shapes other than rectangular also found in several high rise apartments in Surabaya.

1.1.4 Building Geometry and Cooling Energy

According to Yeang (2006) building energy consumption is influenced by building form, orientation, and building volume to surface ratio. Solar radiation received by the building will result in building thermal performance and energy consumption. Different shape of building will have different exposure from the solar radiation thus affect the building thermal performance.

In warm humid equatorial region, cooling energy contributes the most energy consumption in a building. According to Rashdi and Embi (2016) and Raji et al. (2017) compact building shapes produce less cooling energy demand than

expanded shape such as courtyard building. Both studies examined cooling energy of office buildings in Malaysia and Singapore.

Unlike layout arrangement of office building with more flexible options, such as open office arrangement, layout arrangement in high rise residential building is more rigid especially in high density apartments. Several high rise residential buildings developed elongated building shape with inner courtyard as a result of effective layout arrangement. In Surabaya, there are five different geometries of courtyard building, such as U geometry, H geometry, Double U geometry, Double L geometry, and Quadruple L geometry.

According to Rashdi and Embi (2016) and Raji et al. (2017), courtyard building is less energy efficient than the other compact shape in the tropical region. However considering the development of high rise residential building with courtyard, there is requirement to study optimum courtyard shape which produce the least cooling energy demand.

To conclude, there are still limited studies of courtyard and various building shape in warm humid equatorial region, whereas building thermal performance is particularly influenced by its location. As a result, there is a requirement to investigate about shape effect of high rise residential building with courtyard to its cooling load.

Expectantly, this research will contribute to the studies about courtyard of high rise apartment in warm humid tropical area. In addition, this research will provide information about shape effect of apartment with courtyard to the building thermal performance and cooling load.

The implication of this research will guide architect, developer, and government on planning high rise apartment with courtyard with minimum cooling energy requirements.

1.2 Problem Statement

Nowadays, high rise residential buildings rely heavily on mechanical cooling to provide thermal comfort for the occupants, and neglect environmental design parameters which could save building energy consumption. This phenomenon is supported by field survey from Alfata et al. (2015) about apartment

thermal performance and study conducted by Huda and Suheta (2017) about electricity consumption in Surabaya high rise apartment.

Building shape is one of design parameters that influences building energy consumption (Yeang, 2006; Ekici and Aksoy, 2011; Pacheco et al., 2012). Building shape influences amount of solar radiation received. Optimum building shape and orientation can reduce building energy consumption about 36% (Aksoy and Inalli, 2006 cited in Pacheco et al., 2012). The impact of building shape to the building energy consumption is related to the surrounding climatic condition. Building located in different latitude will receive different solar radiation.

In recent development of high rise apartment in Indonesia, building with courtyard emerges as a prominent design element due to effective layout arrangement in accommodating high density apartment. These courtyard building existed in various shape such as U geometry, H geometry, Double U geometry, Double L geometry, and Quadruple L geometry. These building geometries create different courtyard shape, other than rectangular. The combination of different building shapes and courtyard formed by it create different shading effect thus affecting building thermal performance.

Studies about building with courtyard in warm humid equatorial region are still limited. Most studies about courtyard building are conducted in temperate or hot and dry climate. Several courtyard studies conclude that deep and elongated courtyard is suitable for cooling purpose. In addition, most courtyard shape investigated is limited to rectangular courtyard and was conducted for low to middle rise building.

According to the problem statement above, below are the proposed research questions

1. What is thermal performance of various geometries of high rise apartment with courtyard related to the cooling energy?
2. What is the impact of different geometries of high rise apartment with courtyard towards annual cooling energy?

1.3 Research Objective

The aim of this study is to evaluate the concept of building geometry and its impact on cooling energy. In order to achieve the research aim, research objectives are as follows:

1. Evaluate thermal performance of various geometries of high rise apartment with courtyard related to the cooling energy.
2. Analyze and evaluate the impact of various building geometries of high rise apartment with courtyard towards annual cooling energy consumption.

1.4 Research Limitation

Some research limitation in this research that should be considered:

- Subject of the research

This research studies the impact of building geometry with courtyard to the building cooling energy. Building thermal performance is assessed by simulating mechanically ventilated building with various geometries. Indicators of building thermal performance are annual cooling energy per conditioned area. The other aspect of energy consumption in a building, such as lighting, and electronic usage are considered as control variable in this research, in order to evaluate the impact of the building geometry towards annual cooling energy. This research focus on building geometry, courtyard aspect ratio, and courtyard orientation.

- Research object

The research objects are various building geometry with courtyard in high rise residential building in Surabaya. Population of high rise apartment with courtyard in Surabaya is identified and become the basis of research model experiments. The main focus in this research is cooling energy of the apartment units, because they contribute the highest portion of cooling energy in a high rise apartment. Layout of the model experiments are modelled according to arrangement of floor consist of apartment units. Cooling energy for communal facilities such as lobby, gym, and hall is not considered in this research.

CHAPTER 2

LITERATURE REVIEW

2.1 Building and Energy

Most energy consumption in a building is generated from electricity to operate a building. There are various equipment in a building such as lighting, electronic appliances, and system to provide artificial heating or cooling, in order to create comfortable environment for the occupants. According to Pacheco et al. (2012) electricity to provide artificial heating, cooling, and ventilation system accounts for the biggest energy consumption in a building.

In order to provide comfort for occupants, building act as a climate modifier, which create different indoor environment from surrounding outdoor environment. In the hot outdoor environment, building will provide shade for the occupants and create more suitable environment. On the other hand, in the cold environment, building will trap the heat obtained from sun radiation thus create warmer space suitable for living in. The temperature differences, between outdoor environment and indoor environment, are influenced by several building elements which could generate heat loss or heat gain in a building.

2.1.1 Energy Consumption in Warm Humid Climate

Sun radiation intensity varies in different parts of the world, thus creating different climatic conditions. Buildings, as climate modifier, protect occupants from the harsh environmental condition. As a result, requirement of building thermal condition can be different from one place to another.

In warm humid equatorial area, the amount of solar radiation is relatively constant. There is no significant temperature differences throughout the year. Buildings in the warm humid area, require constant cooling to provide thermal comfort for the occupants.

Study by Raji et al. (2017) mentioned that similar building require different energy demand depends on the location of the building. A 40-storey office building with similar building properties was simulated in three different climates in order to obtain dominant energy use in each location. The simulation studies were

conducted in three different cities, Amsterdam, Sydney, and Singapore, which represent temperate, sub-tropical, and tropical climate respectively.

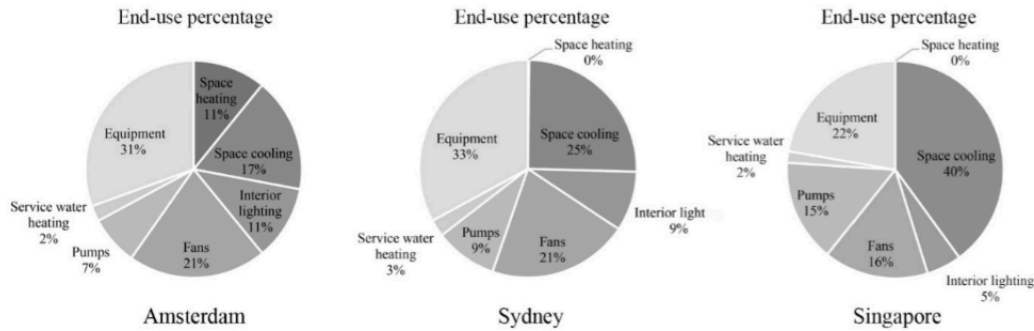


Figure 2.1 Comparison of Energy Consumption of an Office Building in Three Different Climate. (Raji et al., 2017)

As expected in warm humid tropical climate, cooling energy account the most for energy usage, about 40%. Cooling energy consumption in Singapore is about 23% and 15% higher compared to Amsterdam and Sydney respectively (Raji et al., 2017). However, the building in warm humid climate consume the least energy consumption for interior lighting, because of intense sun radiation.

2.1.2 Heat Transfer in a Building

In science perspective, a building is large thermal system which continuously react to the surrounding environment. In this process, heat transfer constantly occur between a building and its surrounding environment. If the surrounding environment has higher temperature than the building, heat will transfer into the building and increase its indoor temperature.

In general, there are five sources of heat in a building, mentioned as follows (Szokolay, 2004) :

- Q_i – internal heat gains
- Q_c – conduction heat gain or loss
- Q_s – solar heat gain
- Q_v – ventilation heat gain or loss
- Q_e – evaporative heat loss

Variables above form equation as follows, with ΔS as heat accumulated in a building.

$$Q_i + Q_c + Q_s + Q_v + Q_e = \Delta S \quad (2.1)$$

Although there are five sources of heat in a building, Q_s (solar heat gain) and Q_i (internal heat gain) are more significant to the overall building thermal performance than the other sources. Q_c (conduction heat gain or loss), Q_v (ventilation heat gain or loss), and Q_e (evaporative heat loss) can be negative which means there are heat released by the building. If equation 2.1 result is negative, the building releases heat to the environment, and indoor temperature will decrease. On the other hand, if the result is positive, the building receives heat gain from the surrounding environment.

Heat transfer in a building occurs through radiation, conduction, and convection. Sun radiation received by the building envelope will heat up the building (solar heat gain). Different building envelope materials contribute different heat gain to the building thermal system. Building envelope material with transparent element (windows) contribute more solar heat gain than opaque element such as wall (Szokolay, 2004).

$$\text{Transparent element} \quad Q_s = A \times G \times \theta \quad (2.2)$$

$$\text{Opaque element} \quad Q_s = [\Sigma (A \times U)] \times [G \times \alpha \times R_{so}] \quad (2.3)$$

Conduction heat transfer occurs through solid building elements such as wall, floor, and ceiling. Walls located in perimeter have higher temperature due to solar heat gain. Heat will transfer from higher temperature to lower temperature.

$$Q_c = [\Sigma (A \times U)] \times [T_o - T_i] \quad (2.4)$$

Convection is the transfer of heat by movement of fluid, such as air movement in a building. Heat transferred depends on air circulation and volume of certain room.

$$Q_v = 0.33 \times N \times \text{Vol} \times (T_o - T_i) \quad (2.5)$$

$$N = \frac{C_v \times V \times A}{\text{Vol}} \times 3600 \quad (2.6)$$

According to equation 2.2 – 2.6, variables affecting heat transfer are as follows:

1. Building Envelope $[\Sigma (A \times U)]$
2. Ventilation rate (N/air change per hour, room volume)
3. Temperature differences between inside and outside ($T_o - T_i$)

Shape of a building determine total area of building envelope (A), while building materials determine building U-value. The more surface area of a building,

the higher exposure from solar radiation. In the warm and humid tropical climate, solar radiation exposure should be minimized.

In warm humid climate, a building thermal system should be able to provide lower indoor temperature than the outdoor in order to provide thermal comfort for the occupants. Thermal comfort is one's satisfaction of thermal environment subjectively. Thermal comfort is influenced by thermal condition of an environment (temperature, MRT, humidity, air velocity) and personal factors (metabolism, clothing).

2.1.3 Cooling Load in a Building

In the conditioned building, cooling load can be defined as the amount of heat which must be eliminated by the air conditioning equipment per unit time to generate and maintain the desired indoor climate. On the other hand, heat gain is the amount of heat which enters the conditioned space, as a result of heat transfer between the conditioned space with the surrounding environment.

There are two classification of heat gain, sensible heat gain and latent heat gain (Ibe and Anyanwu, 2013). Sensible heat gain will alter dry bulb temperature of a space. Sensible heat gain is transmitted either by conduction or convection and radiation or simultaneously by combination of these heat transfer mechanism. The sources of sensible heat gain can be external or internal, such as :

1. Transmission of heat gain through building fabrics such as walls, doors, windows, internal partitions, roof, floor, etc.
2. Effect of direct and refraction solar radiation through glass windows and doors.
3. Electric lighting inside a space
4. Outside air brought into space, due to infiltration or for the purpose of ventilation.
5. Occupancy (number of people in the conditioned space)
6. Heat dissipated by miscellaneous equipment or sources such as motors, office equipment, electric kettles, cooling appliances, etc.
7. In the tropics, the sun is also a source of sensible heat, directly through building windows, and by heating exposed surface.

Latent heat gain in a building results in moisture addition to the conditioned space without changing the dry bulb temperature. Similar with sensible heat gain, sources of latent heat gain can be internal or external, such as :

1. Outside air brought into space, due to infiltration or for the purpose of ventilation.
2. Occupancy (number of people in the conditioned space)
3. Heat dissipated by products brought into space, resulting in the evaporation of moisture.
4. Heat generated from other internal sources.

In order to achieve the desired dry bulb temperature and humidity of a space, sensible cooling and removal of excess moisture (latent cooling) will be conducted by the air conditioners. In the tropics which require cooling, volume flow rate of supply air or conditioned air quantity should be adequate that the supply air should be able to reduce the indoor dry bulb temperature. Similarly, the moisture content of the supply air should be low enough to absorb moisture of the room.

The heat quantity required to be removed in order to achieve desired temperature (sensible cooling) :

$$SC = 1234 V_{sa} (T_{rm} - T_{sa}) \quad (2.7)$$

SC = sensible cooling (kW)

V_{sa} = volume flow of supply air (m³/s)

T_{rm} = room design temperature (C)

T_{sa} = supply air temperature (C)

In order to maintain desired relative humidity in the conditioned space, the heat quantity required to be removed in order to lower the moisture content (latent cooling) :

$$LC = 2954 V_{sa} (W_{rm} - W_{sa}) \quad (2.8)$$

LC = latent cooling (kW)

V_{sa} = volume flow of supply air (m³/s)

W_{rm} = moisture content of room air at required relative humidity (kg/kg of dry air)

W_{sa} = moisture content of supply air (kg/kg of dry air)

Total cooling of a building is the sum of sensible and latent cooling.

2.1.4 Building Design Parameters and Cooling Energy

There are many parameters that affect building energy performance. According to Ekici and Aksoy (2011), these parameters can be divided into two groups, which are physical environmental parameters and artificial design parameters.

Table 2.1 Parameters Affecting Energy Performance

Physical environmental parameters	Artificial design parameters
Hourly outdoor temperature	Building form factor
Solar radiation	Transparency ratio
Wind direction and velocity	Thermo-physical properties of building material
	Building orientation
	Distance between building

Source : Ekici and Aksoy, 2011.

Physical environmental parameters depend on the climate where a building is located. The condition of these parameters is given and varies in different context. On the other hand, artificial design parameters are highly related to the design of a building, which can be modified in order to create low energy consumption building. Building transparency ratio, and thermo-physical properties of building are related to the building envelope. Distance between building can influence a building energy consumption, because surrounding building can provide shading, but also can block upcoming winds and reflect solar radiation.

Similar with Ekici and Aksoy (2011), Pacheco et al. (2012) mentioned that there are six building parameters that influence building energy consumption: building shape, orientation, envelope, shading, passive system and glazing. However, in this case glazing can be categorized as building envelope, because glazing is related to the transparent façade elements or windows.

a. Building Shape

Building shape will affect exposed area to solar radiation thus impact a building energy consumption (Markus, and Morris, 1980). Building with the same volume, a compact building has lower surface-area-to-volume ratio than a

‘spread’ building configuration. According to Lechner (2015), the ‘spread’ building configuration could produce 60% more energy than the compact one. However, according to Ferdous (2012) in Rashdi and Embi (2016) differences of energy consumption of various shapes are relatively small compared with energy consumption of different window to wall ratio. In addition, according to Susrova et al. (2013), room geometry could influence energy saving up to 14% in hot climate.

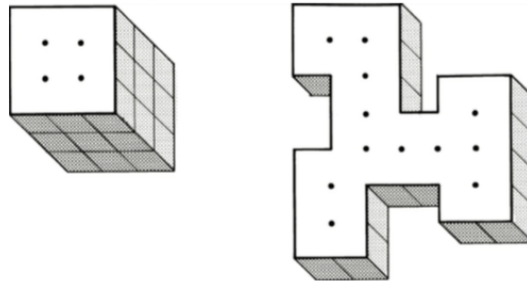


Figure 2.2 Two Building Forms with the Same Volume, but Different Surface Area. (Lechner, 2015)

Design principles of mechanically ventilated building in warm humid tropical climate are the opposite naturally ventilated building design. Ideal form of naturally ventilated building is elongated and narrow to maximize cross ventilation (Szokolay, 2004; Lechner, 2015). On the other hand, mechanically ventilated building in warm humid tropical climate should be as compact as possible in order to minimize solar exposure from the building envelope (Rashdi and Embi, 2016; Raji et al., 2017).

b. Building orientation

The building orientation plays an important role on thermal performance because it will affect building degree of exposure to direct solar radiation (Yeang, 2006). Orienting a building correctly can save building energy use, because it can minimize building direct exposure to solar radiation. (Pacheco et al., 2012).

Solar radiation received by building surfaces vary according to the orientation. In Jakarta, or cities with the same latitude, west-facing surfaces receive the highest solar radiation about 303 Watt/m² every day. While the other orientation, east, north, south surfaces receive 268 Watt/m², 207 Watt/m², and 165 Watt/m² solar radiations respectively (Guidance of Jakarta Green Building, 2012). Therefore, building orientation should be considered properly during the design process.

In equatorial region, where heating is not necessary, building orientation should avoid direct solar radiation as much as possible. The general rule is the longest wall should face northern or southern side, as these orientations receive less solar radiation than east and west in the equator (Szokolay, 2004). This design principle applies for both naturally and mechanically ventilated building.

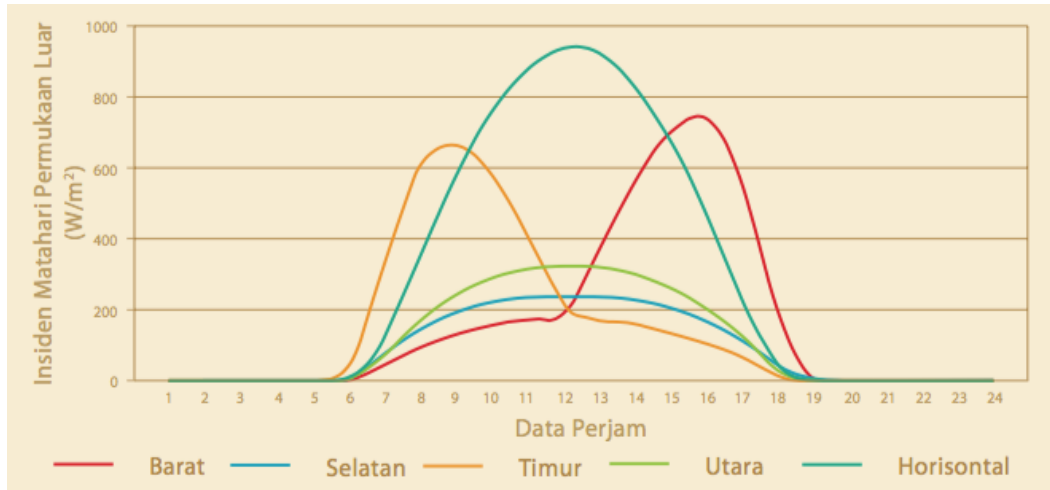


Figure 2.3 Solar Radiation Received by Building Envelope in Jakarta (Jakarta Green Building Guidelines)

Study by Morrissey et al. (2011) mentioned that larger buildings (floor area $> 200\text{m}^2$) are more sensitive to changes in orientation. Smaller buildings perform better with various orientation than larger building. This study was conducted in temperate climate. In Malaysia, Kannan (1991) in Mirrahimi et al. (2016) stated that building lined longitudinally along north south consume 10% less energy than building arranged longitudinally along east west axis, regardless of building form.

c. Building Envelope

Energy consumption of a building is greatly affected by building envelope (Pacheco et al., 2012). There are many elements included in building envelope, such as, foundation, roof, walls, doors, and windows. However, walls, windows, and roof are three design elements that contribute the most to the building thermal performance, because these elements are exposed to solar radiation more frequently than others.

Building envelope acts as climate modifier in building interior climate (Pacheco et al., 2012). The performance of a building envelope will determine additional energy demand for heating and cooling. Exposure of solar radiation heats

up the building envelope. Heating of the building envelope will increase cooling energy consumption.

Among many other components, windows or transparent façade in the building envelope contribute the most to a building cooling load. A study about cooling load in Jakarta office buildings revealed that solar heat gains from the window contribute about 60% to the total building cooling load. Internal heat gain factors also accumulate cooling load for the building, with appliances, occupants, and lighting account for 23%, 8%, 6%, respectively. According to this data, cooling load generated by building wall contributes least to the building thermal performance, only about 3% (Guidance of Jakarta Green Building, 2012).

In building with natural ventilation, increasing window size could lower indoor air temperature and relative humidity. Nevertheless, the larger the window, the higher solar radiation can be received. Study conducted by Liping and Hien (2007) in Singapore natural ventilated building stated that optimum thermal performance is achieved when the window to wall ratio (WWR) is 24%.

Several studies about windows area and cooling energy has been conducted in warm and humid climate. In high rise apartment of Hongkong, increasing window to floor ratio (WFR) of 10.4% lead to higher cooling energy of 12.8% (Cheung et al., 2005). Study in Malaysia of window to floor ratio (WFR) supports the previous study, as the WFR increases 10%, cooling load rises about 1.3% (Al-Tamimi and Fadzil, 2012). Not only window area of a building, substitution of glazing material from single clear glass of 6 mm to double glazed clear glass with lower emissivity could reduce cooling energy up to 19% (Al-Tamimi in Mirrahimi et al., 2016).

d. Building Material

Along with the component of building envelope, materials of building envelope also play important rule to minimize energy consumption. Different materials have different material properties which could affect the thermal performance of a building envelope. Building materials can be organized into two main categories: material with high thermal mass and material with low thermal mass. High thermal mass material absorb heat at slower rate, and release heat in the long period. On the other hand, low thermal mass material absorb heat quickly and

release heat quickly as well. Bricks, cement blocks, are example of high thermal mass material, while low thermal mass materials are steel and timber.

Commonly used property to measure material thermal performance is U-value, or sum of the material thermal resistance including the material surface properties (Szokolay, 2004). Materials with low thermal mass tend to have higher U-Value than material with higher thermal mass. Adding insulation material will influence the building performance. Hassan and Al-Ashwal in Mirrahimi et al. (2016) stated that adding exterior wall thermal insulation of high rise apartment in Malaysia could reduce cooling energy up to 20% and decreasing peak cooling load up to 29%.

e. Shading on buildings

Building exposure to the solar radiation will result in building heat gain. Shading several parts of the building surfaces could decrease the building solar exposure thus minimizing the heat gain. Therefore, the control of shading elements should be able to decrease energy demand for cooling, while maintaining natural lighting.

Shading on building can be generated by several features, such as self-shading by building form, shading devices, greenery and adjacent buildings (Pacheco et al., 2012). Building with courtyard could provide self-shading, as well as additional design element such as veranda. While shade generated by neighboring buildings depends on the inclination angle and size of the adjacent building.

In general, there are two kinds of building shading devices: horizontal shading devices such as awnings, or vertical shading devices such as wall-fin. Combination of horizontal and vertical shading device is called egg-crate. According to Al-Tamimi (2011) in Mirrahimi et al. (2016), egg-crate is the best shading devices in warm and humid equatorial region, because it can block the sun radiation from all angles.

2.1.5 Optimum Building Shape

Olgay (1963) stated that optimum building shape is building that produce the least heat loss during winter and heat gain during summer. For hot climate where constant cooling is required, the building should be able to minimize heat

gain throughout the year. In the warm humid region where intense solar radiation coming from the west and east side, building form should be elongated. The optimum building aspect ratio is 1: 1.7 up to 1 : 3. In addition Szokolay (2004) stated that buildings in tropical climate have aspect ratio of 1: 2 - 3, with the longest side facing north or south. Aspect ratio of a building is the ratio of building width to the length.

Several studies mentioned before are indented for low rise building. Yeang (1999) in “The Green Skyscraper” stated that the optimum buildings shape of high rise building in the warm humid tropic has aspect ratio of 1:3. It is recommended to arrange structural core in the east and west of the building to minimize solar radiation in the main area. High rise building typology addressed in this book is limited to office building only, as high rise residential buildings tend to have more variation of building shape.

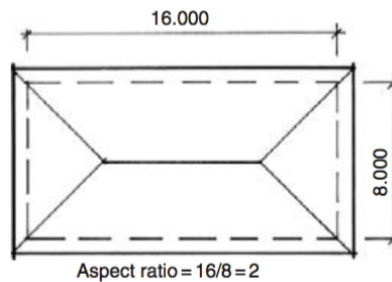


Figure 2.4 Aspect Ratio of a Building (Szokolay, 2004)

In addition, according to Markus and Morris (1980), optimum building shape is a buildings shape which produce the least energy consumption within certain volume. Smaller building tends to produce less energy, than larger building. However, capacity of a building also plays important role in determining energy efficiency building. Therefore, in order to compare various building shape, they have to be in the same volume.

2.1.6 Building Shape Index

Building shape index is variable used to define a building shape. There are various building shape indexes used in previous studies. The most used shape index relates with compactness of a building shape, such as volume to surface ratio and relative compactness (RC) (Raji et al., 2017). Surface to volume ratio (compactness) is the area of external envelope to the building volume. Relative

compactness is the comparison of a building compactness to a reference building, usually a cube with similar volume as the building.

Although there is a correlation between compactness index with energy performance of a building, it is important to note that there are many other variables affect building energy performance. Compactness index does not represent three dimensional geometry of a building shape, thus diminishing impact of self-shading created by building shape (Raji et al., 2017). Self-shading reduces exposed envelope area from solar radiation and affecting thermal performance (Markus, and Morris, 1980). H-shaped building and U-shaped building with similar volume could result in similar volume to surface ratio (compactness), although these different shapes generate different shaded area.

In addition, Markus and Morris (1980) stated that volume to surface ratio is different for cold and warm climate. In cold climate, all external surfaces, including floor surface, should be considered, because the heat transfer from inside the building to the surrounding ground surface (heat loss). On the other hand, in hot climate where sun radiation is the main source of heat gain, it is not essential to include floor surface area.

2.2 High Rise Residential Buildings

According to Indonesian dictionary, KBBI (Kamus Besar Bahasa Indonesia), apartment unit has living room, bedroom, bathroom, kitchen located in the same floor, within a multistory housing, and supported by many facilities such as swimming pool, gym, retail shops, and etc. Akmal (2007) mentioned that an apartment is categorized as high rise apartment if it has more than 10 floor. In addition, according to fire safety standard a building is considered as high rise building if it has more than 10 story. This consideration is related to the maximum height that can be reached by a fire truck elongated stairs.

2.2.1 Shape of High Rise Residential Buildings

According to Neufert (2012), there are five kind of multistory housing according to its site planning :

1. Blocks

The blocks are compact building form that accommodate high number of occupant. These type of building can be individual building or groups of

building. The Blocks multistory housing form two kinds of external spaces: within and around the building, which has different form and function.

2. Linear Arrangement

Elongated layered building which arranged in linear configuration with the surrounding building. On the contrary with the Blocks arrangement, linear arrangement forms no internal spaces. The external spaces around the building has no differentiation.

3. Slab-blocks

Elongated layered building which is almost similar with linear arrangement. However, the slab-blocks often disconnect from the surrounding arrangement.

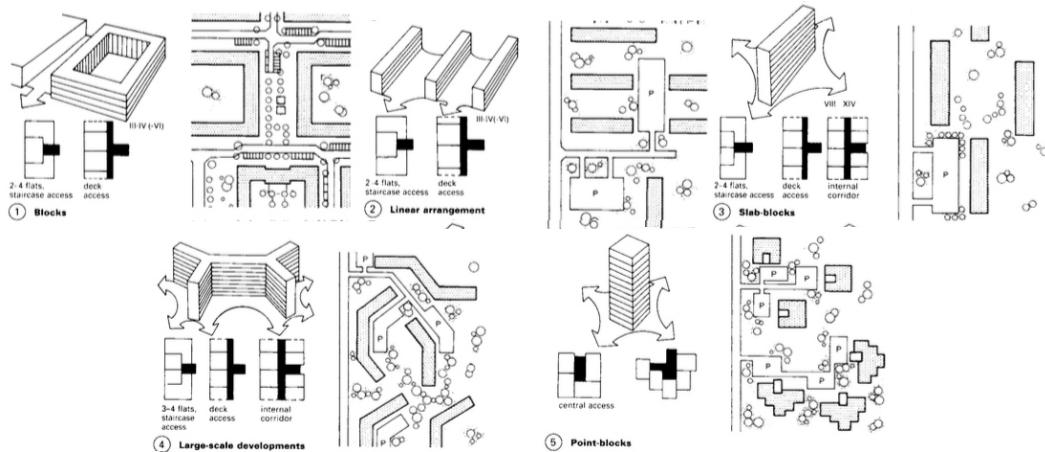


Figure 2.5 Shape of Multistory Residential Building (Neufert, 2012)

4. Large-scale Development

Elongated layered building which has extended form, creating elongated irregular form. Housing in the large-scale development are connected to the surrounding arrangement

5. Point-blocks

These building often are the point of interest in site planning arrangement. The point-blocks often combined with low rise housing arrangement.

Apartments in Surabaya are mostly arranged in block type apartment or point-block type apartment. In Surabaya, block type apartments usually target the middle class segment because it has higher occupant density. On the other hand, the point-block type apartments target upper class economy segment.

Both apartments share the same characteristic about layout arrangement. Both apartment types are arranged in double loaded corridor arrangement in order to maximize profit. However, in the point block apartments, per floor area is smaller, due to lower occupant density.

Alfata et al. (2015) conducted field investigation of indoor thermal environments in Surabaya apartments and studied thermal mass capacity of these apartments. According to this study, the structure of Surabaya apartments is reinforced concrete with comparatively high thermal mass. The external walls of these apartments are made of pre-cast concrete and partition walls made of lightweight concrete.



Figure 2.6 Apartment Plans in Surabaya with Double Loaded Corridor. (skyscapercity.com)

2.2.2 Cooling Energy of High Rise Residential Buildings in Surabaya

In 2015, 43.7% electricity produced by Indonesia national electricity company (PLN) was used in residential sector (djk.esdm.go.id, 2016). One of the main factor that contributes to the electricity consumption in residential sector is the energy for cooling. Study about electricity usage in one of the high rise apartment in Surabaya from Huda and Suheta (2017) stated that Air Conditioner usage accounts for 49.9% electricity consumption in the apartment. Electricity for miscellaneous (such as electronic devices) accounts for 30.5% electricity consumption in the apartment, followed by consumption for elevator, and lighting, which accounts for 10% and 9.6% respectively.

With environmental condition of Surabaya, which require cooling throughout the year, these apartment units rely heavily on mechanical cooling by Air Conditioner. Under condition of natural ventilation, the apartment units rely on one sided ventilation as result of double loaded corridor. According to the field Survey of Apartments in Surabaya, the average air temperatures inside the unit of

private apartments were generally higher than the outdoors under the condition of natural ventilation only (Alfata et al., 2015). Operating Air Conditioner in apartment units with higher temperature than surrounding environment will decrease energy efficiency of an AC thus increase building energy consumption

2.3 Courtyard

A courtyard can be defined as uncovered zone that is totally or partly surrounded by walls or buildings that gives privacy to the house and it has many purposes such as family gathering and safe playing ground for children. In vernacular architecture, courtyard can be found in many parts of the world. The origin of courtyard is believed to be started about 5000 years ago in Middle East area, which has hot and arid tropical climate, then it is transferred to different area like Latin America and China, which have warm and humid tropical climate (Edwards et al., 2006). As a result, there are many researches about thermal performance of courtyard in the hot arid climate, but very few researches about courtyard in the hot and humid climate, especially in the hot and humid area near the equator.

2.3.1 Courtyard Function

Two main function of courtyard in hot climate region is to provide shading and ventilation effect. (Zakaria and Kubota, 2014) Building orientation, height, and exposure to the sky affect shading generated by courtyard (Meir et al., 1995 cited in Kubota). In addition, outdoor wind conditions and indoor air temperature affect stack effect ventilation generated by courtyard. (Koch-Nielsen, 2002; Givoni, 1994 cited in Zakaria and Kubota, 2014).

a. Shading Effect

The absorption of solar radiation on the building and courtyard surfaces could raise the temperature of the building structures and transfer the heat through convection to the surrounding air temperature, that resulting in an increase of air temperature in the surrounding areas (Muhaisen, 2006). Therefore, provide good shading for the building might be required in order to minimize solar radiation or heat gain (Hyde, 2000). There are several types of shading techniques that are normally used for courtyard buildings

- a) Shading generated by building form

- b) Shading generated by building orientation
- c) Shading generated by courtyard roof (direct shading)
- d) Shading by trees.

Zakaria and Kubota (2014) argued that solar radiation is more diffuse than direct in the warm humid regions where the sky is often overcast, so that shading devices for diffuse sky radiation is more important compared to shading of direct solar radiation in warm humid regions.

b. Ventilation Effect

Ventilation in a courtyard is generated by stack effect and wind driven ventilation. Stack effect is generated by pressure differences in height between the intake and outlet and temperature difference of the air. Because of the stack effects, the warmed air rise and discharged to the atmosphere during the daytime and the dense cool outdoor air sinks into the courtyard during the night time (Koch-Nielsen, 2002). On the other hand, the wind driven ventilation occurs when wind creates pressure distribution (positive or negative pressure) around a building surfaces. A positive pressure causes the air flow moving into the courtyard while the negative pressure creates an air suction outward from the courtyard.

In hot and humid climate, continuously ventilated condition is required so that it could remove the heat and humidity from the building for achieving comfort (Koch-Nielsen, 2002). The design of the building is suggested to promote maximum air movement with less internal obstruction. The traditional wooden house is one of the examples, which has a raised timber floor with multiple window openings on the building's façade to achieve the necessary cross ventilation condition.

Rajapaksha et al. (2003) investigated the potential use of a courtyard for passive cooling in a single-story, high thermal mass building located in Colombo, Sri Lanka. The results indicated that the indoor thermal conditions were somewhat improved when the courtyard acted as an air funnel by discharging indoor air to the sky, i.e., upward airflow, compared to when the courtyard acted as a suction zone, i.e., receiving air from the outside.

According to Tablada et al. (2005) courtyard combined with cross ventilation strategies contribute to a better indoor air flow inside the building.

However, most of the airflow study of the courtyard building was focused on increasing the indoor air flow rate, but less included on the effects of the building thermal condition. Therefore, the actual relationship between the increasing of air flow rate and the indoor thermal condition could not be fully determined.

2.3.2 Courtyard Design Variables

a. The shape of courtyard

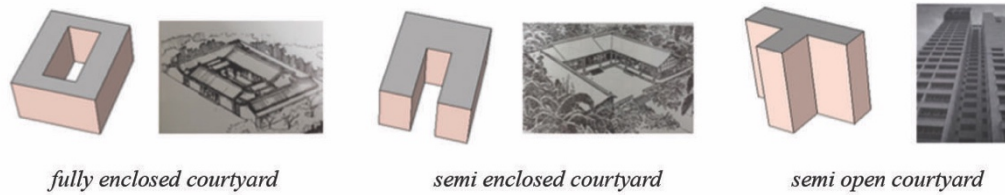


Figure 2.7 Different Courtyard Shape. (Zakaria and Kubota, 2014)

In general, the size and design of the courtyard's enclosure make a significant impact on its performance. Hyde (2000) concluded that the courtyard can be divided into three major types which are: fully enclosed courtyard, semi-enclosed courtyard, and semi-open courtyard. However, little is known about measured impact of different shape of courtyard as most studies about courtyard are conducted in fully enclosed courtyard.

Each courtyard has its characteristic and the appropriate function. For example, a fully enclosed courtyard is suitable for elongated buildings, because the natural lighting, ventilation and also comfortable spaces could be introduced to the core of the buildings through the courtyards. There are two variables, which are usually used to represent shape of the courtyard. Height to width (H/W) courtyard ratio explains the proportion of courtyard height to its width, and courtyard aspect ratio proportion is represented by width to length (W/L) ratio.

According to Muhaisen and Gadi (2006) thermal performance in deep courtyards is better than shallow one, and it require less energy for cooling. When the courtyard has a deeper form, it could provide more shaded areas, hence reduces the heat absorption in the courtyard. However, a tall courtyard building may cause an adverse impact on its air flow, unless it is carefully designed (Littlefield, 2012).

b. Courtyard Orientation

The building orientation plays an important role on the thermal performance by reducing the exposed area to the direct solar radiation of the buildings cover,

opaque walls and openings. The designer should take into account the sun path and the expected shading resulted from the orientation.

The important goal of orienting the courtyard is to obtain the optimum performance for the courtyard regarding to sun. The optimum angle of orientation is measured when the courtyard has a maximum wall-shaded zone in summer and lesser in winter. In the warm and humid regions, choose right orientation of a courtyard is a way to reduce of the direct sun exposure, where have to take into account the movement of sun from east to west, in addition to the wind direction (Zakaria and Kubota, 2014).

c. Shading Devices

The shading tools have a positive impact on thermal performance of buildings especially in hot climates. According to Al-Tamimi and Fadzil (2011), selecting good shading tools increases the comfortable hours by 26% for unventilated buildings and 4.7% in ventilated conditions in hot-humid climate. Shading tools include the usage of awnings, and tress to provide shade in the courtyard. Study by Almhafdy et al. (2015) also mentioned that adding roof to the U-shaped courtyard can slightly increase its thermal performance.

2.4 Courtyard Building and Cooling Energy

2.4.1 Comparison of Courtyard Building and Conventional Building Form towards Cooling Energy

Several researches show that courtyard can act as passive cooling strategy that will reduce energy consumption in building. Aldawould, A. (2008) revealed that building with courtyard is found to be energy efficient in all climates, specifically in the hot arid and hot humid climates. Al-Masri and Abu Hijleh (2012) compared same volume residential building with courtyard and without courtyard in Dubai. The study mentioned that adding the courtyard result in decreasing 6.9% of energy consumption.

Studies of energy efficient building in other climates consider both cooling and heating energy in order to find optimum building configuration. Both condition should be considered, because building that perform the best in summer, could increase the most energy consumption in winter. On the other hand, in warm humid equatorial region, cooling energy in the main concern of energy efficient building.

Studies about various building shape to cooling energy in the warm humid equatorial region were conducted in Malaysia and Singapore. Both studies simulated various alternative of office building. However, study conducted in Malaysia by Rashdi and Embi (2016) is limited to 5 stories building, while the other study in Singapore by Raji et al. (2017) simulated 40 stories building.

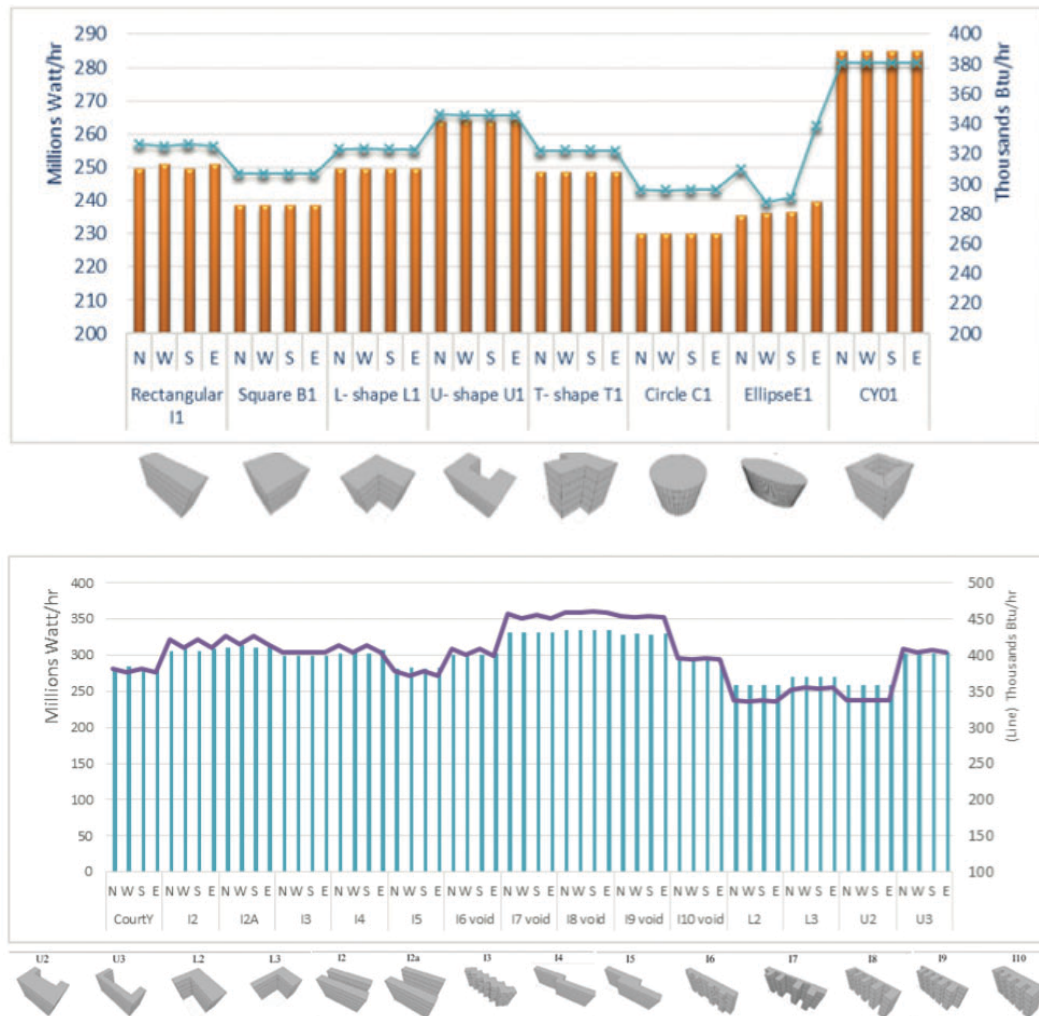


Figure 2.8 Comparison of Basic (above) and Extended (below) building form and Cooling Energy. (Rashdi and Embi, 2016)

Rashdi and Embi (2016) simulated 8 basic shape of office building, as well as 14 more complex office building shape. This study mentioned that compared to other basic shape courtyard buildings have the highest cooling load. Fully enclosed courtyard building, with surface to volume ratio of 1, has the the highest cooling energy compared to other shapes followed by U-shaped courtyard building with has surface to volume ratio of 0.8. In the next step of simulating 14 extended building form, there are two U-shaped courtyard building which produce different cooling

energy. U2 building, with surface to volume ratio of 0.35, has lower cooling energy than U3, with surface to volume ratio of 0.5. This study shows that surface to volume ratio is directly proportional to the cooling energy consumption. In addition, similar courtyard type building (In this case, U-shape) could result in different cooling energy consumption due to area of the courtyard. With the same building volume, U3 building has larger courtyard area than U2 building. The larger the courtyard area, the higher the solar exposure toward building, which lead to higher consumption of cooling energy in U3 building.

Supporting the previous findings, study by Raji et al. (2017) also stated that courtyard building produce higher cooling energy than the other basic shape with the same volume. Three different courtyard buildings, which are rectangular courtyard (shape 7), H-shaped building with courtyard (shape 8), and U-shaped courtyard (shape 10), were investigated. The result shows that rectangular building has the lowest energy consumption, followed by H-shaped building and U-shaped building.

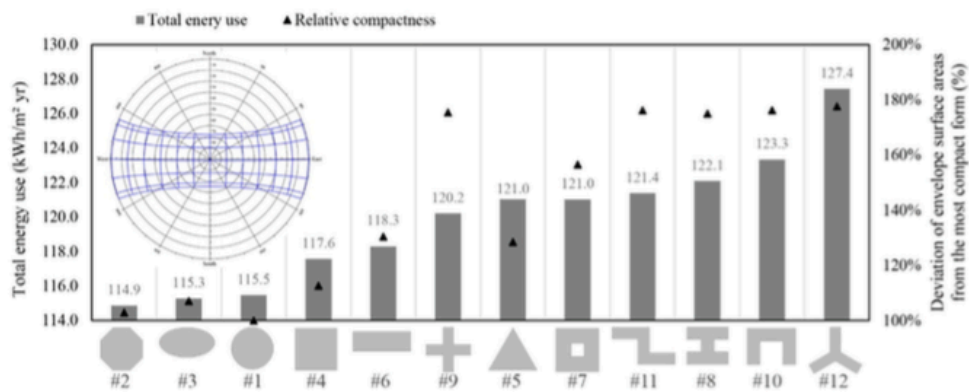


Figure 2.9 Various Building Shape and Cooling Energy (Raji et al., 2017)

In the study of Rashdi and Embi (2016) rectangular courtyard building has higher energy consumption than U-shaped courtyard building. On the other hand, study by Raji et al. (2017) mentioned otherwise. Although both studies simulated similar building volume with various building shape, courtyard buildings simulated have various courtyard area. Comparing both studies, size of courtyard will affect a building energy consumption. Therefore, in order to compare various shape of courtyard building, area of the courtyard should remain the same.

2.4.2 The Impact of Courtyard Size on Thermal Performance

Two variables related to the size of the courtyard are courtyard height and courtyard aspect ratio. Height of the courtyard usually determine the number of floor building surrounding the courtyard, whereas courtyard aspect ratio is the proportion of courtyard width and length. Muhaisen and Gadi (2006) stated that surface area of the envelope contributes more to the overall building heat gain than ground surface on the courtyard. Solar radiation received by the building is directly proportional to the overall heat gain. The lower the building height, the roof surface has higher solar radiation exposure than wall surface area. In taller building, exposure of wall surface area contribute more heat gain than roof surface area. Therefore, taller building with courtyard generate self-shading as a result of its form, thus minimizing exposure to sun radiation on its building envelope.

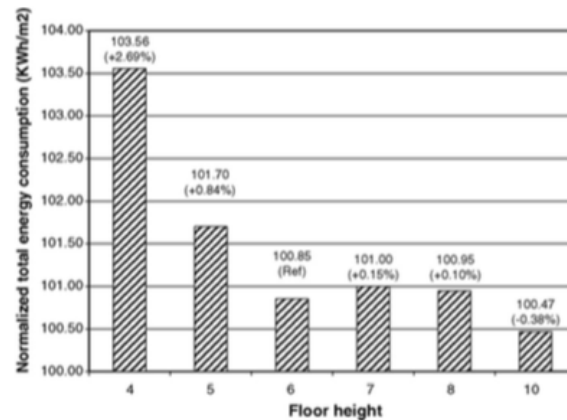


Figure 2.10 Total Energy Consumption of Different Courtyard Heights. (Al-Masri and Abu-Hijeh, 2012)

In hot and dry climate, with similar courtyard aspect ratio (W/L ratio), increase in building height (H/W) will generally save more energy. However, the saving of energy consumption is not significant after six stories height as showed by the graph below (Al-Masri and Abu-Hijleh, 2012). Study of courtyard height in temperate climate mentioned that H/W of 4:5 and 5:5 is suitable for warmer climate. Similar with previous study, the thermal performance of courtyard is relative constant after H/W ratio of 5:5 (Martinelli and Matzarakis, 2017).

Yasa and Ok (2014) studied courtyard aspect ratio (W/L) in different climate of Turkey. In the summer of hot humid climate of Turkey, courtyard with rectangular form is better than the square one, because the longer the courtyard, the

more solar radiation will be received. Similarly, study about courtyard aspect ratio in temperate climate also mentioned that longer courtyard will result in lower cooling load, because it could provide more shading (Muhaisen and Gadi, 2006). Manioglu and Oral (2015) studied various courtyard width to length ratio (W/L) range from 0.2 to 2 on different building area. Building with 100 m² area generate lower cooling load and solar gain when courtyard W/L is 0.2. On the other hand, building with 200 m² area generate lower cooling load and solar gain when courtyard W/L is 1.2 and 2 respectively.

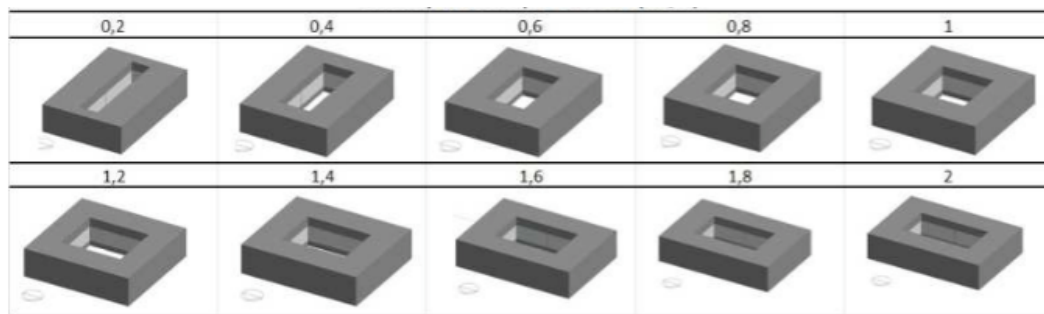


Figure 2.11 Different Courtyard Aspect Ratio (W/L) (Manioglu and Oral, 2015)

Several studies mentioned previously only investigated enclosed rectangular courtyard. Other than rectangular courtyard, Almhafdy et al. (2015) investigated U-shaped courtyard with one open ended side. According to this study, U-shaped courtyard with W/L of 1:2 perform better than U-shaped courtyard with aspect ratio of 1:1, in warm humid climate of Malaysia. However, this study only investigated U-shaped courtyard with two different aspect ratio.

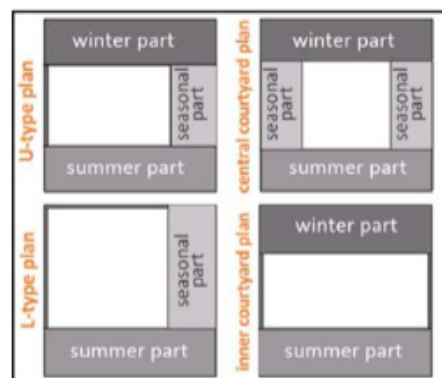


Figure 2.12 Different Courtyard Shapes Studied in Turkey (Kocagil and Oral, 2015)

Kocagil and Oral (2015) studied four different plan configuration of one story courtyard building just like the picture above. According to this study, the

inner courtyard configuration has the minimum energy consumption that the other configuration. However, the study accounts for both cooling and heating energy in hot and dry climate in Turkey.

Several studies mentioned above indicate that courtyard proportion has significant impact on its thermal performance. These findings support earlier study by Muhaisen and Gadi (2006) which mentioned that deeper and elongated courtyard is better than the shallow rectangular one for cooling purpose. However, little is known about optimum courtyard aspect ratio towards cooling energy in warm humid equatorial region, as studies about courtyard are mostly conducted in both temperate and hot dry climate.

2.4.3 The Impact of Courtyard Orientation to Thermal Performance

Orienting courtyard with respect to sun position and latitude can obtain optimum performance of courtyard. Optimum courtyard orientation increases shaded area of both courtyard and building enclosure, thus minimizing building solar heat gain. Studies about courtyard orientation in warm humid equatorial region are mainly conducted in Malaysia. In addition, studies about relationship of courtyard orientation and cooling energy are still limited.

Muhaisen (2006) mentioned that during summer solstice (21st June), optimum shaded area is achieved by orienting courtyard along north – south axis. Whereas, during winter solstice (21st December) orienting courtyard towards 30° from the east result in optimum shaded area. However, this study did not investigate the impact of optimum shading to courtyard thermal performance.

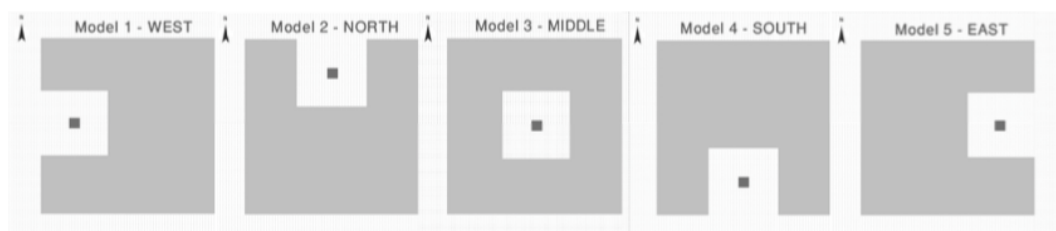


Figure 2.13 U-shape Sourtyard Studied in Malaysia (Ghaffarianhoseini, 2015)

Ghaffarianhoseini (2015) studied different courtyard orientation and its impact on thermal performance in Malaysia. According to this study, U-shaped courtyard facing north and east have higher wind speed and lower outdoor temperature of about 5° C, compared to other orientations. The simulation study was conducted in 5th March, because it has highest radiation recorded in 2013.

2.4.4 Building Shape with Courtyard

Building shape with courtyard is the presence of courtyard inside a building which result in various building shape. Element of courtyard inside a building is beneficial for penetrating daylight, as well as create shade and air circulation. In high rise residential building with high occupancy, it is not feasible at one point to create one massive building block. Several apartment units will have no access of daylight and fresh air. With similar occupancy rate, courtyard building could provide better condition that other compact shapes in high rise residential building.

Thermal performance of this courtyard building is influenced by many aspect, the building itself as well as the courtyard element. Thermal performance of the courtyard will affect thermal performance of the building, and vice versa. Although there are many variables to be considered, this study focuses on the thermal performance of various building shape as a result of different courtyard shape.

2.5 Summary

This research focuses on the effect of high rise residential building geometry with courtyard towards cooling energy. Building geometry defines exposed area to solar radiation thus effecting building thermal performance (Markus and Morris, 1980; Lechner, 2015). Courtyard, an enclosed open space surrounded by the building, has been a prominent design element in the development of high rise apartment in Surabaya. There are five different geometries of courtyard building in Surabaya high rise apartments, such as H geometry, U geometry, Double U geometry, Double L geometry, and Quadruple L geometry. Studies conducted by Aldawould (2008) and Al-Masri and Abu-Hijleh (2012), mentioned that courtyard building is found to be more energy efficient in hot climate.

Two main roles of courtyard are generating self-shading of buildings, and natural ventilation. (Kubota and Zakariya, 2014). In addition, presence of courtyard could induce natural lighting inside a building (Hyde, 2000). According to Hyde (2000), courtyard size and design of envelope that surrounding the courtyard determine the courtyard performance. Two variables related to the size of the courtyard are courtyard height and courtyard aspect ratio. Height of the courtyard usually determine the number of floor building surrounding the courtyard, whereas

courtyard aspect ratio is the proportion of courtyard width and length. Muhaisen and Gadi (2006) stated that surface area surrounding the courtyard contribute more heat gain than ground surface of the courtyard. In the case of high rise apartment, surfaces surrounding the courtyard have significant portion rather than courtyard ground surface.

Several studies mentioned that increase in courtyard height will generally save more energy. In hot and dry climate, increasing of thermal performance is not significant after 6 stories height, while in temperate climate after H/W ratio of 5: 5 (Al-Masri and Abu-Hijleh (2012), Martinelli and Matzarakis (2017)). Studies about courtyard aspect ratio in hot arid and temperate climate stated that elongated courtyard provide more shading than square courtyard. (Yasa and Ok (2014), Muhaisen and Gadi (2006)). Manioglu and Oral (2015) also stated that rectangular courtyard generate lower cooling load and cooling energy.

Several studies mentioned previously only investigated enclosed rectangular courtyard. In warm humid tropical region, Almhafdy et al. (2015) investigated U-shaped courtyard with one open ended side. According to this study, U-shaped courtyard with W/L of 1:2 perform better than U-shaped courtyard with aspect ratio of 1:1. This study also stated that opening area of the courtyard will influence thermal condition surrounding the opening.

Muhaisen (2006) stated that orienting courtyard along north-south axis will achieve optimum shaded area during summer solstice in Malaysia. Study by Ghaffarianhoseini (2015) about U-shaped courtyard stated that orienting courtyard according to the upcoming wind will increase courtyard thermal performance. Nevertheless, studies about courtyard orientation conducted in warm and humid equatorial region investigate about courtyard outdoor thermal condition (Muhaisen (2006), and Ghaffarianhoseini (2015)), are not related to energy consumption.

Most of the studies about courtyard are mconducted in temperate or hot and dry climate. In general, these studies only investigated rectangular courtyard shape. Although several studies about courtyard have been conducted in warm humid tropical region, studies evaluating various building shape with courtyard and cooling energy are still limited.

This research focuses on various shapes of high rise courtyard apartments existed. Courtyard shape is defined by building geometry surrounding the courtyard. Two dominant variables that define courtyard shape are height/width ratio (H/W) and width to length ratio (W/L). In addition, thermal performance of a building depends on the building orientation which related to building relative position toward the sun angle. These four variables are investigated in this research.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Research Paradigm

This research aims to investigate five different shapes of high rise apartment with courtyard towards building thermal performance and identify courtyard building shape that produce minimal cooling energy. Variables studied in this research are courtyard building geometry, courtyard aspect ratio and building orientation. Courtyard building geometry consider both building shape and courtyard formed by the building shape.

According to Groat and Wang (2013) this research could be categorized as quantitative research, with has characteristics as follows:

- a. Deductive way of thinking, in which research findings are identified as causality. In this research, various building shape (cause) will result in different cooling energy (effect).
- b. The research is free from researcher subjective. The study of causality in this research will use series of calculation via computer program. The research findings are analyzed from data obtained in the program.
- c. The research findings can be measured by number. Variables studied in this research are objective and measurable. Cooling energy consumption is represented by electricity consumption in Kilowatt hour/m² of a building.

Research paradigm of quantitative research can be either positivism or post-positivism research. Positivism research assumes that every physical condition can be objectively measured or can be assumed to represent reality perfectly (Groat and Wang, 2013). On the other hand, post-positivism believe that measurement and observation of a physical condition could be imperfect and has probability of errors. This research studies thermal condition of high rise residential building as a result of building shape. Thermal condition of existing building is measured and represented by number. Experimental research by modification of variables in this research is conducted by standardized and validated tools. Nevertheless, there is probability that result of this research fails to represent reality perfectly. As a result, this research can be categorized as post-positivism research.

3.2 Research Method

This research uses experimental research with simulation as research method, because some variables are manipulated in order to investigate causality through the use of treatments. According to Groat and Wang (2013) the characteristic of experimental research strategy are as follows :

1. The use of treatment or independent variable

In order to study the impact of identifiable variables in the research, the independent variables are manipulated in several condition. Building shape, building aspect ratio, and building orientation will be modified to see the impact on building cooling energy.

2. The measurement of one or more outcome variables

The impact or result of the treatment from the first characteristic is measured by the certain outcome measure or dependent variables. Building energy consumption will be measured through its electricity consumption (kWh/m²)

3. The designation of Unit of Assignment

The experimental treatment is applied to specific unit of assignment such as mock up model or depends on the research. Unit of assignment in this research is simulated building models, which represent various shape of high rise apartment existed in real life.

4. The use of comparison or Control Group

The control group is defined by a condition in which the treatment is not applied in order to compare the result of the treatment. The control group in this research is the existing apartment model and thermal condition (base case).

5. A focus on causality

The cause and effect relationship is studied through several features of the experimental research such as the treatment, unit of assignment, and the control group. The causality in this research is shape of high rise apartment with courtyard (cause) towards cooling energy consumption (effect).

According to Groat and Wang (2013) simulation method can be used as tactic for the others research methodology. Simulation method create a “copy” of reality using computer program. In the experimental research, unit of assignments are modified in order to investigate causality (the use of treatment). Without using

simulation, real scale mock-up models are required in order to manipulate some variables within a certain climate. In the case of investigating various effect of high rise building with courtyard toward building thermal performance, using simulation method will be costly efficient. In addition, it is impossible to investigate impact of building orientation in the real scale mock up model.

In order to obtain reliability of the simulation result, field measurement for the purpose of software verification was conducted. Verification is the process of comparing simulated building model with real life environmental condition. Verification method used in this study is according to the study of Raftery et al. (2011), Royapoor and Roskilly (2015), and Ruiz and Bandera (2017).

3.3 Research Procedure

Procedure in this research consist of identification, verification, experiment, analysis and optimization. Identification process consist of two step, with the first step is doing literature review in order to identify studied variables. The second step of identification consist of field observation of high rise apartment in Surabaya and conducting field measurement in sampling apartment.

Macro climate data of Surabaya is required in order to compare the result of field measurement and surrounding climate. Macro climate data of Surabaya will be obtained from Surabaya Metrological Authority Bureau (BMKG). Comparison of macro and micro climate is necessary to evaluate the similarity between climate data of BMKG and outdoor thermal condition of field measurement for the purpose of simulation weather data. If there is no significant difference between macro and micro climate data, weather data of BMKG is considered appropriate for input weather data in the software simulation.

In the process of software verification, simulated model, which represent the measured building, will be generated by Design Builder software version 5.0. The verification model will be simulated under the same circumstances as in the field measurement. Later, the simulation result of the software will be compared with result from the field measurement, in order to identify how accurate simulated model represent real life condition.

In the next step, experimental research with several treatments are simulated using Design Builder. Analysis of causality between variables is generated from

outcome data of different treatment. Optimization of studied variables is analyzed from comparison of various simulation result and base case condition.

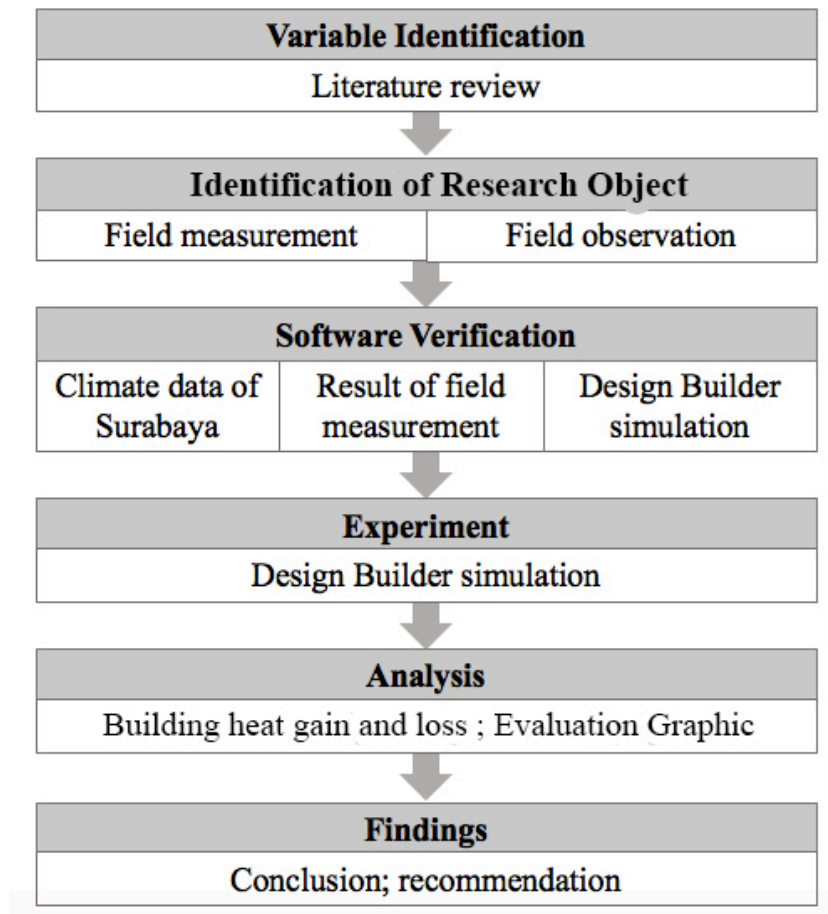


Figure 3.1 Diagram of Research Procedure

3.4 Research Variable and Operational Definition

Research variables in this study are determined by research question and research objective, with further identification through literature review. Research variables consist of independent, dependent, and control variable. In order to get better understanding about variables in this research, Figure 3.2 illustrates the terminology of geometries variables of courtyard building.

3.4.1 Independent Variables

Independent variables are manipulated variables within treatment process of designated unit assignments. Independent variables in this research are building geometry, courtyard aspect ratio (W/L), and orientation.

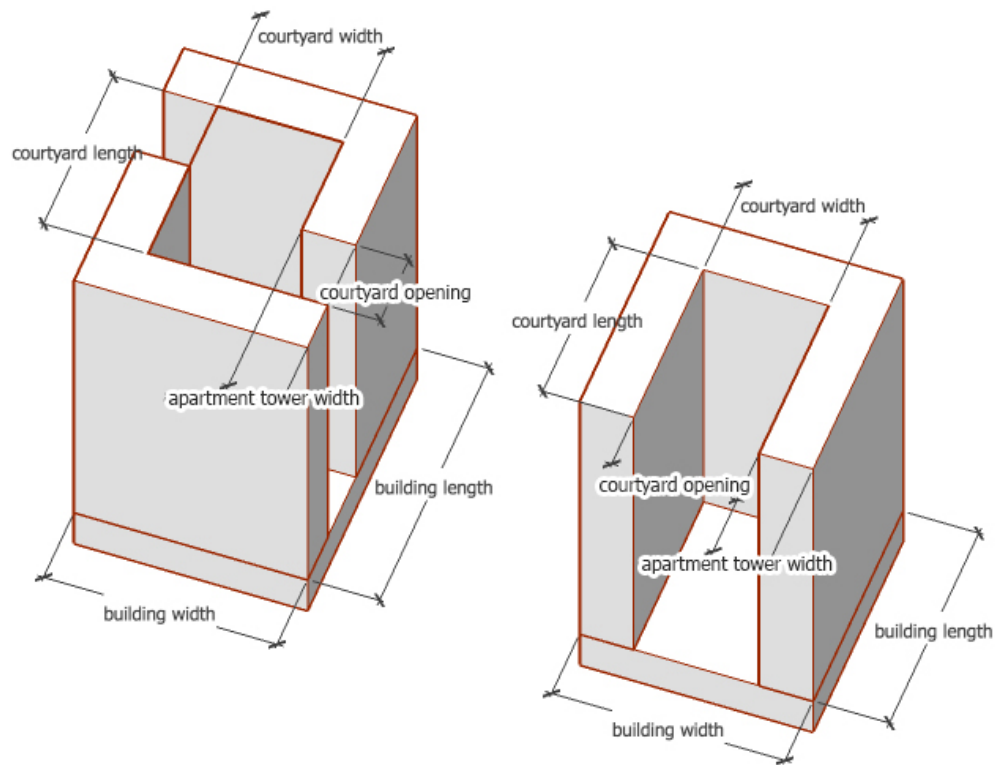


Figure 3.2 Illustration of Courtyard Building Variables

a. Building Geometry

Building geometry is the external form or outline of a building. Courtyard building geometry are influenced by the shape of the building and the shape of the courtyard created by the enclosing building. Variables of building geometry are determined by building shape and courtyard aspect ratio. Shape of the building define the courtyard shape formed by it, and courtyard aspect ratio determine building width and length proportion as the building will follow to shape of the courtyard. Courtyard aspect ratio is chosen as the independent variable rather than overall building aspect ratio in order to identify the impact of courtyard toward the building thermal performance, as well as to compare the result of this research to the pervious courtyard studies.

1. Building shape

Building shape is the shape of building outline which can be identified by perimeter walls. There are five different building shapes investigated in this research : U-shape, H-shape, double U-shape, double L-shape, and quadruple

L-shape, which result in five different courtyard shape. Courtyard area in the five different shape will remain the same, because increasing the courtyard area could lead to more solar radiation exposure. Courtyards shape formed by surrounding building are rectangular shape as well as rectangular courtyard shape with courtyard gaps.



Figure 3.3 Different Courtyard Shapes Evaluated in this Research

2. Courtyard Aspect Ratio

Courtyard is the open area enclosed by surrounding wall of buildings. Parameter to define the courtyard shape is courtyard aspect ratio (L/W) is the ratio of courtyard length (L) to the courtyard width (W). Courtyard shape with gaps in between the building area, such as courtyard formed by double U-shape, double L-shape, and quadruple L-shaped, obtain the courtyard aspect ratio (L/W) by comparing the courtyard length (L) to the courtyard width (W).

Height (H) of the courtyard will remain the same, as this research investigates various courtyard shape in high rise residential building. Height variable in this research are not modified.

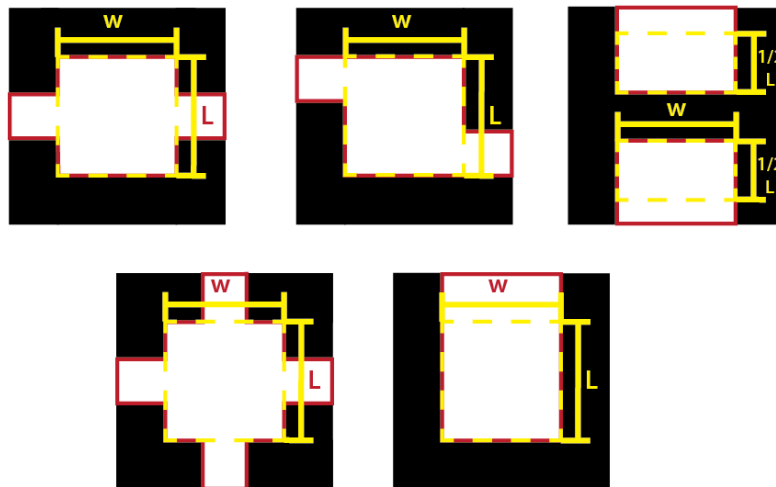


Figure 3.4 Illustration of Courtyard Aspect Ratio in Various Courtyard Shapes

b. Building Orientation.

Orientation of the courtyard is angle formed by courtyard width (L) to the north orientation. Courtyard width is the shortest side of the courtyard. Angle of 0° means that courtyard width is facing north. For U-shaped courtyard, the open-ended side is facing north at 0° .

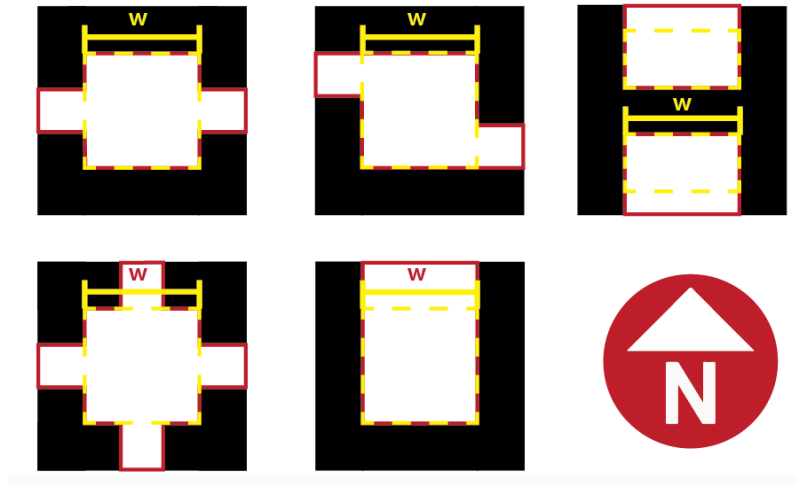


Figure 3.5 Illustration of Courtyard Width and Orientation.

3.4.2 Dependent Variables

Dependent variables are variables affected by the modification of independent variables. The dependent variable of this research is as follow building annual cooling energy. Building cooling energy is accumulation of building cooling load from sensible heat and latent heat. Building cooling energy consumption will be measured though energy consumption per square meter annually ($\text{kWh}/\text{m}^2/\text{yr}$). The calculation of building cooling energy will be simulated annually. A building cooling energy contributes to overall building Energy Use Intensity (EUI), which is the accumulation of various energy usage of a building, such as energy required for heating and cooling, lighting, pump, hot water, and other electricity loads. In this research, internal heat gain is included in the control variable group, therefore cooling energy is the only energy source that can make the EUI of a building is different from another building. In order to differentiate total energy consumption of model experiments and cooling energy of zones for apartments units, this studies only analyse calculation of annual cooling energy per conditioned zones.

The focus in this study is cooling energy consumption of courtyard buildings. The others energy usage, such as energy for lighting, appliances, and etc,

are considered the same in all simulation of experimental model (units of assignments). The building cooling energy will be analysed according to:

1. Building heat gain

Building heat gain accounts for heat that simultaneously enter the building because of heat transfer mechanism as well as heat generated inside the building (internal heat gain). Design Builder differentiates building heat gain into four different categories : fabric gain, solar gain, infiltration gain, and internal heat gain, with definition as follows :

- a) Fabric heat gain accounts for heat gain generated by the building envelope, such as wall, window, floor, ceiling, and roof. Heat gain from both conduction and convection process are included in the fabric heat gain, expect heat gain from window solar radiation.
- b) Solar heat gain accounts for heat gain caused by window solar radiation.
- c) Infiltration heat gain accounts for heat gain caused by exchange of air through cracks from inside and outside as well as exchange air between two different rooms.
- d) Internal heat gain accounts for heat gain generated by building occupants, lighting and electronic appliances.

2. Building heat loss

In the conditioned building, heat loss accounts for heat removed from the conditioned space in order to achieved desired thermal condition by cooling process. Design Builder differentiates building heat loss by cooling process into two different categories : sensible cooling and latent cooling.

a) Sensible cooling load

Sensible cooling load refers to the heat quantity required to be removed in order to achieve desired temperature. Sensible cooling load is influenced by heat transfer of a building (conduction, convection, and radiation of building elements), as well as infiltration through building cracks which bring the outside heat inside.

b) Latent Cooling Load

Latent cooling load refers to the the heat quantity required to be removed in order to lower the moisture content. Latent cooling load is

influenced by the number of occupants, equipment and appliances, and air infiltration through cracks in the building. Latent cooling influences humidity of a conditioned space.

Total cooling load or cooling energy consumption of a building is the sum of sensible and latent cooling load of a building. Four different heat gain factors of a building contribute differently to a building sensible and latent cooling load. Evaluating each factor of a building heat gain, and results of sensible and latent cooling will determine the cause of different cooling energy of a building, when independent variables are modified.

3.4.3 Control Variables

The control variables in this research are:

a. Courtyard Area

Courtyard area is the ground surface area of the courtyard. Size of the courtyard determine thermal performance of a courtyard. In order to compare various building geometry with courtyard, all model experiments have similar courtyard area. As stated by Muhaisen and Gadi (2006) surface area of the envelope contributes more to the overall building heat gain than the ground surface of the courtyard. Increasing the courtyard area will increase the area of walls surrounding the courtyard, especially in high rise building where building envelope is more dominant.

b. Apartment tower width

Apartment tower width is the smallest dimension of an elongated building structure. Apartment tower width for the simulated models are generated from the field observation data of apartment population. According to table 3.2 about building shape variable in high rise apartment with courtyard in Surabaya, the average apartment tower width is 14.6 m. In order to simplify the simulated model, the apartment tower width will be 14 m, similar with the median data of apartment tower width in table 3.2.

c. Building podium

Building podium is the base form of a building structure. Building podium in all simulated model will have similar rectangular shape and volume. Building podium is included in the simulated models because most of high rise

apartments with courtyard in Surabaya are designed with podium. According to the field observation of Surabaya apartments (table 3.2), the average floor story height of these apartments are 4 story height.

d. Building material

Building material is the material used for walls surrounding the courtyard volume. Material data for the simulated models will be based on field investigation study by Alfata et al. (2015) in Surabaya apartments. The external walls of these apartments are made of pre-cast concrete and partition walls made of lightweight concrete, with per unit thermal mass is 1,100 kg/m². Glazing material of the windows are made of 3 mm single clear glass.

e. Building Window to Wall Ratio (WWR)

Building WWR is the percentage of window area to the overall envelope area. Liping and Hien (2007) stated that optimum thermal performance is achieved when the window to wall ratio (WWR) is 24% in Singapore natural ventilated building. In addition, the average WWR of courtyard apartment in Surabaya is 26.9%. In order to simplify the WWR calculation, WWR for the simulated models is 30%.

f. Building Internal Heat Gain

Building internal heat gain consist of the sensible and latent heat emitted from the building indoor condition. Building internal heat gain depends on occupants, lighting, cooking and electrical equipment. Detailed explanation of the building heat gain input in the model experiments are explained in table 3.15.

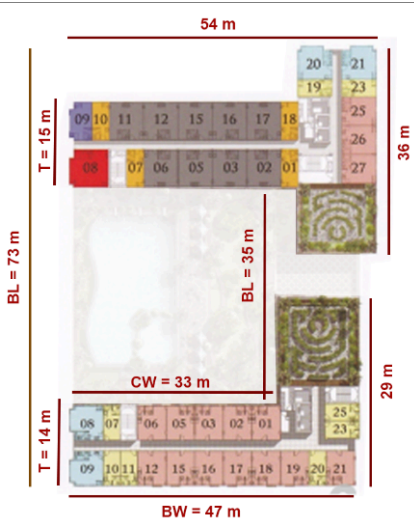
3.5 Object of the Research

The impact of courtyard shape to the cooling energy is the subject of this research, while high rise residential apartment is object investigated in this research. Apartment with courtyard is a common form of high density apartment in Surabaya. This type of apartment exists in various shape configuration. In order to find characteristics of various apartments shape, population study was conducted by field observation. Population study of high rise apartment with courtyard will determine simulated building models of the experimental research.

3.5.1 Population

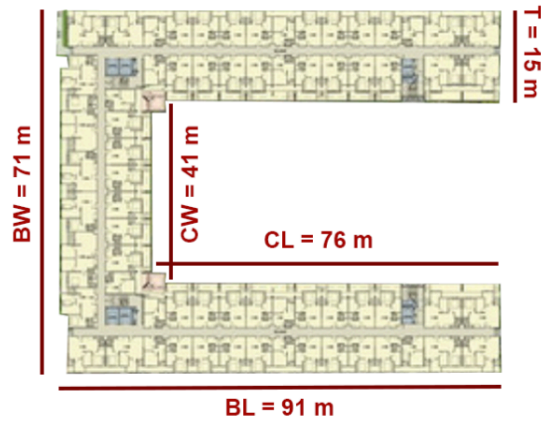
The population in this research is apartment with courtyard in the city of Surabaya. Table 3.1 shows the population data from high rise courtyard apartment in Surabaya according to the field observation

Table 3.1 The Shape Typology of Apartment with Courtyard in Surabaya

Apartment Name	Dimension	Height & Unit
 Puncak Dharmahusada Apartment Land area = 61,600 m²		35 story height with 4 storys podium Studio = 21.32 2 BR = 35.21; 42.4 ; 56.74 m² 3BR = 78.13 ; 98.68 ; 92.72 m²
 Gunawangsa Merr Apartment Land area = 8,250 m²		31 story height with 4 storys podium Studio = 21.79; 23.58; 28.95 2 BR = 36.31; 40.87 ; 43.57; 47.14; 52.23 m²
Note : BL = building length; BW = building width; CL = courtyard length; CW = courtyard width; T = apartment tower width (refers to Figure 3.2)		



East Coast
Residence
Apartment
Land area =
22,700 m²



13 - 20 story
height
with no podium

2 BR = 35 m²
(nett)

3BR = 53; 71
m² (nett)

4 BR = 140 m²
(nett)



Puncak Permai
Apartment
Land area =
22,700 m²



21 story height
with 3 storeys
podium

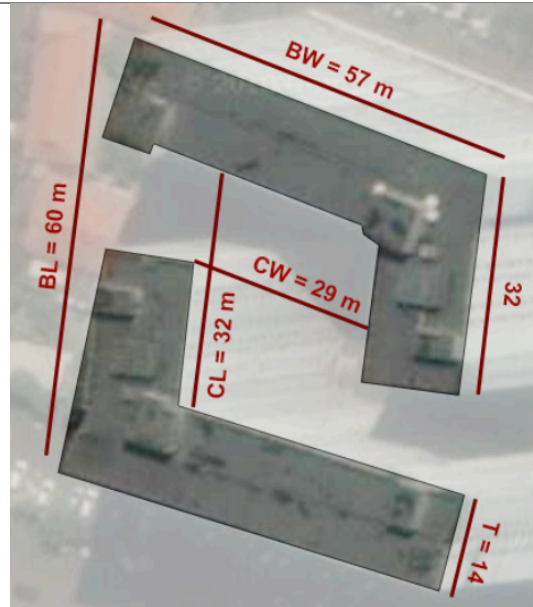
Studio = 27 m²

2 BR = 36 m²





Gunawangsa
Manyar Apartment

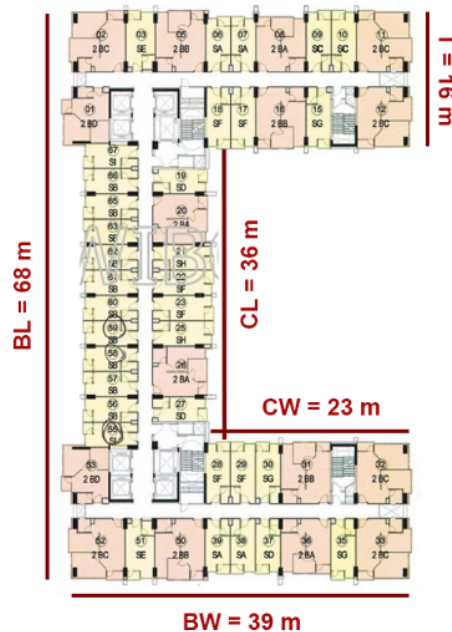


30 story height
with 3 storys
podium

Studio = 27 m²
(nett)
2 BR = 36 m²
(nett)



East Coast Mansion
Apartment (under
construction)

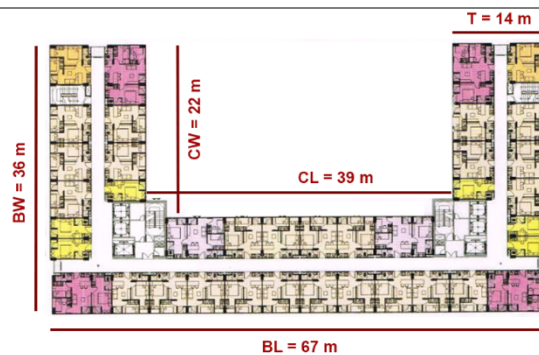


40 story height
with 10 storys
podium

Studio = 18; 20;
23 m² (nett)
2BR = 37.5; 42;
45 m² (nett)



Puncak Merr
Apartment (under
construction)

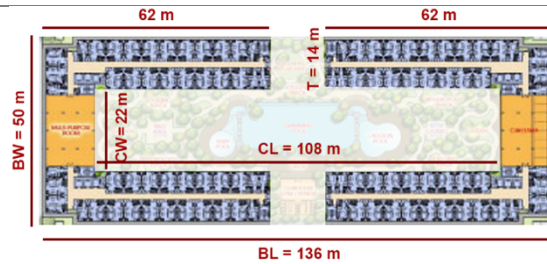


35 story height
with 5 storys
podium

Studio = 21.05 m²
2 BR = 38.58;
40.69 m²
3BR = 59.63;
61.73 m²

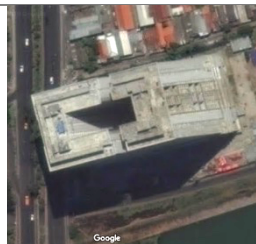


Puncak Kertajaya
Apartment
Land area =
15,800 m²



20 story height
with 2 storys
podium

Studio = 18 m²
(nett)
2 BR = 30 m²
(nett)



Bale Hinggil
Apartment
Land area =
9,600 m²

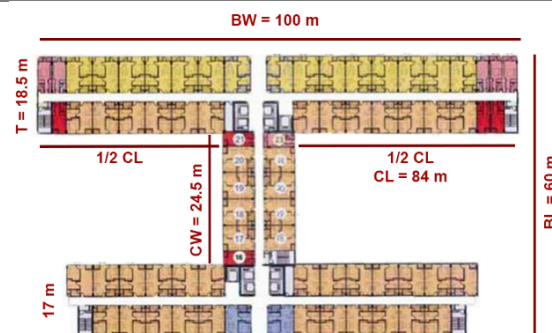


30 story height
with 5 storys
podium

Studio = 19.14
m² (nett)
2BR = 37.63 m²
(nett)
3BR = 53.08 m²
(nett)



Puncak Bukit Golf
Apartment
Land area =
16,000 m²



32 story height
with 4 storys
podium

Studio = 22.8;
20.1 m² (nett)
2BR = 41.8;
36.85 m² (nett)



Taman Melati
Apartment (under
construction)

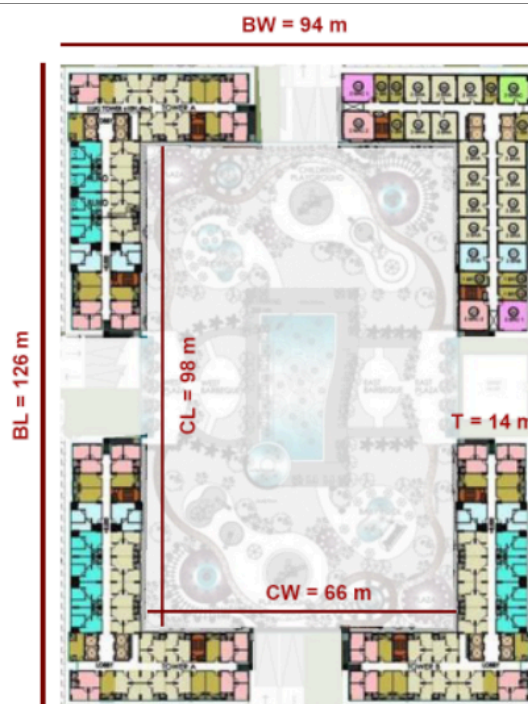


30 story height
with 5 storys
podium

Studio = 24.7 ;
28.95
2 BR = 49.4; m²



Educity Apartment
Land area =
23,000 m²



30 story height
with 3 storys
podium

Studio = 18 m²
(nett)
2BR = 31.8 m²
(nett)
3BR = 37.8 m²
(nett)

According to the field observation, variations of different apartment shape and dimension depends on several factor such as the land area, land shape, and target market of an apartment. According to the population of apartment with courtyard, most of apartments with courtyard are for middle class economy. U-shaped apartment is the most commonly found apartment shape in Surabaya, while quadruple L-shaped is only found in one apartment. The average and median height of these apartment is about 30 stories with 4 stories podium.

Population of the courtyard apartments have wide range of building length and width. However according to figure 3.5, trend of the total building width is

between 30 – 60 m, and trend of total length is between 40 - 90 m. Wide variation of apartments total width and length result in different apartments volume and capacities. In addition, courtyard in these apartment also have different size as shown by figure 3.6. Trend of the courtyard width is between 18 – 38 m, and trend of the courtyard length is between 20 – 60 m. According to figure 3.5 and 3.6 there are four apartments whose building and courtyard size different from majority of the population.

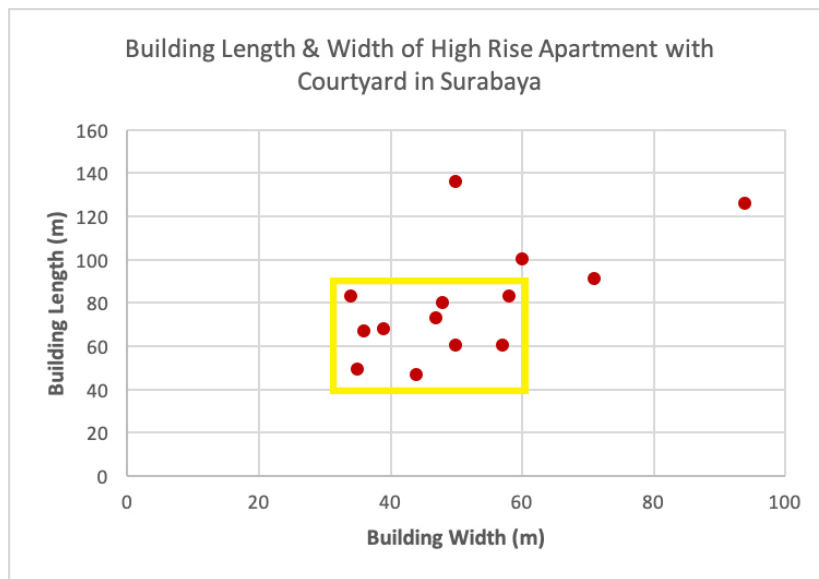


Figure 3.6 Building Length & Width of High Rise Apartments with Courtyard in Surabaya

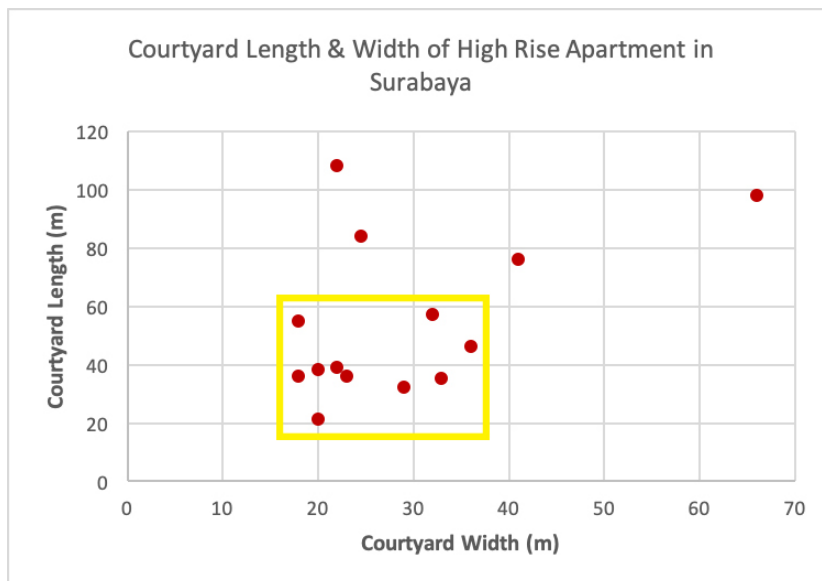


Figure 3.7 Courtyard Width & Length of High Rise Apartments in Surabaya

The similarity from these courtyard apartment is the apartment tower width. Although the population do not have the same apartment tower width, it has the least variation rather than the other shape variables. Although the apartment tower width varies from 14 m to 18 meters, most of apartments have apartment tower width of 14 m. The similarity in apartment tower width is a result of these apartments circulation. All of them have double loaded corridor block in order to maximize occupancy rate.

Table 3.2 Building Shape Variables of High Rise Apartment with Courtyard in Surabaya

Apartment	W (m)	L (m)	Area/ floor (m ²)	Podi- um	No. of Floor	Apartment tower width (T)	Aspect Ratio (W/L)
Puncak Dharma- husada	34	83	1722	4	35	14	1 : 2.44
	35	49	1274				1 : 1.4
Gunawang- sa Merr	47	73	1993	4	31	$\frac{15}{14}$	1 : 1.55
East Coast Residence	71	91	3345	0	20	15	1 : 1.28
Puncak Permai	58	83	2574	3	21	13	1 : 1.43
	50	60	1848			14	1 : 1.2
Gunawang- sa Manyar	57	60	2100	3	30	14	1 : 1.05
East Coast Mansion	39	68	1788	10	40	16	1 : 1.74
Puncak Merr	36	67	1554	5	35	14	1 : 1.86
Puncak Kertajaya	50	136	4088	2	20	14	1 : 2.72
Bale Hinggil	48	80	2848	5	30	14	1 : 1.66
Puncak Bukit Golf	60	100	3644	4	32	$\frac{17}{18.5}$	1 : 1.66
Taman Melati	44	46.5	1484	5	30	13	1 : 1.05
Educity	94	126	4256	3	30	14	1 : 1.34
Max	94	136	4256	10	40	18.5	
Min	34	46.5	1274	0	20	13	
Average	51.6	80.8	2465.6	4.00	29.5	14.63	
Median	49	76.5	2046.5	4	30	14	

Table 3.3 Courtyard Shape Variables of Surabaya High Rise Apartments

Apartment	Courtyard					
	Width	Length	Area (m ²)	Height*	H/W	L/W
Puncak Dharmahusada	18	55	990	93	1.72	3.06
	20	21	420		1.55	1.05
Gunawangsa Merr	33	35	1155	81	0.82	1.06
East Coast Residence	41	76	3116	60	0.49	1.85
Puncak Permai	32	57	1824	54	0.56	1.78
	22	46	1012		0.50	2.09
Gunawangsa Manyar	29	32	928	81	0.93	1.10
East Coast Mansion	23	36	828	90	1.30	1.57
Puncak Merr	22	39	858	90	1.36	1.77
Puncak Kertajaya	22	108	2376	54	0.82	4.91
Bale Hinggil	20	38	760	75	1.25	1.90
Puncak Bukit Golf	24.5	84	2058	84	1.14	3.43
Taman Melati	18	36	648	75	1.39	2.00
Educity	66	98	6468	81	0.41	1.48
max	66	108	6468	31	1.72	4.91
min	18	21	420	31	0.41	1.05
average	27.89	54.36	1674.36	76.50	1.02	2.08
median	22.5	42.5	1001	81	1.04	1.82

*courtyard height is the result of building height minus podium, and estimating floor to floor height of 3 m.

Table 3.4 Floor to Ceiling Height of Several Apartments with Courtyard

Apartment	Floor to Ceiling Height	Source
Bale Hinggil	2.7 m	Field measurement
Gunawangsa Manyar	2.7 m	Field measurement
Puncak Permai	2.7 m	Alfata et al. (2015)
Puncak Kertajaya	2.68 m	Sari et. Al. (2017)

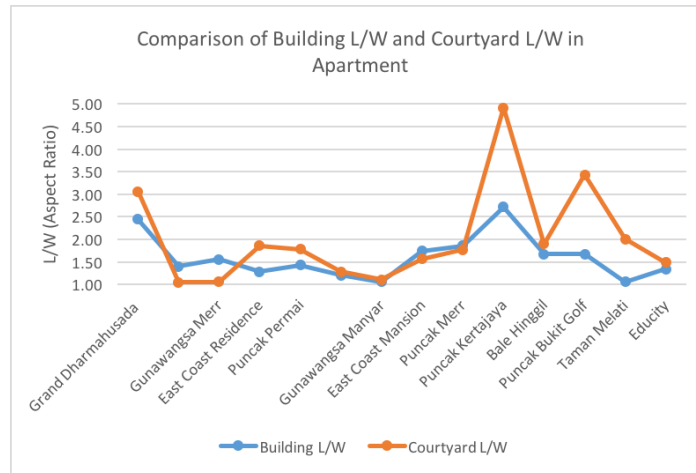
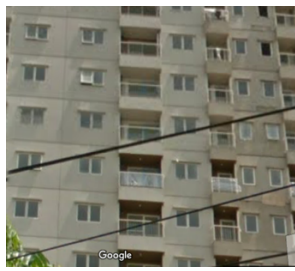


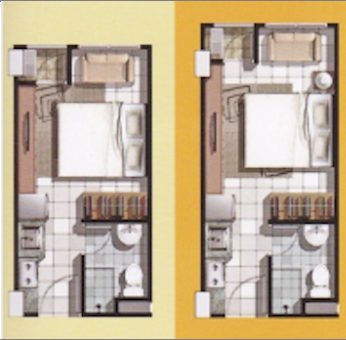
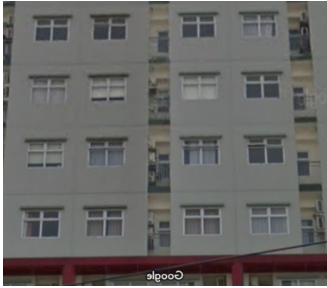
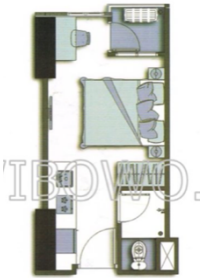
Figure 3.8 Comparison of Building L/W and Courtyard L/W in Surabaya Apartments

Aspect ratio of a building could be different with aspect ratio of the building's courtyard. In high rise apartment of Surabaya, most of buildings and courtyards aspect ratio (L/W) have deviation of 0.5. This difference is a result of various building apartment tower width and very elongated buildings tend to have wide deviation between building and courtyard aspect ratio.

According to table 3.5, all of high rise apartment with courtyard in Surabaya have similar loggia type balcony. 4 Apartments have window facing the balcony, 5 Apartments have glass door facing the balcony, and only two apartment have both door and windows facing balcony. The average window to wall ratio (WWR) of high rise apartment in Surabaya is 26.94% per unit. Another characteristic of these apartments is that lower WWR area in the apartment tower width of the building as explained by table 3.6.

Table 3.5 Facade and WWR of High Rise Apartments with Courtyard in Surabaya

Apartment	Unit Plan	Apartment Façade	WWR/unit
Puncak Dharmahusada			19.8%

Gunawan gsa Merr			19.8 %
East Coast Residence	-		24.17%
Puncak Permai	-		17.8%
Gunawan gsa Manyar	-		16.3%
East Coast Mansion		Under construction	43.3%
Puncak Merr		Under construction	19.8%

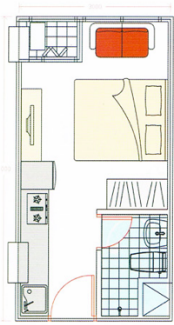
Puncak Kertajaya			28.75%
Bale Hinggil	-		29.3 %
Puncak Bukit Golf	-		33.36%
Taman Melati			50.9%
Educity			20%
Average			26.94%

Table 3.6 Characteristic of Apartment Tower Width of Courtyard High Rise Apartments

	
Taman Melati Apartment	Puncak Bukit Golf Apartment
	
Gunawangsa Merr Apartment	Bale Hinggil Apartment
	
Gunawangsa Manyar Apartment	East Coast Residence Apartment



3.5.2 Sample of The Study

Sampling apartment with courtyard is required in order to obtain thermal condition of apartment with courtyard in real life. The field measurement conducted in the sampling apartment will be used in validation data of the research. Bale Hinggil Apartment is chosen for profiling thermal conditions of existing apartment.

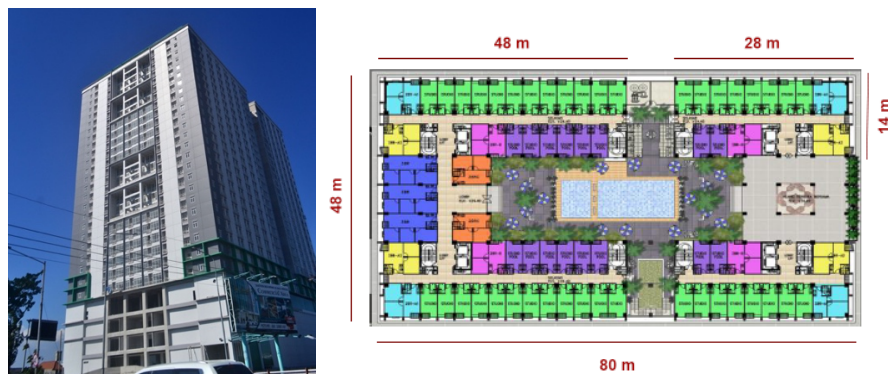


Figure 3.9 Perspective and floor plan of Bale Hinggil Apartment

Bale Hinggil is a high rise apartment located in the east of Surabaya with 30 floor height, and 4 story podium. This apartment consists of two U-shaped towers facing each other. The construction process is not 100% completed, therefore there is no occupant yet in the Bale Hinggil Apartment. However, the

construction process of Bale Hinggil Tower A ,where the field measurement will take place, is already completed.

Conducting field measurement in an unoccupied apartment will beneficial for the verification process of simulation. Apartment with high rate occupancy will produce additional internal heat gains which are hardly to predict. Heat produces by occupants, activity pattern, lighting, electronic appliances, etc., will affect overall thermal conditions.

3.6 Data Collection Method

Table 3.7 Data Collection Method of Research Data

Primary Data	Sub Primary Data	Data Collection	Instrument
Building shape	Building volume, width, length, height, and apartment tower width	Field observation, and literature review	Review of existing floor plan
Thermal condition of existing apartment	indoor air temperature, indoor relative humidity, outdoor temperature, outdoor relative humidity	Field Measurement	HOBO Data Logger
		Simulation	Design Builder
Simulated thermal conditions	indoor air temperature, indoor relative humidity	Simulation	Design Builder
Cooling load of a building	-		
Secondary Data	Sub Secondary Data	Data Collection	Instrument
Climate Data	-	Obtained from government and companies.	-

There are several data required in order to conduct this research. These data consist of primary data which is obtained by author through field measurement, and observation, and secondary data collected by government or companies.

3.6.1 Field Measurement

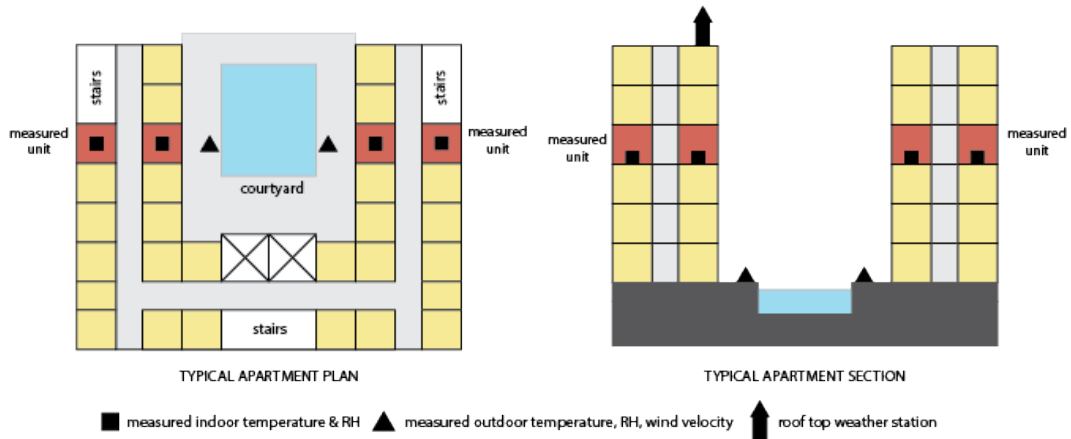


Figure 3.10 Diagram of field measurement

The existing thermal condition of apartment with courtyard will be measured for validation. The field measurement was conducted in sampling apartment obtained from population of high rise apartment with courtyard in Surabaya. The apartment measured was Bale Hinggil apartment. The field measurement was conducted between 6th – 14th November 2017.

The methodology for the field measurement follows the measurement conducted in courtyards of Chinese Shophouses in Malaysia by Kubota (2016). This research studied the thermal effect of courtyard in two story residential building. However, in this research the building scope is apartment building, as a result the instrument that will be use still the same but the setting is different. The diagram for the field measurement is represented as follow.

In the roof top of the apartment a weather station will be set up. This weather station record temperature, relative humidity, solar radiation, and wind velocity as well as the direction. The function of this weather station is to record the climate data for the surrounding environment. The other instruments used located in the apartment units in the different side of apartment, because every side may receive different solar radiation depends on the orientation. Instrument located inside the unit will measure temperature and air humidity, while instrument located in the courtyard will measure temperature, air humidity, and wind velocity.

3.6.2 Simulation

Simulation of different treatment in the experimental research will be generated by Design Builder Software version 5.0, which is capable to simulate

building thermal performance, energy consumption and natural lighting. Energy Plus is embedded in Design Builder version 5.0, as a tool to analyze building performance.

Features of Design Builder are:

- Building thermal, energy and lighting analysis.
- Model and site visualization
- Building energy performance using Energy Plus
- Wind and pressure distribution analysis in CFD
- Hourly, daily, weekly, and monthly output

Output of Design Builder

- Building energy consumption
- Heat transfer (by envelope and ventilation)
- Thermal comfort: discomfort hours, climate factors (air temperature, relative humidity, mean radiant temperature (MRT), operative temperature)
- Production of CO₂
- Design of HVAC

Annual simulation weather data in Design Builder is available in the format of Energy Plus Weather Data (EPW). In Surabaya, the simulation weather data will be obtained from the closest metrological station in Juanda Airport. As a result, there is possibilities of slight differences thermal condition in the city center, where apartments are located, and the airport that located in the suburban.

These are several researches that use design builder for model simulation, such as:

1. “Energy Conservation Measure in an Institutional Building in Sub-tropical Climate in Australia” by M.M. Rahmah, M.G. Rasul, and M.M.K. Khan. *Journal of Applied Energy* 87 (2010).
2. “Thermal Comfort and Energy Performance of Public Rental Housing under Typical and Near-extreme Weather Conditions in Hong Kong” by Yu Ting Kwok, Alan Kwok Lung Lai, Kevin Ka-Lun Lau, Pak Wai Chan, Yahya Lavafpour, Justin Ching Kwan Ho, and Edward Yan Yung Ng. *Journal of Energy and Buildings* (2017).

3.6.3 Verification

In order to minimize error of simulated building models, verification process is required. Verification is the process of comparing simulated building model with real life environmental condition. The simulation result should be able to represent real life condition as closely as possible. Verification process was conducted and evaluated before beginning the experimental research.

According to Ruiz and Bandera (2017), there are three different indicators to evaluate Energy Models : Normalized Mean Bias Error (NMBE), Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) and coefficient of determination (R^2). The ASHRAE Guidelines, IPMVP (International Performance Measurement and Verification Protocol), FEMP (Federal Energy Management Program) recommend not to use the NMBE indices alone, as it is subject to cancellation errors. CV(RMSE) indices is more recommended to verify the simulated energy models. According to Ruiz and Bandera (2017) several journals use both NMBE and CV(RMSE) together to calibrate their energy models. In this research, the verification process will use CV(RMSE) and R^2 , because these two indices are considered more reliable.

Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) calculate the error variance between measured and simulated values. In the equation, $\bar{m}$ is the mean value of measurement, m_i are measured values, s_i are simulated values, and n is the number of measured data points. In CV(RMSE) equation, the value of p is recommended to be 1. ASHRAE Guideline and FEMP recommend the value of CV(RMSE) should be $\leq 15\%$ for monthly data, and $\leq 30\%$ for hourly data. While IPMVP do not have recommendation for monthly data, and value of CV(RMSE) of hourly data should be $\leq 20\%$.

$$CV(RMSE) = \frac{1}{\bar{m}} \sqrt{\frac{\sum_{i=1}^n (m_i - s_i)^2}{n - p}} \times 100(\%)$$

R^2 (Coefficient of Determination) calculate how close simulated value to the regression line of the measured value. The value of R^2 is between 0 and 1, in which the closer the value to 1, the higher accuracy of simulated models. ASHRAE Guideline and IPMVP both recommend the value of R^2 should be higher than 0.75.

$$R^2 = \left(\frac{n \cdot \sum_{i=1}^n m_i \cdot s_i - \sum_{i=1}^n m_i \cdot \sum_{i=1}^n s_i}{\sqrt{(n \cdot \sum_{i=1}^n m_i^2 - (\sum_{i=1}^n m_i)^2) \cdot (n \cdot \sum_{i=1}^n s_i^2 - (\sum_{i=1}^n s_i)^2)}} \right)^2$$

Table 1 Indices for Verification Model

Data Type	Index	FEMP	ASHRAE Guideline 14	IPMVP
Monthly Data	CV(RMSE)	≤15%	≤15%	-
Hourly data		≤30%	≤30%	≤20%
	R ²	-	>0.75	>0.75

Source : Ruiz and Bandera (2017)

In addition to the indicators mentioned by Ruiz and Bandera (2017), Safikhani and Baharvand (2017) use maximum and minimum error of air temperature for verification process. Safikhani and Baharvand (2017) studied indoor temperature and surface temperature as a result of double skin façade usage. Simulation in this study was conducted by Design Builder. Table below shows acceptable average temperature difference, and maximum temperature difference.

Table 3.8 Standard Validation of Design Builder Software

Average Typical Errors of Validation	
Average typical error for Inside Air Temperature	1.1° C
Average typical error for Inside Surface Temperature	0.9° C
Average typical error for Outside Surface Temperature	0.9° C
Maximum Errors of Validation	
Maximum error for Inside Air Temperature	2.4° C
Maximum error for Inside Surface Temperature	2.2° C
Maximum error for Outside Surface Temperature	2.2° C

Source : Safikhani and Baharvand, 2017

3.7 Experimental Research Design

3.7.1 Units of Assignment

The model experiments are generated from field observation courtyard high

rise apartments in Surabaya as well as considering regulation of high rise building in Indonesia. Ministry of Public Works Regulation (29/PRT/M/2006) about minimum distance between two towers in one base, and Ministry of Public Works Regulation (10/KTPS/2000) about emergency access in buildings are taken into account in generating the model experiments. In the case of high rise apartment with courtyard, there are two towers facing each other with window on both side. As a result, the minimum courtyard width should be 25 m because the towers on both side have windows.

Table 3.9 Distance Regulation of High Rise Apartment in Indonesia

Regulation	Subject
Ministry of Public Works Regulation (29/PRT/M/2006)	Minimum distance of two towers in one base with window on both is 25 m
	Minimum distance of two towers in one base with window on one tower is 12.5 m
	Minimum distance of two towers in one base without window on both is 6.25 m
Ministry of Public Works Regulation (10/KTPS/2000)	Minimum building distance higher than 40 m is 8 m.
	Minimum distance to emergency stair is 30 m

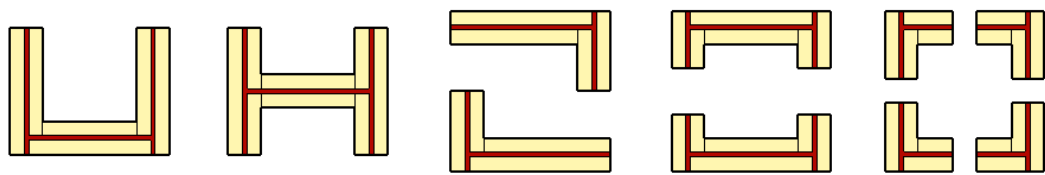


Figure 3.11 Layout of Model Experiments with Corridor Area (red) and Merged Room of Apartment Units (yellow)

According to Design Builder Manual Guide, in the case of working with large model, it is recommended to simplify the model experiment. Simulating high rise apartment with complex modelling can cause the simulation engine to fail. It is recommended to reduce the number of surface by avoiding indents. In the case where indents on the building perimeter create shaded area, it is recommended to create flat surface and use local shading from the Design Builder feature. As a

result, the loggia balconies are removed on the apartment model experiment, and replaced by 1 m flat awning above the windows, available in Design Builder feature.

In order to create building energy model which represent reality better, the model experiments are not modelled as one single zone on each floor. On each floor, there are two different zones, zones for the apartment units, and zone for the corridor area. However, for the simplification process, zones for the apartment units are merged into one zone, when located next to each other. In addition, zone functioning as corridor is set as a natural ventilated zone, and not calculated in the annual energy result of the model experiments. Figure below represent the zones for corridor and zone for apartment units in five different building geometries studied.

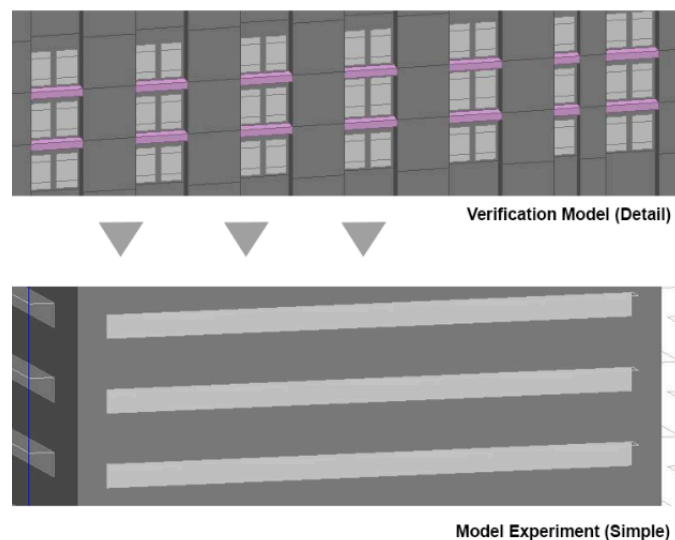


Figure 3.12 Simplified Window to Wall Ratio of Model Experiments

Window to wall ratio (WWR) is one of the important variable in building energy model. According to table 3.5, the average window wall ratio of courtyard apartment in Surabaya is 4 26,94 %. In order to simplify the window to wall ratio calculation, WWR of the model experiments will be 30%. Design Builder Manual Guide recommends to reduce the number of windows in the model experiment. Instead of drawing many windows on the same height, there will be one single window with the similar size of several windows on each level. Study of Bokel (2007) and Koranteng (2015) stated that the amount of window wall ratio (WWR) has greater influence on cooling energy than the position the window.

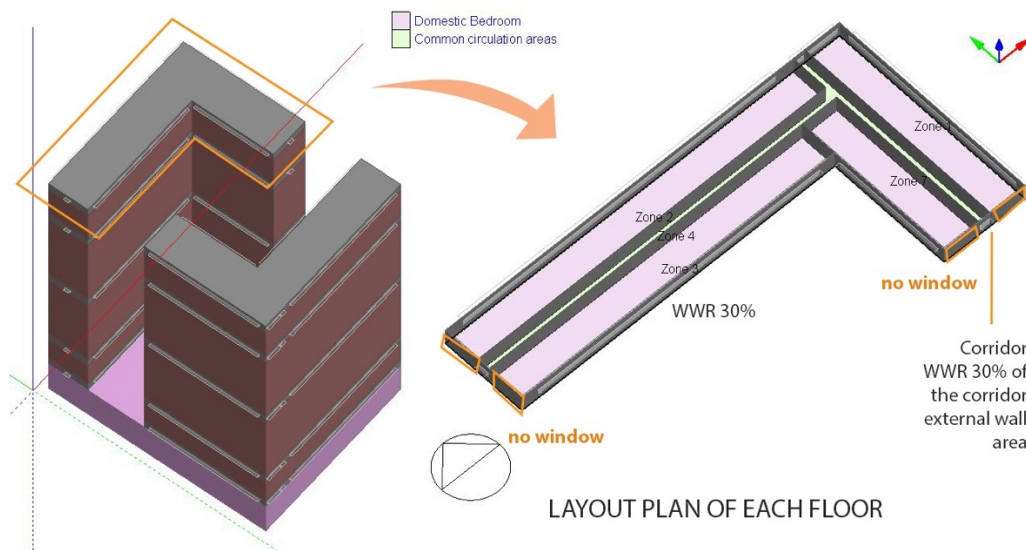


Figure 3.13 Window Area Illustration of Model Apartment Tower Width

As explained in table 3.6, one of the characteristic of courtyard high rise apartment in Surabaya is less WWR on the apartment tower width of the building. In the model experiments, the apartment tower width consists of the corridor end, and side area of the apartment units. In reality, usually there will be window on the end of the corridor, while side area of the apartment units usually has smaller window area than the front side of the apartment unit or has no window at all. In order to represent the reality better, on the apartment tower width of model experiments, the WWR for the corridor outer wall area is 30%, but the side areas of the apartment don't have window at all. The window for the apartment area located in the elongated side of the apartments unit with WWR of 30%.

Table 3.10 Model Experiments and Reasoning

Variable	Model Experiment	Reason
Courtyard Area	1600 m ²	According to table 3.3, the average courtyard area is 1720.36 m², thus simplified to 1600 m². Courtyard with area 1600 m² and ratio 1:2 has length of 57 m and width of 28 m, which are close to the average courtyard width of Surabaya apartment (28.89 m) and the average length is 54.36 m according to table 3.2.

Number of floor	30 storey building	According to table 3.2, the average number of floor of courtyard apartment in Surabaya is 30 storey height
Number of podium	4 storey podium	According to table 3.2, the average number of podium of courtyard apartment in Surabaya is 4 storey height
Apartment Tower Width	14 m	According to table 3.2, the average apartment tower width of courtyard apartment in Surabaya is 14.63 m
Floor to floor height	3 m	According to table 3.4, it could be assumed that most courtyard apartment in Surabaya have floor to floor height of 3 m.
Building Material	Lightweight concrete	According to Alfata et al. (2017), and verification result.
WWR	30%	According to table 3.5, the average window wall ratio of courtyard apartment in Surabaya is 4 26,94 %

3.7.2 Use of Treatments

There are three different treatment applied in the units of assignment. Treatment applied depends on the independent variables of this research, which are different building geometries, courtyard aspect ratio (W/L), and building orientation.

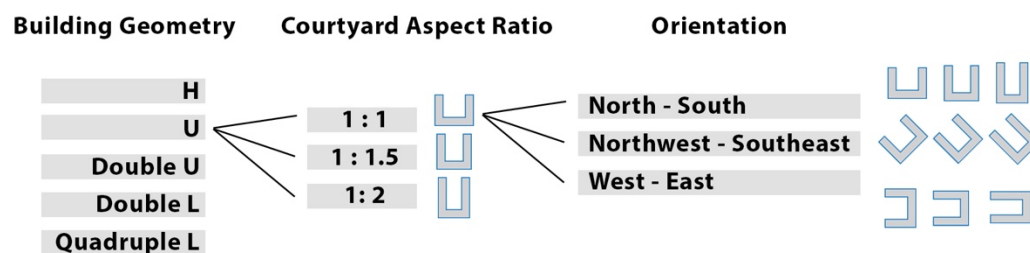


Figure 3.14 Illustration of the Experimental Research

Table 3.11 Matrix of experimental research

Geometry	Courtyard L/W	Orientation
H	1	0°; 45°; 90°
	1.5	0°; 45°; 90°
	2	0°; 45°; 90°

U	1	0°; 45°; 90°
	1.5	0°; 45°; 90°
	2	0°; 45°; 90°
Double U	1	0°; 45°; 90°
	1.5	0°; 45°; 90°
	2	0°; 45°; 90°
Double L	1	0°; 45°; 90°
	1.5	0°; 45°; 90°
	2	0°; 45°; 90°
Quadruple L	1	0°; 45°; 90°
	1.5	0°; 45°; 90°
	2	0°; 45°; 90°

a. Building Geometry

There are five different geometries of high rise residential building with courtyard that will be investigated, which are H Geometry, U Geometry, two U-shaped building facing each other (Double U Geometry), two L-shaped building facing each other (Double L Geometry), and four L-shaped building facing each other (Quadruple L Geometry). These building shapes are generated from the shape of courtyard apartment in Surabaya.

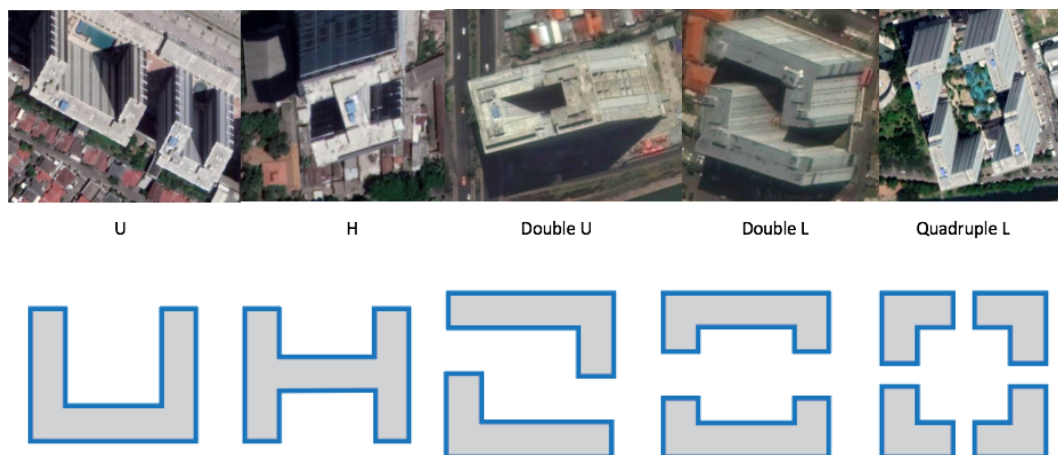


Figure 3.15 Various Building Geometries of Model Experiments.

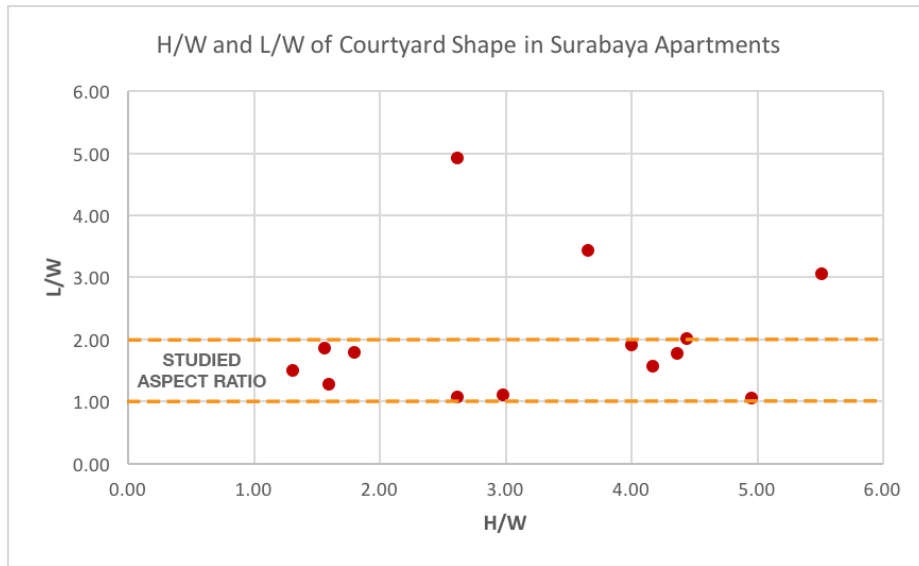


Figure 3.16 H/W and L/W of Courtyard Shape in Surabaya Apartments

b. Courtyard Aspect Ratio (W/L)

There is a wide variation of courtyard height to width ratio (H/W) and length to width ratio (L/W) in the existing high rise apartment with courtyard in Surabaya. According to the observation, H/W ratio of courtyard apartments in Surabaya has more variation than L/W ratio. Most Surabaya courtyard apartments have L/W ratio between 1 and 2. As a result, this research will investigate three courtyard aspect ratio, which are 1:1, 1:1.5, and 1:2. All courtyard in simulated models have almost similar area.

Table 3.12 Aspect Ratio of Model Experiments.

Aspect Ratio	Courtyard Dimension	Courtyard Area
1 : 1	40 x 40	1600
1 : 1.5	32.5 x 49	1592.5
1 : 2	28 x 57	1596

c. Building orientation

There are three different orientations that will be simulated, which are 0°, 45°, and 90°, which are building elongated to north south, northwest southeast, and west east respectively.

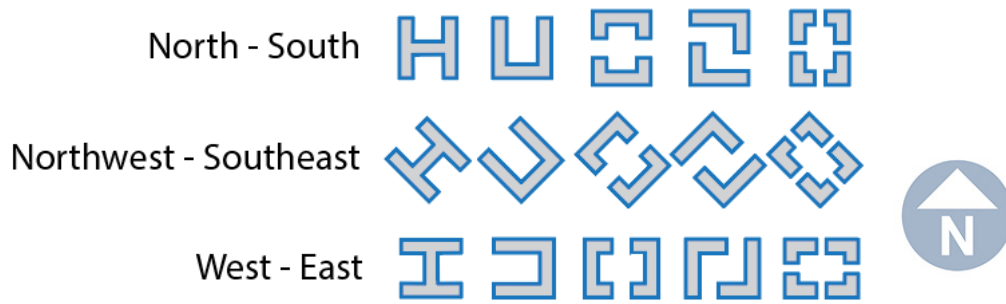


Figure 3.17 Illustration of Orientation in Simulating the Model Experiments

Table 3.13 Naming of Model Experiments.

Building Geometries	Code	Courtyard Aspect Ratio	Code	Orientation	Code
H	U	1 : 1	1	0°	N-S
U	H	1 : 1.5	1.5	45°	NW-SE
Double U	2L	1 : 2	2	90°	W-E
Double L	2U				
Quadruple L	4L				

3.7.3 Simulation Method and Input

The model experiment will be simulated within two different conditions. The first condition is the active mode, in which the cooling energy of each building will be simulated annually. Annual simulation is considered effective in predicting different cooling energy demand throughout the year. The second condition is simulating the building energy model under natural ventilation condition. The passive simulation is required in order to evaluate building thermal performance without additional cooling. The passive simulation will be conducted on hottest month and coolest month of the year.

The high rise model experiments will be simulated within one energy model. The building energy consumption is the result of simulating 30 storey of apartment building. The building podium is present in the energy model but does not contribute to the building thermal condition and building cooling energy. The model simplification allows the simulation engine to simulate large model of high rise residential building at one time.

In order to simulate 30 storey apartment, Design Builder manual guide

recommends to use “Zone Multiplier” for the modelling method. Zone Multiplier is a feature by Design Builder in which a single zone can represent similar identical zone at the same time. Figure 25 compares simulating seven storey building with manual method versus Zone Multiplier Modelling. Model on the left simulate seven storey building by stacking identical building zone seven times, which could cause the engine to fail in the case of simulating much higher building. Right model with Zone simulation method only require three different building zone to simulate seven storey building. The bottom and upper Zone which represent one building floor each. The middle zone, which apply zone multiplier of five, represent five storey building at the same time. During the calculation, Design Builder will calculate the amount of energy generated in this floor by five times.

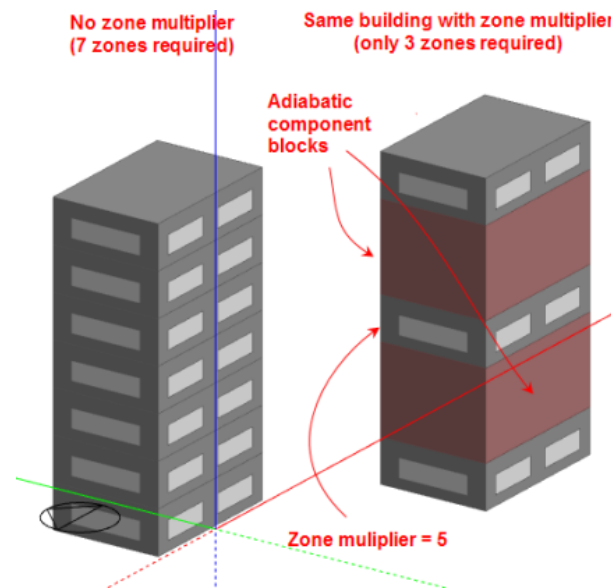


Figure 3.18 Manual Modelling versus Modelling with Zone Multiplier for Multistorey building (Design Builder Manual Guide)

In this research, in order to simulate 30 storey of building model require 5 different zone. Two zone represent the bottom and upper zone, and the other three Zones use Zone Multiplier Method to represent the remaining 28 storeys. The three zones exist on the 5th, 15th, and 25th floor, each floor represent thermal condition of lower, middle, and upper part of high rise apartment. Separating high rise building into three different part is necessary in order to understand thermal performance in high rise building. By simulating the model experiments with Zone Multiplier method, each floor of the model experiments can be modelled in more detailed condition, which more representative from the reality. Each floor of the model

experiments consist of zone for corridor and zone for apartment rooms merged into one zone. Corridor zones are simulated with natural ventilation method, and opening open for 24 hours. On the other hand, zones of apartment rooms are simulated with air conditioner.

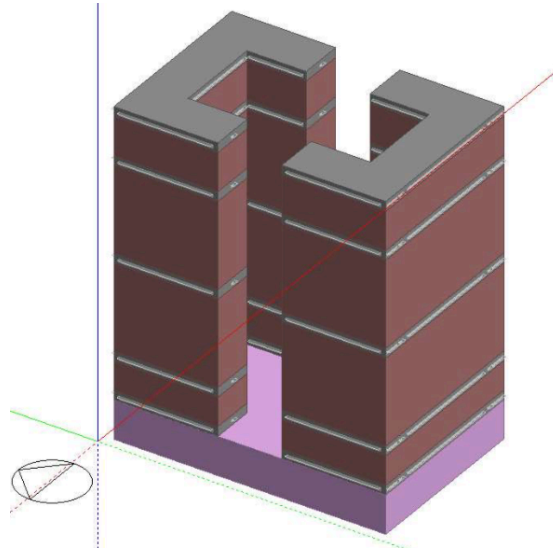


Figure 3.19 Base Case Model Experiment with Zone Multiplier Modelling

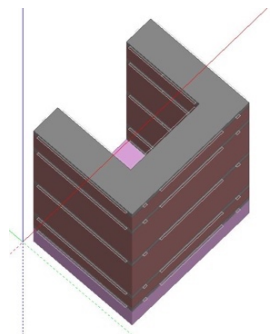
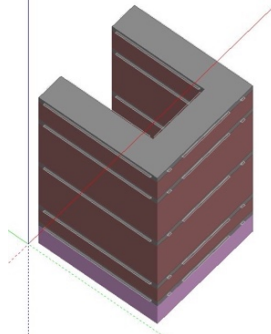
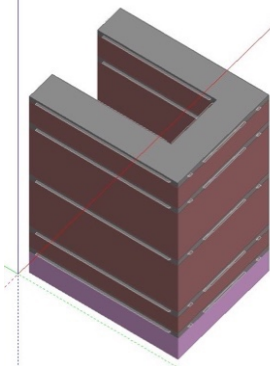
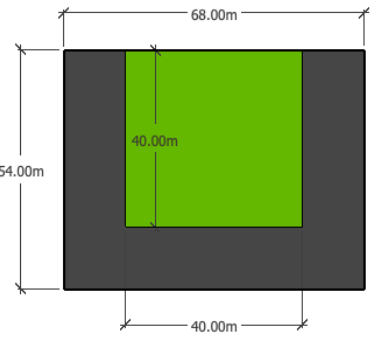
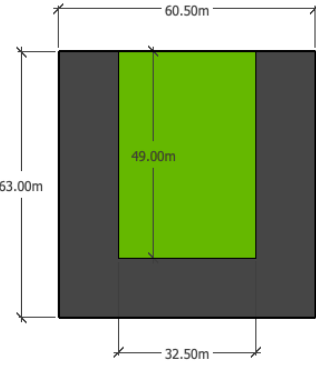
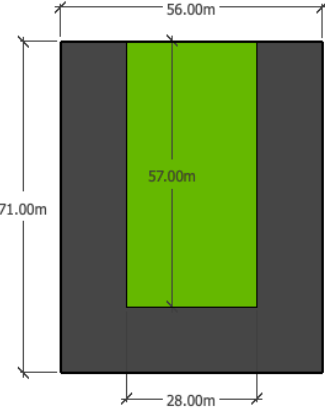
In order to differentiate total energy consumption of model experiments and cooling energy of zones for apartments units, this studies only analyse calculation of annual cooling energy per conditioned zones. Energy from lighting, electrical equipment are not calculated in the “annual cooling energy per conditioned zones” result, as well as unconditioned zone such as the corridor. By analysing annual cooling energy per conditioned zone, this study can evaluate cooling energy caused by the apartments units in high rise apartment. As the main “living space” in high rise apartment, apartments units contribute to the highest annual cooling energy of high rise apartment. Annual cooling energy of the apartment units is the main focus of this study. Cooling energy from the lobby, and facilities, which usually located in the podium is neglected in this study.

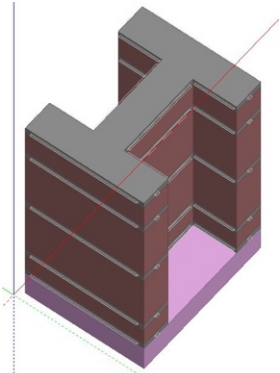
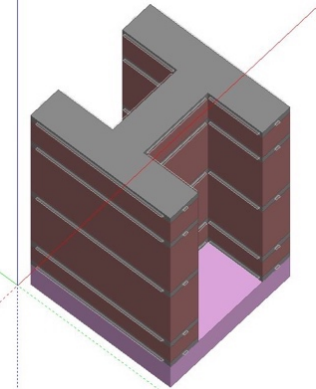
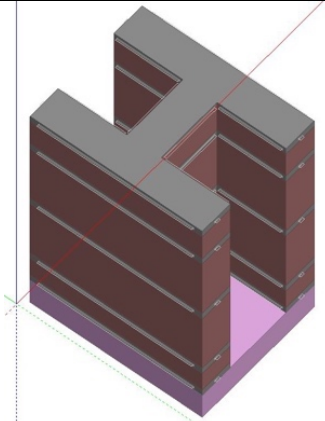
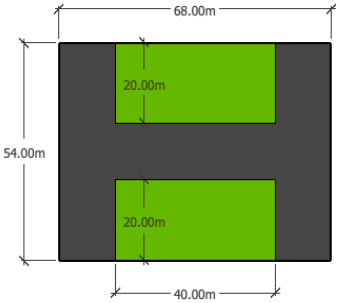
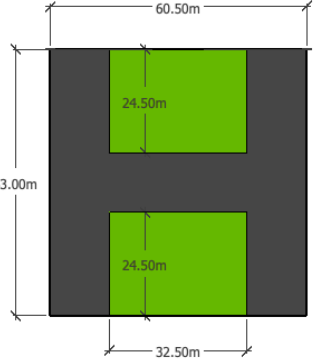
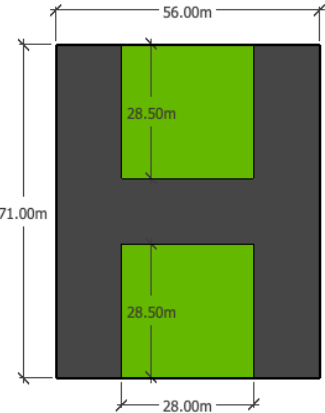
Table 3.14 Simulation Input of the Model Experiments

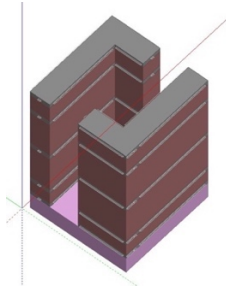
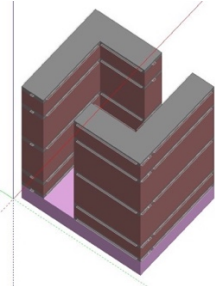
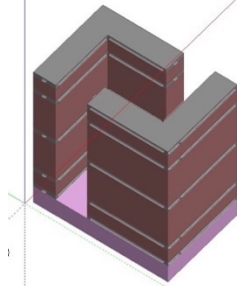
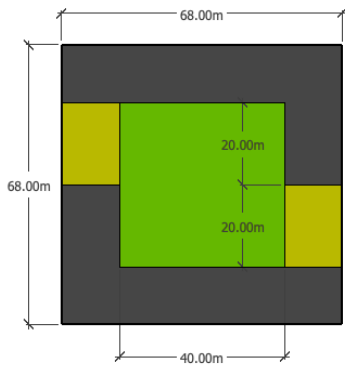
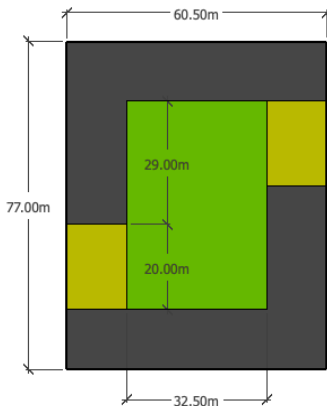
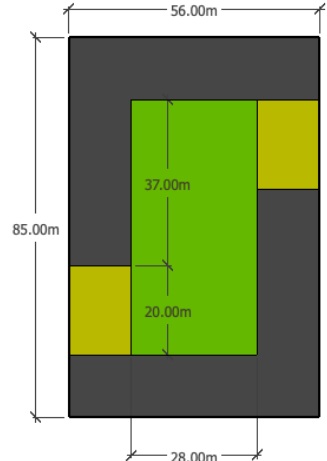
	Simulation Input	Source & Note
Occupancy	0.077 people/m ²	Metric Handbook
		Planning and Design
		Data (2015)

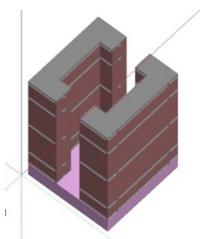
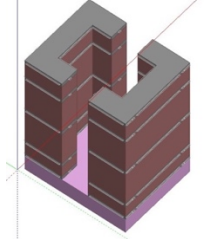
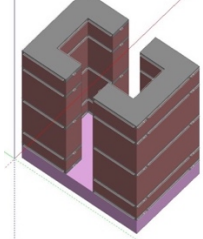
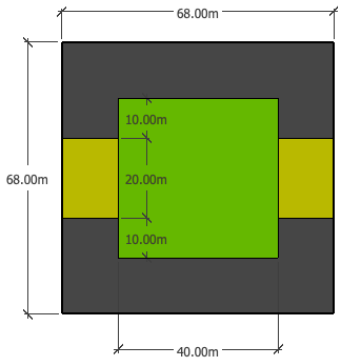
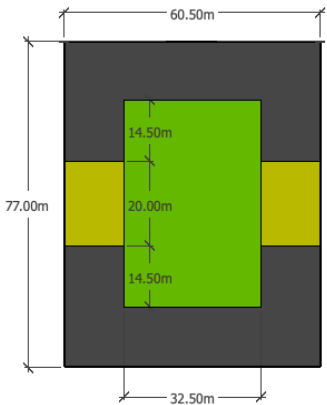
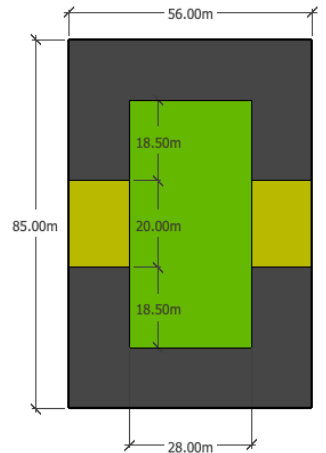
		Recommended single bedroom size with study and bathroom is 13 m ²
Occupancy Schedule	Weekdays : 0.00 – 08.00 = 100% 08.00 – 18.00 = 0% 18.00 – 24.00 = 100% Weekend : 01.00 – 24.00 = 100%	
Metabolic	Metabolic rate : 100 W/person with factor of 0.9 (general factor of both men and women)	CIBSE
Clothing	0.5	Standard of summer clothing
Lighting	6.6 W/m ² at 100 Lux	Dormitory standard ASHRAE 90.1 – 2010 and SNI 03 – 6197 2011
Lighting Schedule	Weekdays : 0.00 – 06.00 18.00 – 24.00 Weekend : 0.00 – 06.00 17.00 – 24.00	
HVAC System	Split (no fresh air)	
Cooling setpoint	25° C	SNI 6390 year 2011
HVAC Schedule	Weekdays : 0.00 – 08.00 18.00 – 24.00 Weekend : 01.00 – 24.00	

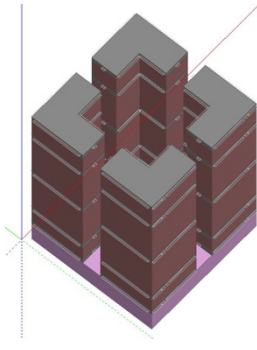
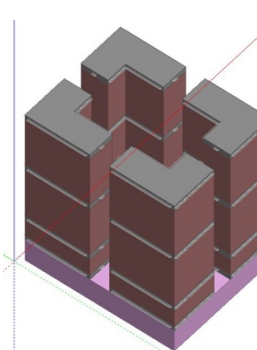
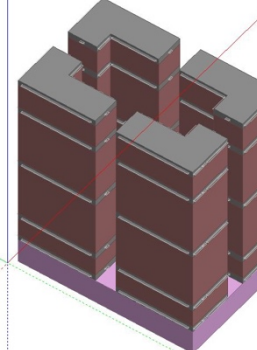
Table 3.15 Table of Simulated Model Experiments.

Building Geometry	Variable	Courtyard L/W		
		1 : 1	1 : 1.5	1 : 2
U	Design Builder Model			
	Building Plan			
	Courtyard Area (m2)	1600	1592.5	1596
	Building area/floor (m2)	2072	2219	2380

	Building Volume (m3)	186480	199710	214200
	Building Surface Area (m2)	31232	33269	35500
	Surface to Volume Ratio	0.167	0.167	0.166
	Relative Compactness	0.523	0.513	0.504
H	Design Builder Model			
	Building Plan			

	Courtyard Area (m2)	1600	1592.5	1596
	Building area/floor (m2)	2072	2219	2380
	Building Volume (m3)	186480	199710	214200
	Building Surface Area (m2)	31232	33269	35500
	Surface to Volume Ratio	0.167	0.167	0.166
	Relative Compactness	0.523	0.513	0.504
Double L	Design Builder Model			
	Building Plan			

	Courtyard Area (m2)	1600	1592.5	1596
	Total Courtyard gaps area (m2)	560	560	560
	Building area/floor (m2)	2464	2506	2604
	Building Volume (m3)	221760	225540	234360
	Building Surface Area (m2)	39184	39766	41124
	Surface to Volume Ratio	0.177	0.176	0.175
	Relative Compactness	0.468	0.466	0.462
Double U	Design Builder Model			
	Building Plan			

	Courtyard Area (m2)	1600	1592.5	1596
	Total Courtyard gaps area (m2)	560	560	560
	Building area/floor (m2)	2464	2506	2604
	Building Volume (m3)	221760	225540	234360
	Building Surface Area (m2)	39184	39766	41124
	Surface to Volume Ratio	0.177	0.176	0.175
	Relative Compactness	0.468	0.466	0.462
Quadruple L	Design Builder Model			

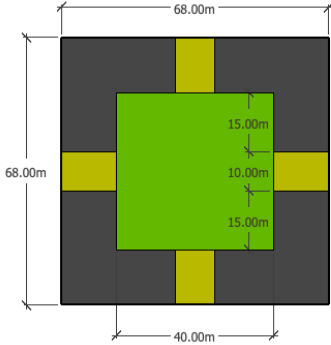
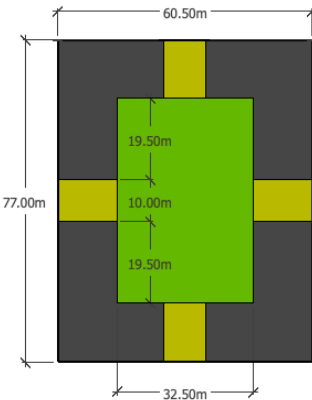
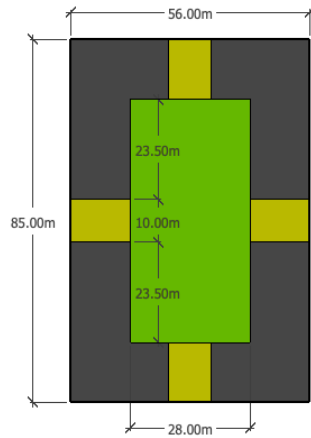
	Building Plan			
	Courtyard Area (m2)	1600	1592.5	1596
	Total Courtyard gaps area (m2)	560	560	560
	Building area/floor (m2)	2464	2506	2604
	Building Volume (m3)	221760	225540	234360
	Building Surface Area (m2)	44224	44806	46164
	Surface to Volume Ratio	0.199	0.199	0.197
	Relative Compactness	0.414	0.413	0.412

Table 3.16 Characteristic of Model Experiments

Geometry	Court- yard L/W	Courtyard Area (m ²)	S/V ratio	RC	Windows on Perimeter Area/floor (m ²)	Windows on Courtyard Area/floor (m ²)	Total Windows area/floor (m ²)
H	1	1600	0.167	0.523	104.4	144	248.4
	1.5	1592.5	0.167	0.513	120.6	146.7	267.3
	2	1596	0.166	0.504	135	153	288
U	1	1600	0.167	0.523	104.4	108	212.4
	1.5	1592.5	0.167	0.513	149.85	117.45	267.3
	2	1596	0.166	0.504	160.2	127.8	288
Double U	1	1600	0.177	0.468	208.8	115.2	324
	1.5	1592.5	0.176	0.466	211.5	117.9	329.4
	2	1596	0.175	0.462	217.8	124.2	342
Double L	1	1600	0.177	0.468	187.2	136.8	324
	1.5	1592.5	0.176	0.466	189.9	139.5	329.4
	2	1596	0.175	0.462	196.2	145.8	342
Quadruple L	1	1600	0.199	0.414	187.2	122.4	309.6
	1.5	1592.5	0.199	0.413	189.9	125.1	315
	2	1596	0.197	0.412	196.2	131.4	327.6

3.7.4 Output of Simulation Result

As mentioned in 3.4.2, the results of this research will identify annual cooling energy, as well as heat gain and heat loss of the model experiments. Design Builder by Energy Plus presents the results of heat gain and heat loss of simulated buildings in the heat balance system. Building heat gains are presented in positive value. On the other hand, heat losses of a building are presented in negative value. Refers to equation 2.1 about thermal system of a building, positive value means the building receives heat gain from the surrounding environment, and negative value means the building releases heat to the environment, and indoor temperature will decrease.

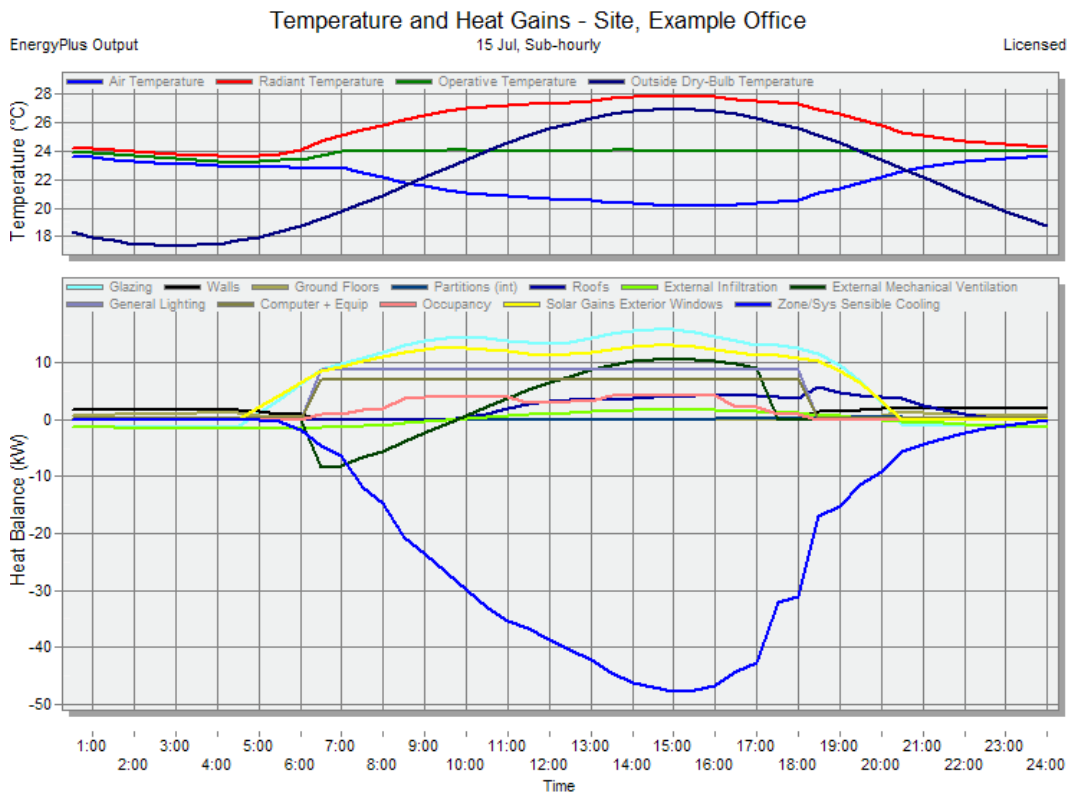


Figure 3.20 Hourly Simulation Result of Design Builder (Design Builder Manual Guide)

In the simulation result, building heat gain such as : fabric gain, solar gain, infiltration gain, and internal heat gain have positive value. In the case of conditioned building as in this research, cooling processes are responsible for the heat loss of the simulated building. As a result, sensible cooling and latent cooling are presented in negative value. The lower the value, the more heat should be removed by the cooling process.

Figure above is the result of one day hourly simulation in Design Builder. Notice that zone sensible cooling is the lowest during the peak hours of building heat gains. In this simulation result, sensible cooling of -40 kW has higher cooling load than sensible cooling of -20 kW. Sensible cooling of -40 kW removes 40 kW heat gain of the building in order to achieved desired temperature compared with sensible cooling of -20 kW which removes less 20 kW heat gain of the building.

3.8 Data Analysis and Presentation

3.8.1 Climate Data Analysis

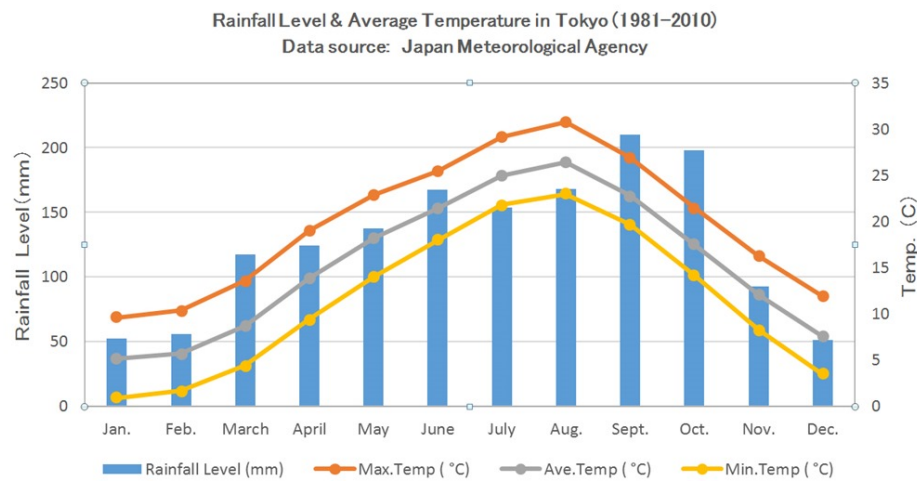


Figure 3.21 Rainfall Level and Average Temperature. (jma.go.jp)

Analysis of climate data is presented in the form of graph and diagram. Temperature and relative humidity will be presented in the form of graph such as diagram of “Rainfall Level and average Temperature in Tokyo” below. In addition, the wind data will be presented in the form of wind rose diagram.

3.8.2 Field Measurement Data Presentation

Data of field measurement will be presented in graph comparing indoor thermal environment to outdoor thermal environment. Variables that will be presented are outdoor and indoor air temperature, relative humidity, solar radiation, and wind speed. Similar graphics are presented in study of Alfata et al. (2015).

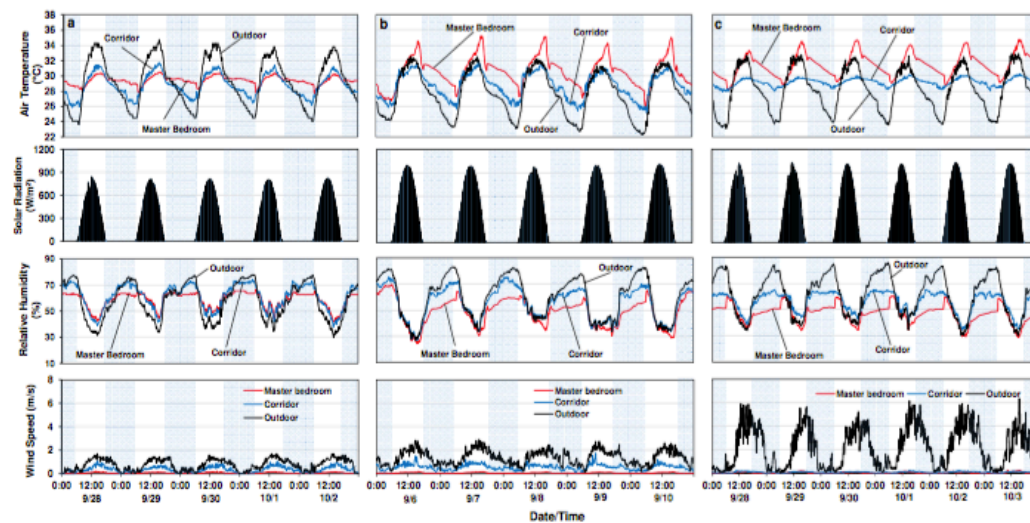


Figure 3.22 Indoor Thermal Environment in the Old Public Apartment, New Public Apartment and Private Apartment. (Alfata et al., 2015)

3.8.3 Analysis Method of Independent Variables and Cooling Energy

This research focuses in cooling energy of various building shape as a result of courtyard configuration. Cooling energy is represented by electricity consumption per square meter (kWh/m^2). Variables studied are building geometry, courtyard aspect ratio, and courtyard orientation. In this step, impacts of each modified variable toward cooling energy are studied while the other two variables remain constant.

Analysis method of independent variables toward cooling energy consists of three different evaluations, as follows:

1. The impact of building shape to cooling energy, compared with similar aspect ratio and orientation.
2. The impact of courtyard aspect ratio to cooling energy, compared with similar building shape, and orientation.
3. The impact of courtyard orientation to cooling energy, compared with similar building shape, and courtyard aspect ratio.

Graphic analysis of those three different evaluation will be presented in bar chart diagram, with reference from study of various building shape to heating load, with similar orientation and volume by Gratia and Herde (2003). The bar chart compares modification of one variable, and the other two variables remain constant.

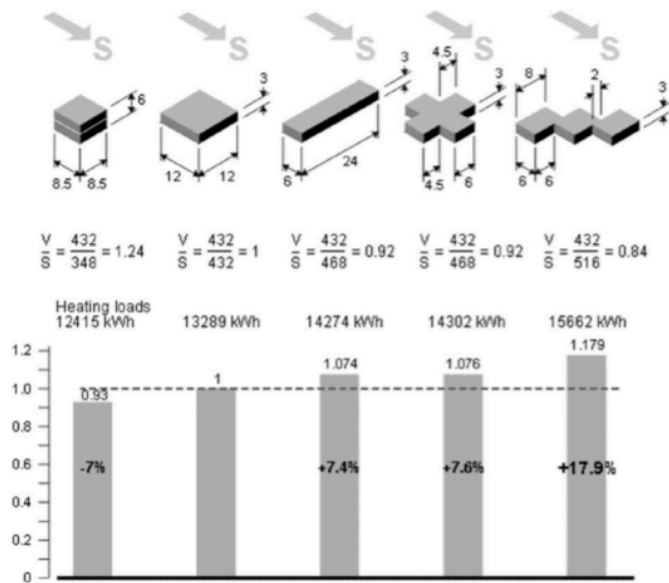


Figure 3.23 Impact of Building Shape on Heating Load (Gratia and Herde, 2003)

3.8.4 Evaluation Method of Building Shape and Cooling Energy

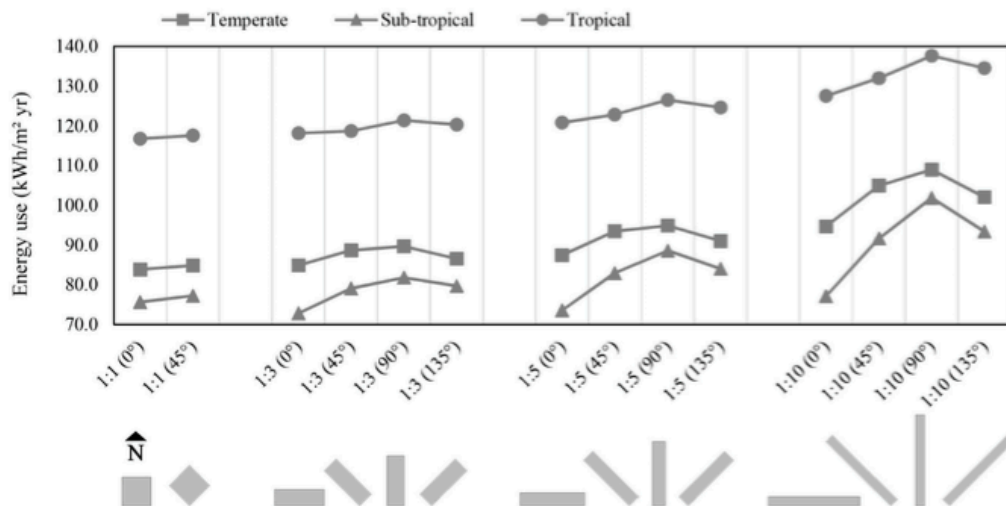


Figure 3.24 Energy Impact of Building Aspect Ratio and Orientation in Three Different Climate (Raji et al, 2017)

Impact of three different modified variables toward cooling energy are evaluated in order to identify which variable has the most impact. Line chart diagram is used for presenting cooling energy result of different modified variables. Similar diagram comparing different result of cooling energy with three different variables is obtained from the study of Raji et al. (2017). Variables in the reference diagram are building shape, orientation, and climate.

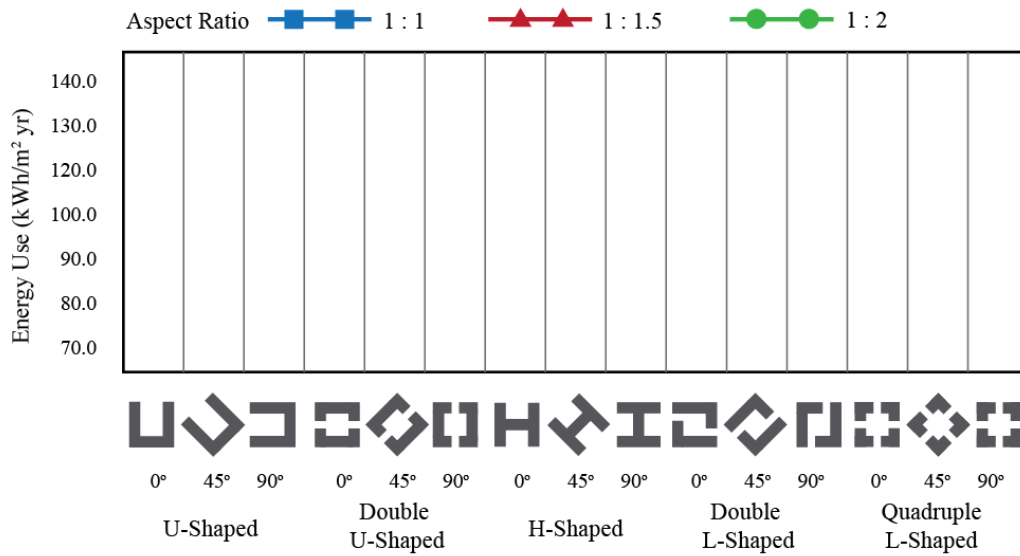


Figure 3.25 Evaluation Diagram of Three Different Variables

3.8.5 Method to Evaluate Building Geometry

FIRST STEP OF EVALUATION

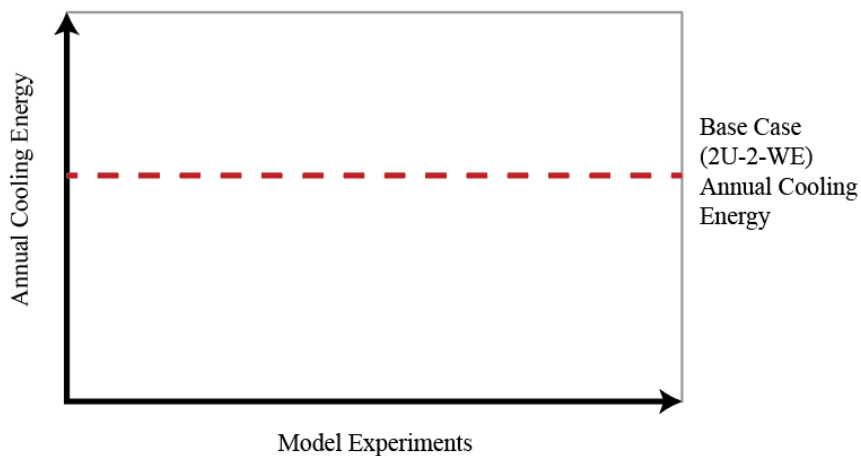


Figure 3.26 Diagram to Evaluate Performance of Model Experiments According to Base Case Condition

There are two steps in order to identify the performance of model experiments. The first step identifies cooling energy performance of model experiments using parameter from the base case condition. In the second step, the optimum building shape is identified by Indonesian Green Building standard of energy consumption.

In the first step, annual cooling energy of model experiments are compared with cooling energy of the base case condition. Model experiments which have lower annual cooling energy than the base case has better thermal performance. On

the other hand, model experiments which have higher annual cooling energy than the base case are analyzed.

In the second step of evaluating performance of model experiments, IKE (*Intensitas Konsumsi Energy*) or EUI (Energy Use Intensity) indicator is used to analyze the building energy consumption. According to GBCI, or Green Building Council Indonesia (2011), the maximum energy consumption for apartment building is 350 kWh/m² year. However, the maximum energy usage accounts for energy consumption from all aspect in a building, such as cooling energy, lighting, electronic appliances, and pumping. Regulation of maximum cooling energy consumption is not stated in the green building guide of GBCI.

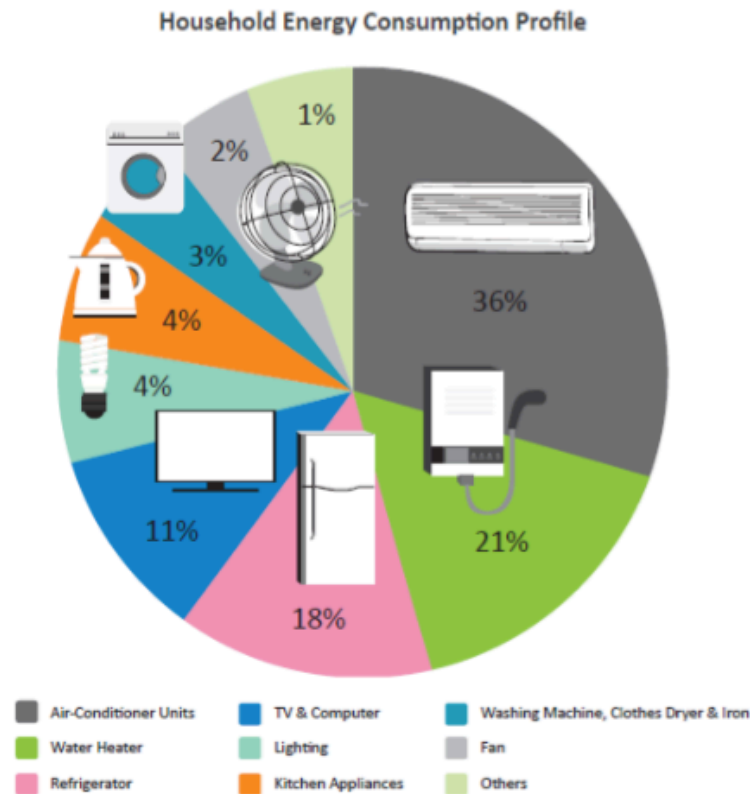


Figure 3.27 Household Energy Consumption Profile (Singapore Household Consumption Survey, 2012)

In order to identify cooling energy usage in an apartment building, it is necessary to look at several literature of apartment energy usage. In Indonesia, study of apartment energy usage is still limited. David and Suheta (2017) stated that Air Conditioner usage in Metropolis Apartment Surabaya accounts for 49.9% energy consumption in the apartment. However, one sample of apartment does not

represent the majority of population. Several studies of energy from air conditioner usage are conducted in Singapore, which has similar climate with Indonesia. According to Boranian (2013) and survey from National Environment Agency of Singapore (2014), cooling energy consume 30 – 37% energy consumption in a residential building. In addition, Singapore Household Consumption Survey (2012) stated that air conditioner accounts for 36% energy consumption in residential building. The survey was conducted from various type of residential building type, such as flats, apartments, and landed house. Therefore according to the several literature mentioned before, benchmark of green apartment cooling energy in this study range from 30 – 37% of 350 kWh/m²/year. In this study, green apartment should have annual cooling energy range from 105 – 129.5 kWh/m² year.

SECOND STEP OF EVALUATION

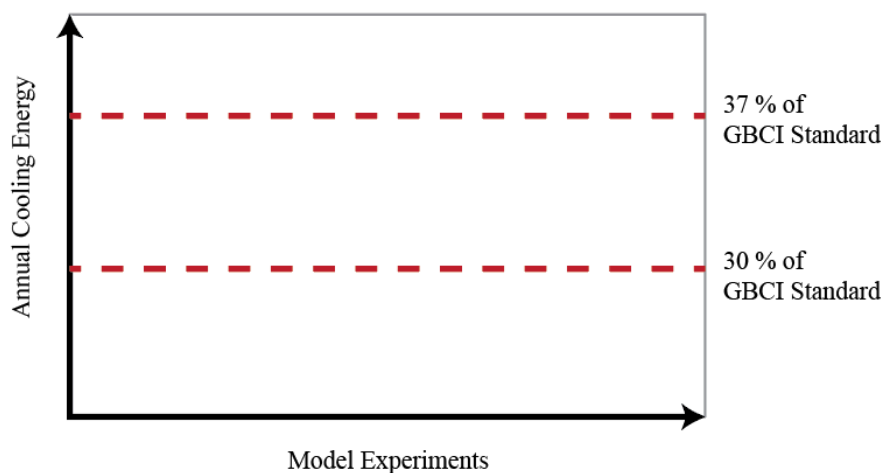


Figure 3.28 Diagram to Evaluate Performance of Model Experiments According to Indonesian Standards

CHAPTER 4

VERIFICATION AND SIMULATION RESULT

4.1 Verification Process

Verification is the process of comparing simulated building model with real life environmental condition. Verification process is required in order to evaluate how close the simulation model represent the measured data. Verification process was conducted before beginning the experimental research. The result of the verification process determines reliability of the model experiments.

Field measurement was conducted in order to support the software verification process, and identify real life condition of the research object. Thermal condition of sample apartment in this study was recorded during field measurement, as well as field observation of building existing condition.

4.1.1 Location of The Sample Apartment

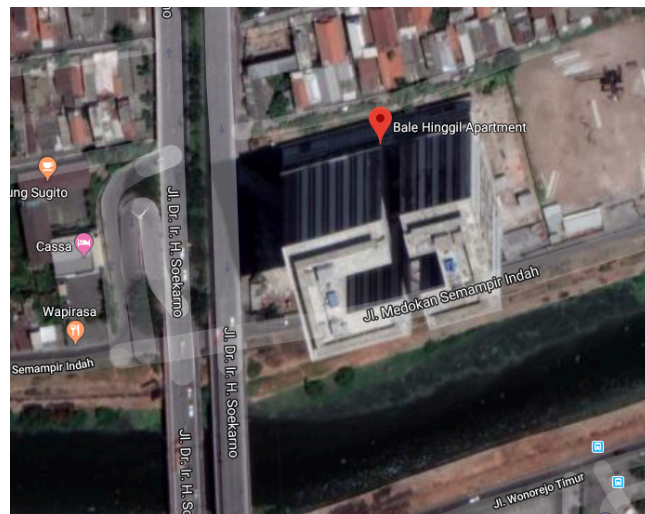


Figure 4.1 Surrounding Condition of Bale Hinggil Apartment (maps.google.com)

The sample apartment is located in the city of Surabaya, East Java, Indonesia. Bale Hinggil Apartment is located on Jalan Medokan Semampir Indah in the east of Surabaya, with borders as follows :

- North : low rise residential building
- South : Medokan Semampir Street and Jagir River
- East : Empty land

- West : Middle East Ring Road (MERR) of Surabaya

Bale Hinggil Apartment is oriented to the south side, and connected to Medokan Semampir Street. Bale Hinggil Apartment is surrounded by low rise residential buildings. Bale Hinggil Apartment was exposed to sun radiation and upcoming wind, because buildings surrounding the apartment were unable to provide shading or block upcoming wind. As a result during field measurement process, which conducted on 20th floor, thermal performance of Bale Hinggil Apartment was not affected by surrounding buildings.

4.1.2 Building Existing Condition

Bale Hinggil Apartment consists of two U-shaped tower (Tower A and Tower B) facing each other. Courtyard in between the two towers is functioned as swimming pool area for the resident. Similar to other middle class apartments in Surabaya, Bale Hinggil is a double loaded corridor building. The units inside the apartment can be categorized as two different categories : units facing courtyard and units located on the building perimeter.

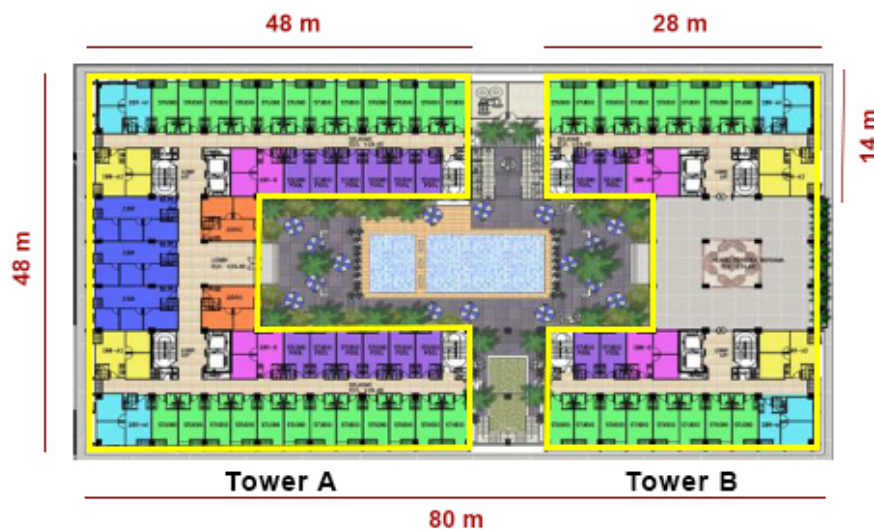


Figure 4.2 Site Plan of Bale Hinggil Apartment

During field measurement in 2017, Bale Hinggil Apartment was an unfinished building with no occupants. The main building structure was completed but several construction details of the apartment was unfinished, such as the courtyard space, and details of Tower B. Indoor thermal condition of the apartment was measured in Tower A of the apartment. Different from Tower B, the

construction process of Tower A was already finished and was ready to be occupied.

During the measurement process, the apartment general lighting was off, and there was no electrical appliances inside the apartment. There was no occupant except researchers who were recording the data. As a result, thermal performance of Bale Hinggil apartment during measurement was not influenced by internal heat gains, such as people and electronic appliances.

a. Building Material

Structures of Bale Hinggil Apartment is made of reinforced concrete, with concrete grid structural system. Building envelope of Bale Hinggil apartment is made of lightweight concrete, as well as wall partitions between apartment units. The building envelope is painted light grey, except corners of the building envelope which are painted dark grey. In addition, the interior inside the apartment units is dominated by white color. The walls and ceiling are painted white, and creamy colored tiles are installed inside the apartment units.



Figure 4.3 Interior of Measured Units

b. Building Façade

The apartment façade is characterized by loggia type balconies and vertical windows. Fences on the balcony were made of white painted steel hollow. In the single unit apartment, the window dimension is 120 x 220 cm. The window frame was made of aluminum with single clear glass. Although the window dimension is considered large for a single unit apartment, only 22% of the total window area could be opened. The window wall ratio of each single apartment unit was 29.3 %.



Figure 4.4 Illustration of Building Facade and Window Detail

Table 4.1 Material of Bale Hinggil Apartment

Building Element	Material
Walls	Lightweight concrete, painted light grey (eksterior), painted white (interior)
Window	120 x 220 cm, aluminium frame painted white 3 mm of single clear glass
Floor	40 x 40 creamy colored ceramic tiles
Ceiling	White painted plastered ceiling
Internal Door	Wooden door with dimension of 2.1 x 0.8 m.

4.1.3 Measurement Point

Building thermal measurements was conducted in both indoor and outdoor areas. The indoor measurement was conducted in four different rooms within the same level, namely Room A2050, A2031, A2020, and A2010. WBGT Heat Index was assigned in each of these rooms to record unit thermal conditions. The apartment units for measurement were all single type units, which consist of the main living area, and bathroom. The outdoor thermal measurement was conducted in the courtyard and rooftop area. Two weather stations were used for the outdoor measurement.



Figure 4.5 Measurement Points in Bale Hinggil Apartment

4.1.4 Discussion of Field Measurement

Field measurement of Bale Hinggil Apartment was conducted on 8th – 10th November 2017. The results of the field measurement will support the verification process for software validation. In addition, data from the field measurement is used for evaluating thermal performance of existing high rise apartment with courtyard.

The thermal performance of Bale Hinggil Apartment represents heavy weight structures. Comparing indoor and outdoor air temperature reveals the heat transfer process between outdoor and indoor thermal environment. Heavy weight structure takes a long time to absorb heat as well as release the heat. Indoor air temperatures of apartment units were generally lower than the outdoor between 09:00 – 15:00, but the indoor experienced higher air temperature for the rest of the day. During peak hours in the afternoon, the building structure could reduce the air temperature up to 2.69° C. However, in the night time when the average minimum outdoor air temperature reached 26.6° C, the average minimum indoor temperature only 30.6° C. Between 20:00 – 05:00, indoor air temperature was significantly higher than the outdoor, with maximum air temperature difference was 6.6° C.

According to the field measurement, the average outdoor diurnal temperature of Bale Hinggil apartment was 6.7° C, but the average diurnal temperature inside the apartment units was 1.4° C. The indoor apartment units experienced small range of temperature variation compared to the outdoor. Indoor air temperature inside the apartment units never fell below 30.3° C.

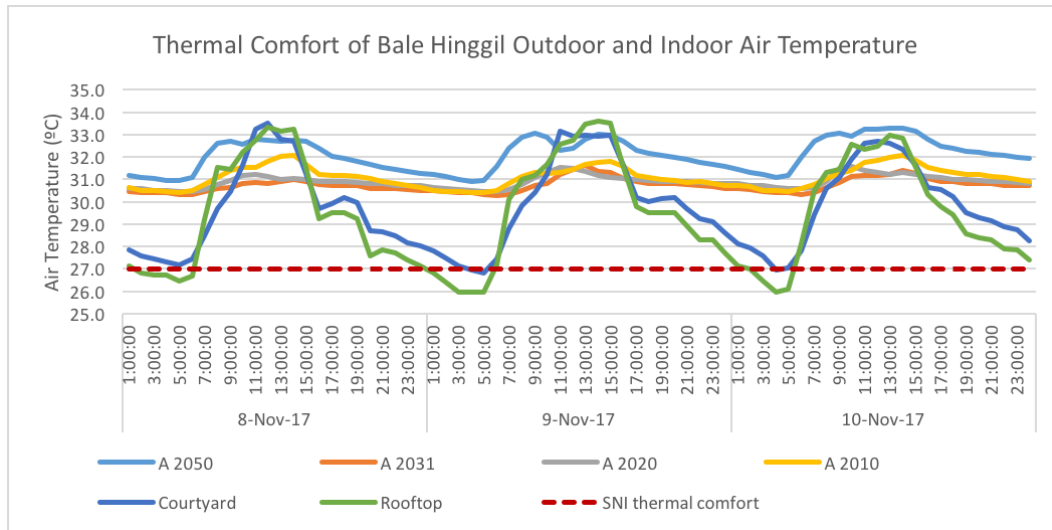


Figure 4.6 Comparison of Outdoor and Indoor Air Temperature of Bale Hinggil Apartment

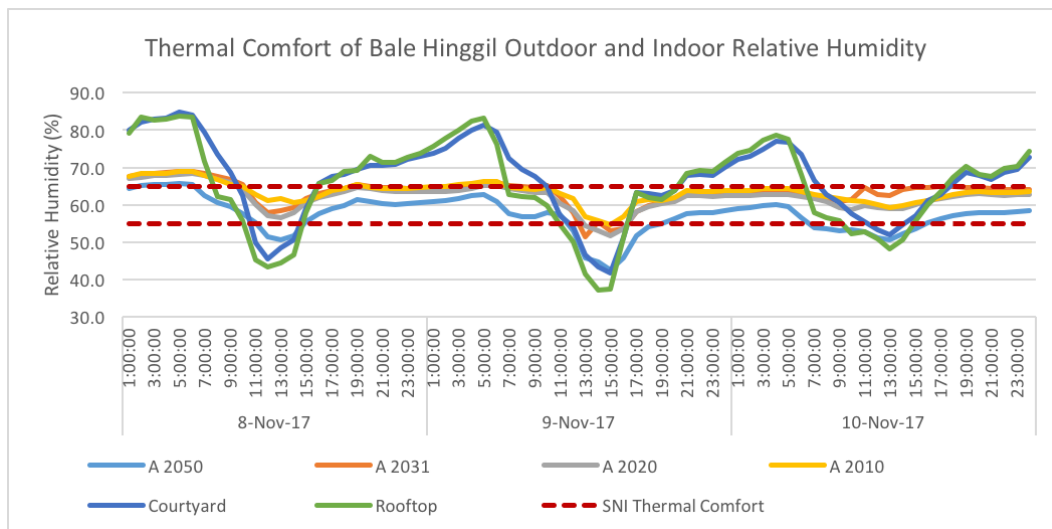


Figure 4.7 Comparison of Outdoor and Indoor Relative Humidity of Bale Hinggil Apartment

Comparison of relative humidity between indoor and outdoor of Bale Hinggil Apartment showed that indoor relative humidity was higher at 11:00 until 15:00, but indoor air humidity was lower than the outdoor for the rest of the day. During three days of measurement, average indoor relative humidity was 61.5% and average outdoor relative humidity was 65.8%. However, indoor relative humidity had smaller range of variation, while the indoor relative humidity range was between 42.6 – 68,9%. Outdoor relative humidity of Bale Hinggil Apartment was between 37.17% - 84.82% during three days of measurement.

Table 4.2 Resume of Indoor Air Temperature Measurement

Date	Max Air Temperature (Daytime)				Min Air Temperature (Nighttime)				Diurnal Temperature			
	A 2050	A 2031	A 2020	A 2010	A 2050	A 2031	A 2020	A 2010	A 2050	A 2031	A 2020	A 2010
8-Nov-17	32.8	31.0	31.2	32.1	31.0	30.3	30.5	30.4	1.8	0.7	0.7	1.7
9-Nov-17	33.1	31.6	31.5	31.8	30.9	30.3	30.5	30.4	2.2	1.4	1.1	1.4
10-Nov-17	33.3	31.4	31.6	32.1	31.1	30.3	30.6	30.4	2.2	1.1	1.0	1.6
Average maximum indoor air temperature										31.9		
Average minimum indoor air temperature										30.6		
Average diurnal indoor air temperature										1.4		

Table 4.3 Resume of Outdoor Air Temperature Measurement

Date	Max Air Temperature (Daytime)		Min Air Temperature (Nighttime)		Diurnal Temperature	
	Courtyard	Rooftop	Courtyard	Rooftop	Courtyard	Rooftop
8-Nov-17	33.5	33.3	27.2	26.5	6.4	6.8
9-Nov-17	33.2	33.6	26.8	26.0	6.3	7.6
10-Nov-17	32.7	33.0	27.0	26.0	5.7	7.0
Average maximum outdoor air temperature					33.2	
Average minimum outdoor air temperature					26.6	
Average diurnal outdoor air temperature					6.7	

4.1.5 Verification of Macroclimate and Microclimate during Measurement

The verification of weather data can be achieved by comparing macroclimate and microclimate data. The verification process is necessary to obtain reliable data used for weather data input during simulation. Identifying the difference between macroclimate and microclimate could verify whether the macroclimate data could represent macroclimate data during simulation process.

The macroclimate data in Surabaya was obtained from Surabaya Meteorology, Climatology, and Geophysical Agency (BMKG). The nearest data available to the Bale Hinggil Apartment was data from the Wonorejo area, East Surabaya. However, during the measurement, relative humidity data in Wonorejo area was not available. Therefore, relative humidity data were obtained from Kebonsari area in West Surabaya.

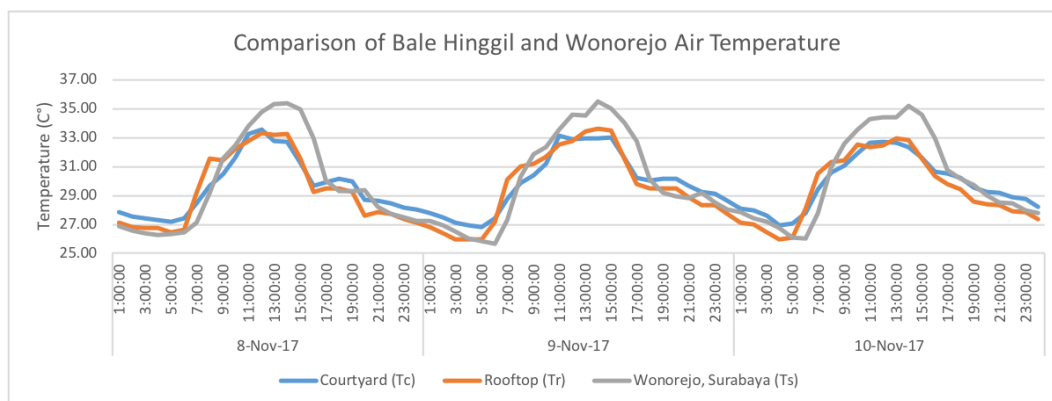


Figure 4.8 Comparison of Air Temperature Between Bale Hinggil and Wonorejo Area

In general, there was no significant difference in air temperature between Bale Hinggil Apartment and Wonorejo area, except during peak hours. The Wonorejo area had higher temperature ($0.56 - 3.71^{\circ}\text{C}$ higher) during 11:00 – 17:00. However in the morning between 05:00 – 07:00, the temperature of the Wonorejo area was slightly lower than the apartment ($0.12 - 2.79^{\circ}\text{C}$ lower).

Unlike relative humidity in the Bale Hinggil Apartment, relative humidity in the Kebonsari Area showed an irregular pattern during three days of measurement. The relative humidity of Kebonsari area, Surabaya was significantly higher on 8th November 2017 at 01:00 – 08:00. Relative humidity of Kebonsari area, Surabaya, was lower than Bale Hinggil area at 14:00 – 16:00 on 8th November, and 13:00 – 18:00 on 9th – 10th November 2017. Considering that there is no significant

difference between macro and microclimate, it can be stated that micro climate surrounding the building can be represented by macroclimate data obtained from BMKG.

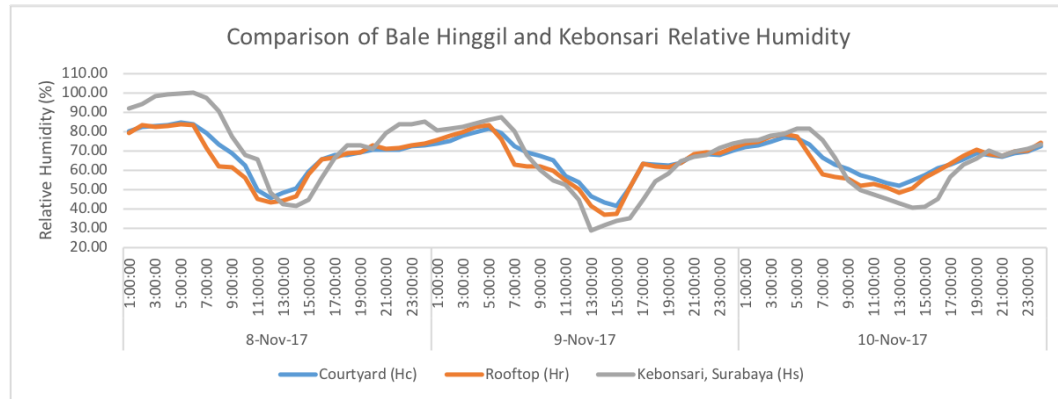


Figure 4.9 Comparison of Outdoor Relative Humidity between Bale Hinggil and Kebonsari Area

Table 4.4 Average Air Temperature of Bale Hinggil and Wonorejo on 8th – 10th November 2017

Hour	Average Courtyard Temp. (Tc)	Average Rooftop Temp. (Tr)	Average Wonorejo, Surabaya Temp. (Ts)	Average ΔT (Tc - Ts)	Average ΔT (Tr - Ts)
1:00:00	27.92	27.01	27.33	0.59	0.32
2:00:00	27.67	26.73	26.99	0.67	0.26
3:00:00	27.38	26.38	26.71	0.67	0.33
4:00:00	27.07	26.21	26.37	0.71	0.16
5:00:00	27.01	26.17	26.09	0.92	0.08
6:00:00	27.55	27.32	26.04	1.51	1.28
7:00:00	28.89	29.93	27.42	1.47	2.52
8:00:00	30.03	31.28	30.13	0.10	1.14
9:00:00	30.65	31.37	32.00	1.35	0.64
10:00:00	31.57	32.14	32.80	1.23	0.67
11:00:00	33.01	32.55	33.89	0.88	1.34
12:00:00	33.04	32.85	34.59	1.55	1.74
13:00:00	32.80	33.19	34.75	1.95	1.55
14:00:00	32.65	33.22	35.35	2.70	2.13
15:00:00	31.96	32.19	34.84	2.88	2.65
16:00:00	30.64	30.36	33.32	2.68	2.96
17:00:00	30.21	29.68	31.17	0.96	1.49
18:00:00	30.14	29.48	29.85	0.28	0.38
19:00:00	29.88	29.10	29.40	0.48	0.30

20:00:00	29.38	28.49	29.10	0.28	0.62
21:00:00	29.17	28.35	28.51	0.66	0.16
22:00:00	28.86	27.98	28.47	0.39	0.49
23:00:00	28.68	27.85	28.00	0.67	0.16
0:00:00	28.29	27.41	27.70	0.59	0.29
Min Air Temperature Difference of Courtyard and Wonorejo					0.10
Max Air Temperature Difference of Courtyard and Wonorejo					2.88
Average Air Temperature Difference of Courtyard and Wonorejo					1.09
Min Air Temperature Difference of Rooftop and Wonorejo					0.16
Max Air Temperature Difference of Rooftop and Wonorejo					2.96
Average Air Temperature Difference of Rooftop and Wonorejo					0.98
Standard Deviation of Courtyard and Wonorejo					0.79
Standard Deviation of Rooftop and Wonorejo					0.88

Table 4.5 Average Relative Humidity of Bale Hinggil and Wonorejo on 8th – 10th November 2017

Hour	Average Courtyard RH (Hc)	Average Rooftop RH (Hr)	Average Kebonsari, Surabaya RH (Hs)	Average ΔH (Hc - Hs)	Average ΔH (Hr - Hs)
1:00:00	75.29	76.19	82.45	7.15	6.25
2:00:00	76.79	78.64	83.77	6.97	5.13
3:00:00	78.58	80.00	86.09	7.50	6.09
4:00:00	80.04	81.39	87.58	7.53	6.19
5:00:00	80.98	81.50	89.17	8.19	7.67
6:00:00	78.92	75.89	89.63	10.72	13.75
7:00:00	72.74	64.17	84.41	11.67	20.24
8:00:00	68.58	60.19	74.96	6.38	14.77
9:00:00	65.60	59.67	64.02	1.58	4.35
10:00:00	61.68	55.92	57.42	4.26	1.50
11:00:00	54.07	50.86	55.16	1.09	4.30
12:00:00	50.94	48.06	46.07	4.87	1.98
13:00:00	48.93	44.64	38.06	10.87	6.58
14:00:00	49.53	44.75	37.83	11.71	6.92
15:00:00	52.64	50.36	39.64	12.99	10.72
16:00:00	59.34	58.97	45.38	13.96	13.59
17:00:00	64.58	64.39	55.86	8.71	8.53
18:00:00	65.61	66.06	63.26	2.35	2.80
19:00:00	66.81	67.06	65.66	1.15	1.39
20:00:00	67.47	68.33	68.69	1.22	0.36
21:00:00	68.43	69.08	71.16	2.72	2.07

22:00:00	69.16	70.14	73.81	4.65	3.67
23:00:00	69.94	70.67	75.47	5.53	4.80
0:00:00	71.87	73.11	77.51	5.64	4.40
Min Air Temperature Difference of Courtyard and Wonorejo					1.09
Max Air Temperature Difference of Courtyard and Wonorejo					13.96
Average Air Temperature Difference of Courtyard and Wonorejo					6.64
Min Air Temperature Difference of Rooftop and Wonorejo					0.36
Max Air Temperature Difference of Rooftop and Wonorejo					20.24
Average Air Temperature Difference of Rooftop and Wonorejo					6.59
Standard Deviation of Courtyard and Wonorejo					3.92
Standard Deviation of Rooftop and Wonorejo					4.90

4.1.6 Weather Data Input

Design Builder software uses simulation weather data in EPW (Energy Plus Weather Data) format to generate its simulation result. Default EPW data of Surabaya, Indonesia was not available in the software, thus the EPW data of Juanda Airport 2017 was bought from White Box Technology. Weather data from Surabaya BMKG are available in Juanda Airport and Tanjung Perak Harbor. Weather data from Juanda Airport was chosen because it was closer to Bale Hinggil Apartment than Tanjung Perak Harbor. The weather data from Juanda Airport was transformed into an EPW format by White Box Technology.

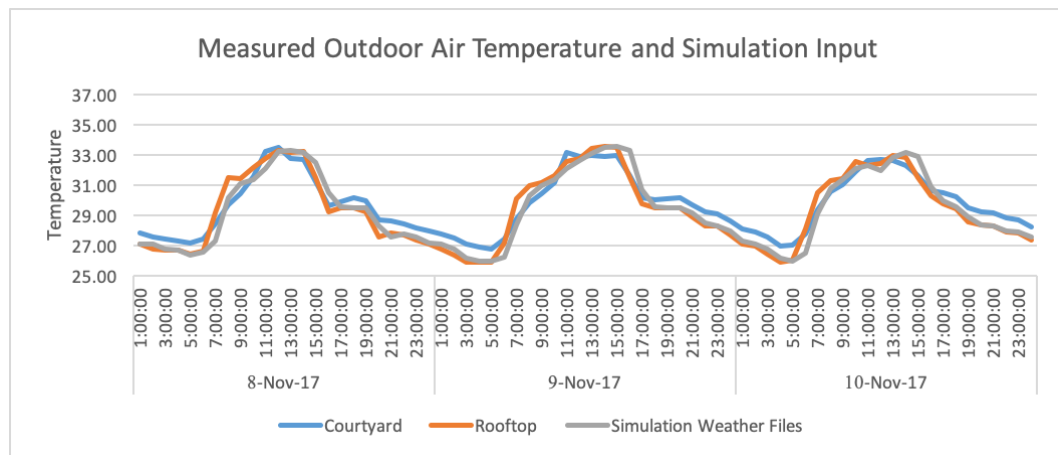
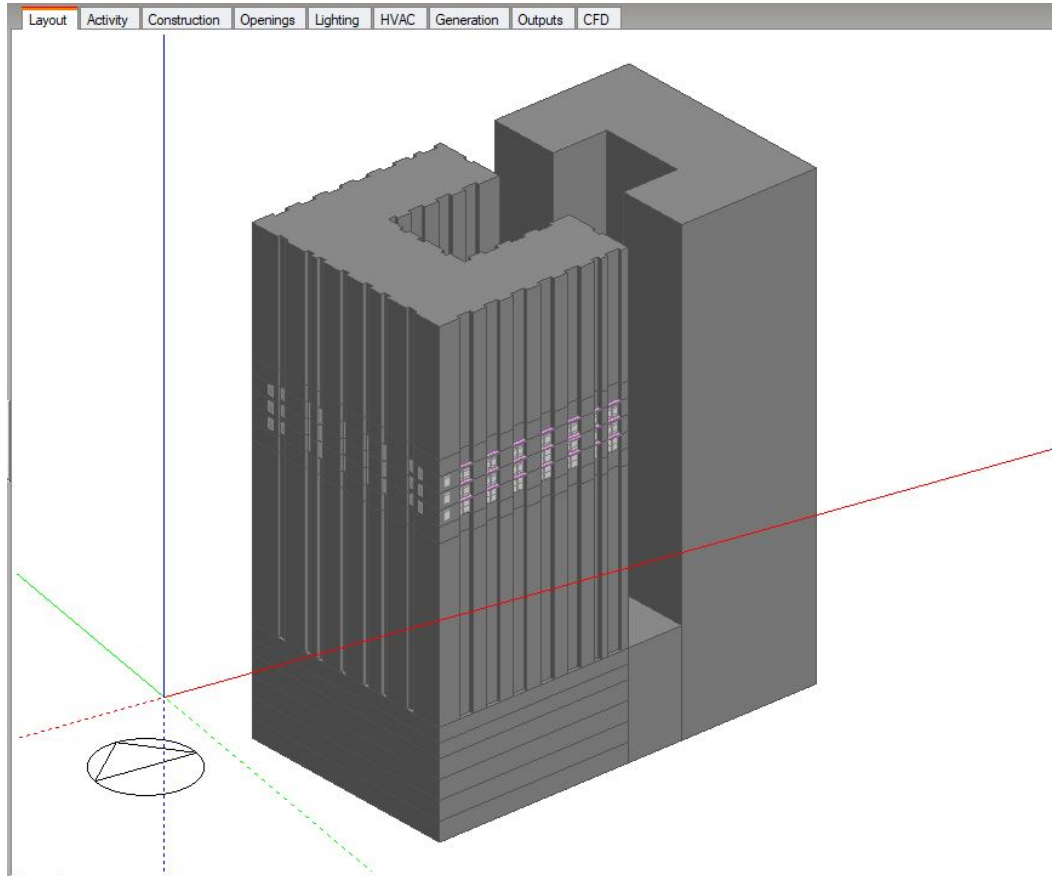


Figure 4.10 Comparison of Measured Outdoor Air Temperature and Simulation Weather File

Outdoor air temperature, relative humidity, and radiation recorded by rooftop weather station during field measurement was input to the weather data used in verification process. As a result, weather data bought from White Box

Technology match the outdoor condition of the apartment during measurement. Figure 4.16 shows the outdoor air temperatures in the verification model match the measurement condition.

4.1.7 Building Verification Model



Building verification model is generated by Design Builder Software with input as follows :

Building Element	Material	U-value
Walls	- plaster, painted white	1.852 W/m ² -K
	- cast concrete (lighthouse)	
Window	Aluminum frame	5.894 W/m ² -K
	window with 3mm single clear glass	
Floor & ceiling	- ceramic/porcelain	1.685 W/m ² -K
	- cast concrete (lighthouse)	

4.1.8 Verification Result

In general, the verification result showed that the simulated model could generate similar air temperature and relative humidity of the measurement.

a. Room A2050 Verification

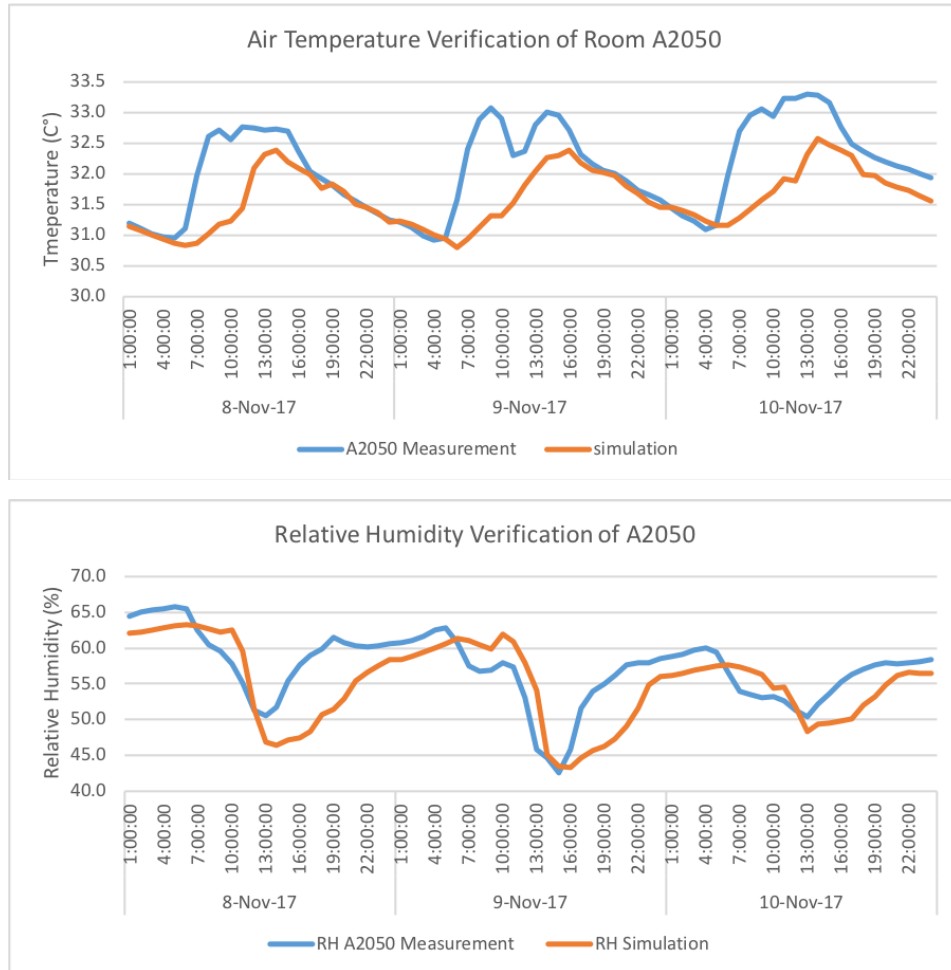


Figure 4.11 Air Temperature and Relative Humidity Verification of Room A2050

Room A2050 the highest temperature than the other measured apartment units. The simulated value of Room A2050 air temperature was close to the measurement at 16:00 – 04:00. However, during the daytime (06:00 – 14:00), air temperature of measured value was much higher than the simulated value inside room A2050. Simulated relative humidity of room A2050 resulted in lower relative humidity values between 13:00 – 05:00, and slightly higher between 05:00 – 13:00 than the measured values. The R^2 value of Room A2050 air temperature is 0.39, while CV(RMSE) value of Room A2050 is 2.30%. The R^2 value of relative

humidity inside room A2050 is 0.49, with CV(RMSE) value of 8%.

Table 4.6 Hourly Average Measurement and Simulation of Room A2050 Air Temperature

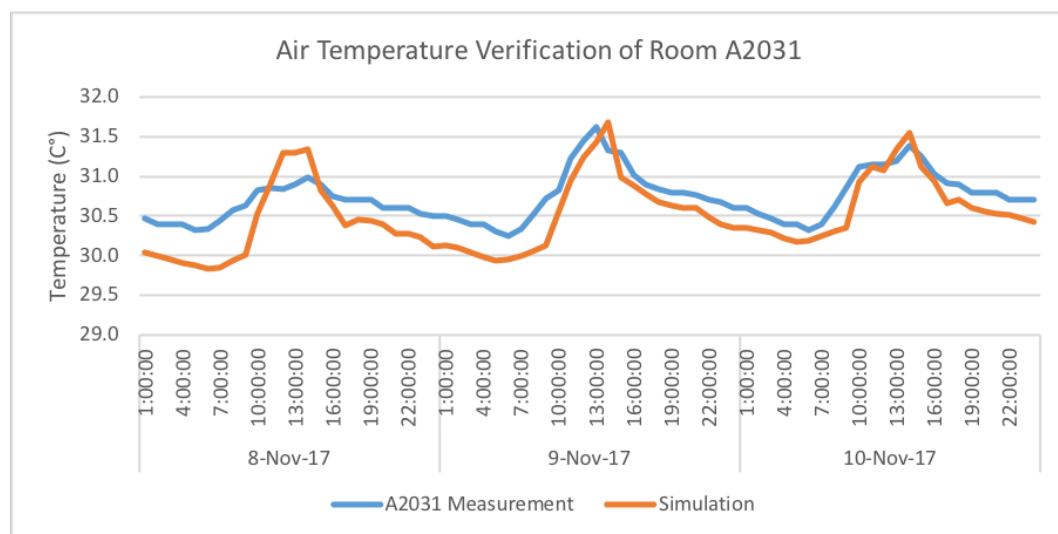
Hour	Average A2050 Measurement Temp. (C°)	Average Simulation Temp. (C°)	Average ΔT (C°)
1:00:00	31.3	31.3	0.0
2:00:00	31.2	31.2	0.0
3:00:00	31.1	31.1	0.1
4:00:00	31.0	31.0	0.1
5:00:00	31.0	31.0	0.0
6:00:00	31.5	30.9	0.6
7:00:00	32.4	31.0	1.3
8:00:00	32.8	31.2	1.6
9:00:00	32.9	31.3	1.6
10:00:00	32.8	31.4	1.4
11:00:00	32.8	31.6	1.1
12:00:00	32.8	31.9	0.9
13:00:00	32.9	32.2	0.7
14:00:00	33.0	32.4	0.6
15:00:00	32.9	32.3	0.6
16:00:00	32.6	32.3	0.3
17:00:00	32.3	32.1	0.1
18:00:00	32.1	31.9	0.2
19:00:00	32.0	31.9	0.1
20:00:00	32.0	31.8	0.1
21:00:00	31.9	31.7	0.2
22:00:00	31.8	31.6	0.1
23:00:00	31.7	31.5	0.2
0:00:00	31.6	31.4	0.2
Min Air Temperature Difference			0.0
Max Air Temperature Difference			1.6
Average Air Temperature Difference			0.5
Standard Deviation			0.5

Table 4.7 Hourly Average Measurement and Simulation of Room A2050 Relative Humidity

Hour	Average A2050 Measurement RH (%)	Average Simulation RH (%)	Average ΔRH (%)
1:00:00	61.4	58.9	2.5
2:00:00	61.8	59.2	2.5
3:00:00	62.2	59.6	2.6

4:00:00	62.6	60.0	2.6
5:00:00	62.7	60.4	2.3
6:00:00	61.0	60.7	0.3
7:00:00	58.0	60.5	2.5
8:00:00	56.9	60.0	3.0
9:00:00	56.5	59.5	3.0
10:00:00	56.3	59.6	3.3
11:00:00	55.0	58.3	3.3
12:00:00	51.9	53.7	1.8
13:00:00	48.9	49.8	0.9
14:00:00	49.5	46.9	2.6
15:00:00	50.6	46.7	3.9
16:00:00	52.9	46.8	6.1
17:00:00	55.7	47.7	8.0
18:00:00	56.9	49.4	7.5
19:00:00	58.0	50.3	7.7
20:00:00	58.3	51.7	6.6
21:00:00	58.6	53.5	5.1
22:00:00	58.7	54.9	3.8
23:00:00	58.8	56.3	2.5
0:00:00	59.2	57.0	2.2
Min Relative Humidity Difference			0.3
Max Relative Humidity Difference			8.0
Average Relative Humidity Difference			3.6
Standard Deviation			2.1

b. Room A2031 Verification



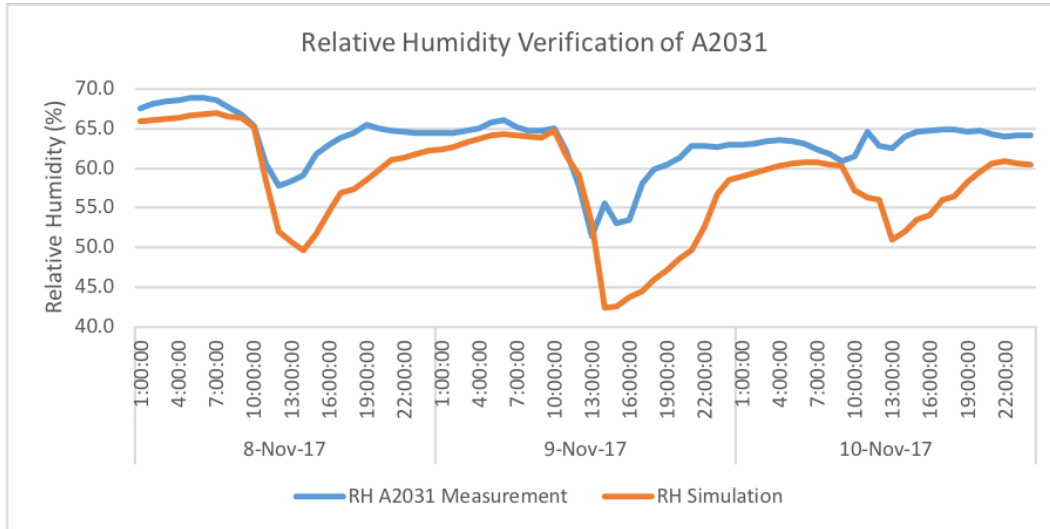


Figure 4.12 Air Temperature and Relative Humidity Verification of Room A2031

Verification result of air temperature in room A2031 was generally lower than the simulated value with maximum temperature difference of 0.6 C. On 9th and 10th November 2017. Comparing to the simulation result of relative humidity, the air temperature simulation result could predict the measurement value more accurately, especially in the peak hours at 11:00 – 16:00. Simulated value of relative humidity inside room A2031 was much lower than the measured value especially between 13:00 – 24:00. R^2 value of Room A2031 air temperature is 0.84, while CV(RMSE) value of Room A2031 is 1.00%. The R^2 value of relative humidity inside room A2031 is 0.62, with CV(RMSE) value of 10.12%.

Table 4.8 Hourly Average Measurement and Simulation of Room A2031 Air Temperature

Hour	Average A2031 Measurement Temp. (C°)	Average Simulation Temp. (C°)	Average ΔT (C°)
1:00:00	30.5	30.2	0.3
2:00:00	30.5	30.1	0.3
3:00:00	30.4	30.1	0.3
4:00:00	30.4	30.0	0.4
5:00:00	30.3	30.0	0.3
6:00:00	30.3	30.0	0.3
7:00:00	30.4	30.0	0.4
8:00:00	30.6	30.1	0.5
9:00:00	30.7	30.2	0.6
10:00:00	30.9	30.7	0.3
11:00:00	31.1	31.0	0.1

12:00:00	31.1	31.2	0.1
13:00:00	31.2	31.4	0.1
14:00:00	31.2	31.5	0.3
15:00:00	31.2	31.0	0.2
16:00:00	30.9	30.8	0.1
17:00:00	30.8	30.6	0.2
18:00:00	30.8	30.6	0.2
19:00:00	30.8	30.6	0.2
20:00:00	30.7	30.5	0.2
21:00:00	30.7	30.5	0.3
22:00:00	30.7	30.4	0.2
23:00:00	30.6	30.4	0.3
0:00:00	30.6	30.3	0.3
Min Air Temperature Difference			0.1
Max Air Temperature Difference			0.6
Average Air Temperature Difference			0.3
Standard Deviation			0.1

Table 4.9 Hourly Average Measurement and Simulation of Room A2050 Relative Humidity

Hour	Average A2031 Measurement RH (%)	Average Simulation RH (%)	Average ΔRH (%)
1:00:00	65.0	62.4	2.6
2:00:00	65.2	62.7	2.5
3:00:00	65.5	63.1	2.4
4:00:00	65.7	63.5	2.3
5:00:00	66.0	63.8	2.2
6:00:00	66.0	64.0	2.1
7:00:00	65.3	63.9	1.4
8:00:00	64.8	63.7	1.1
9:00:00	64.1	63.5	0.7
10:00:00	64.0	62.4	1.6
11:00:00	62.5	58.8	3.7
12:00:00	59.5	55.7	3.8
13:00:00	57.4	51.6	5.9
14:00:00	59.5	48.0	11.6
15:00:00	59.8	49.2	10.6
16:00:00	60.4	50.8	9.6
17:00:00	62.3	52.5	9.8
18:00:00	63.1	53.2	9.8
19:00:00	63.5	54.6	8.9
20:00:00	63.7	56.0	7.7

21:00:00	63.9	57.1	6.8
22:00:00	63.8	58.3	5.5
23:00:00	63.7	59.7	4.1
0:00:00	63.8	60.4	3.4
Min Relative Humidity Difference			0.7
Max Relative Humidity Difference			11.6
Average Relative Humidity Difference			5.0
Standard Deviation			3.5

c. Room A2020 Verification

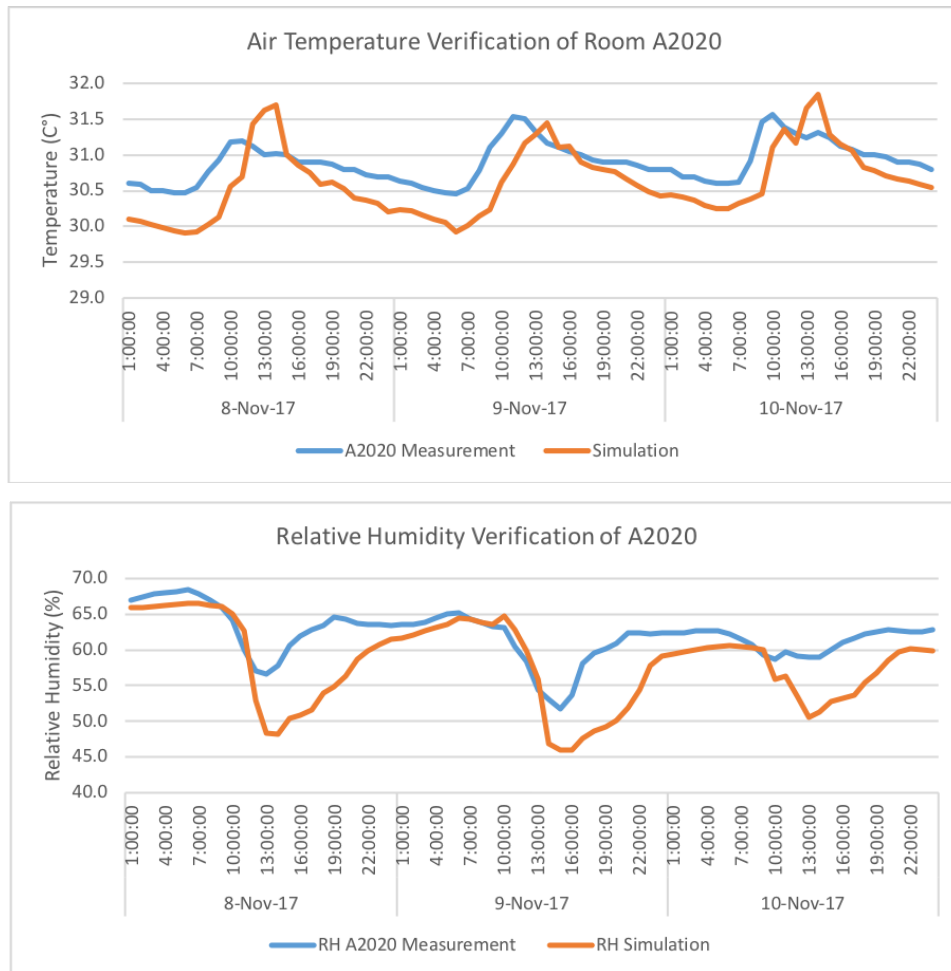


Figure 4.13 Air Temperature and Relative Humidity Verification of Room A2020

The simulation result of air temperature inside Room A2020 was generally lower than the measured value, except at 13:00 – 15:00 which was higher than the simulated value. Simulated value of relative humidity inside room A2020 was much lower than the measured value especially between 13:00 – 24:00. R^2 value of Room A2020 air temperature is 0.6, while CV(RMSE) value of Room A2020 air

temperature is 1.30%. The R^2 value of relative humidity inside room A2020 is 0.61, with CV(RMSE) value of 8.80%

Table 4.10 Hourly Average Measurement and Simulation of Room A2020 Air Temperature

Hour	Average A2020 Measurement Temp. (C°)	Average Simulation Temp. (C°)	Average ΔT (C°)
1:00:00	30.7	30.3	0.4
2:00:00	30.6	30.2	0.4
3:00:00	30.6	30.2	0.4
4:00:00	30.5	30.1	0.4
5:00:00	30.5	30.1	0.4
6:00:00	30.5	30.0	0.5
7:00:00	30.6	30.1	0.5
8:00:00	30.8	30.2	0.6
9:00:00	31.2	30.3	0.9
10:00:00	31.3	30.8	0.6
11:00:00	31.4	31.0	0.4
12:00:00	31.3	31.3	0.1
13:00:00	31.2	31.5	0.3
14:00:00	31.2	31.7	0.5
15:00:00	31.1	31.1	0.0
16:00:00	31.0	31.0	0.0
17:00:00	31.0	30.9	0.1
18:00:00	30.9	30.7	0.2
19:00:00	30.9	30.7	0.2
20:00:00	30.9	30.7	0.2
21:00:00	30.9	30.6	0.3
22:00:00	30.8	30.5	0.3
23:00:00	30.8	30.5	0.3
0:00:00	30.8	30.4	0.4
Min Air Temperature Difference			0.0
Max Air Temperature Difference			0.9
Average Air Temperature Difference			0.3
Standard Deviation			0.2

Table 4.11 Hourly Average Measurement and Simulation of Room A2020 Relative Humidity

Hour	Average A2020 Measurement RH (%)	Average Simulation RH (%)	Average ΔRH (%)
1:00:00	64.3	62.3	2.0

2:00:00	64.5	62.6	1.9
3:00:00	64.8	62.9	1.9
4:00:00	65.0	63.2	1.8
5:00:00	65.3	63.5	1.8
6:00:00	65.3	63.9	1.4
7:00:00	64.6	63.8	0.8
8:00:00	63.8	63.5	0.4
9:00:00	62.8	63.2	0.4
10:00:00	62.0	61.9	0.1
11:00:00	60.1	60.6	0.6
12:00:00	58.2	55.4	2.8
13:00:00	56.7	51.6	5.1
14:00:00	56.6	48.8	7.8
15:00:00	57.5	49.7	7.7
16:00:00	58.9	50.0	8.8
17:00:00	60.8	50.9	9.9
18:00:00	61.8	52.7	9.1
19:00:00	62.5	53.6	8.9
20:00:00	62.7	55.0	7.7
21:00:00	62.9	56.7	6.2
22:00:00	62.8	58.1	4.7
23:00:00	62.8	59.5	3.2
0:00:00	62.9	60.2	2.7
Min Relative Humidity Difference			0.1
Max Relative Humidity Difference			9.9
Average Relative Humidity Difference			4.1
Standard Deviation			3.3

d. Room A2010 Verification

The simulation result of air temperature inside Room A2010 was generally higher than the measured value, except at 07:00 – 10:00 which was slightly lower than the simulated value. Simulated value of relative humidity inside room A2010 was lower than the measured value all the time. R^2 value of Room A2010 air temperature is 0.69, while CV(RMSE) value of Room A2010 air temperature is 1.30%. The R^2 value of relative humidity inside room A2010 is 0.7, with CV(RMSE) value of 13.20%

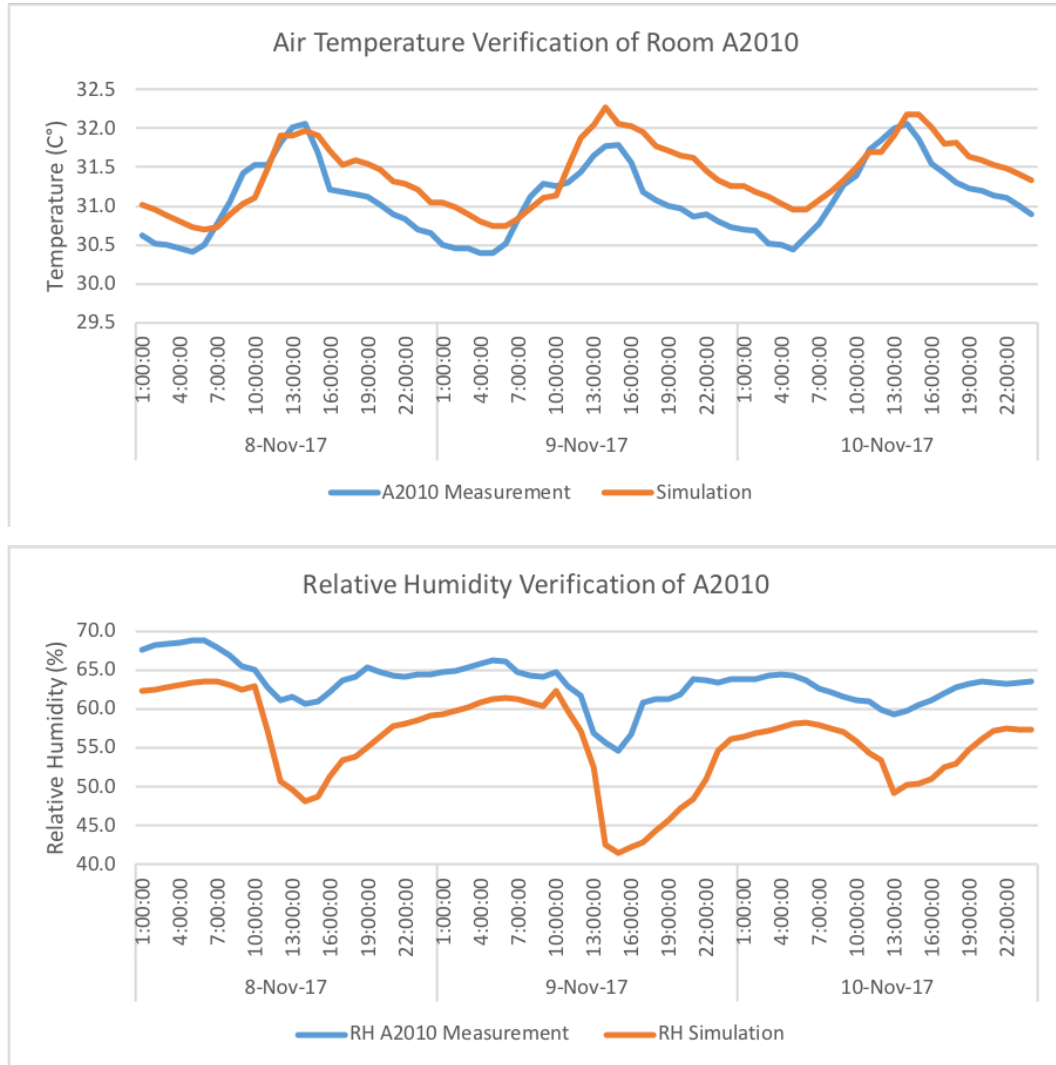


Figure 4.14 Air Temperature and Relative Humidity Verification of Room A2010

Table 4.12 Hourly Average Measurement and Simulation of Room A2010 Air Temperature

Hour	Average A2010 Measurement Temp. (C°)	Average Simulation Temp. (C°)	Average ΔT (C°)
1:00:00	30.6	31.1	0.5
2:00:00	30.6	31.0	0.5
3:00:00	30.5	31.0	0.5
4:00:00	30.5	30.9	0.4
5:00:00	30.4	30.8	0.4
6:00:00	30.5	30.8	0.3
7:00:00	30.8	30.9	0.1
8:00:00	31.1	31.0	0.1
9:00:00	31.3	31.2	0.2
10:00:00	31.4	31.2	0.1

11:00:00	31.5	31.6	0.0
12:00:00	31.7	31.8	0.1
13:00:00	31.9	32.0	0.1
14:00:00	32.0	32.1	0.2
15:00:00	31.8	32.1	0.3
16:00:00	31.4	31.9	0.5
17:00:00	31.3	31.8	0.5
18:00:00	31.2	31.7	0.6
19:00:00	31.1	31.6	0.5
20:00:00	31.1	31.6	0.5
21:00:00	31.0	31.5	0.5
22:00:00	30.9	31.4	0.5
23:00:00	30.8	31.3	0.5
0:00:00	30.8	31.2	0.4
Min Air Temperature Difference			0.0
Max Air Temperature Difference			0.6
Average Air Temperature Difference			0.3
Standard Deviation			0.2

Table 4.13 Hourly Average Measurement and Simulation of Room A2010 Relative Humidity

Hour	Average A2010 Measurement RH (%)	Average Simulation RH (%)	Average ΔRH (%)
1:00:00	65.4	59.4	6.1
2:00:00	65.7	59.7	6.0
3:00:00	66.0	60.1	5.9
4:00:00	66.2	60.6	5.7
5:00:00	66.5	60.9	5.6
6:00:00	66.2	61.1	5.1
7:00:00	65.1	60.9	4.2
8:00:00	64.4	60.4	4.0
9:00:00	63.8	60.0	3.7
10:00:00	63.6	60.4	3.2
11:00:00	62.2	57.1	5.1
12:00:00	60.9	53.7	7.2
13:00:00	59.2	50.4	8.8
14:00:00	58.7	46.9	11.7
15:00:00	58.8	46.8	11.9
16:00:00	60.0	48.2	11.9
17:00:00	62.2	49.6	12.6
18:00:00	62.8	50.4	12.4

19:00:00	63.3	51.8	11.5
20:00:00	63.4	53.3	10.1
21:00:00	63.8	54.5	9.4
22:00:00	63.7	55.6	8.1
23:00:00	63.8	56.8	6.9
0:00:00	64.0	57.5	6.4
Min Relative Humidity Difference			3.2
Max Relative Humidity Difference			12.6
Average Relative Humidity Difference			7.6
Standard Deviation			3.1

According to the standard of R^2 analysis, only one verification result meet the criteria set by ASHRAE Guidelines and IPMVP. The R^2 standard stated that the verification model should have larger R^2 value of 0.75. Verification result of air temperature in Room A2031 has R^2 value of 0.84, but the other verification of air temperature and relative humidity did not meet the standard.

On the other hand, all the verification results meet the standard of CV(RMSE) value, which is below 30% according to FEMP and ASHRAE Guideline, and 20% for IPMVP standard. Safikhani and Baharvand (2017) also stated that the maximum error of inside air temperature was 2.4 C, and the verification result maximum error for inside air temperature was 1.8 C for Room A2050. However study by Safikhani and Baharvand (2017) did not mention the maximum error of relative humidity. According to this evaluation, the verification results are considered sufficient.

Table 4.14 Evaluation of Verification Results

	Index	A 2050	A 2031	A 2020	A 2010
Air Temperature	CV(RMSE). Standard : $\leq 20\%$	2.30%	1.0%	1.30%	1.30%
	R^2 Standard : > 0.75	0.39	0.84	0.6	0.69
Relative Humidity	CV(RMSE) Standard : $\leq 20\%$	8.0%	10.12%	8.80%	13.20%
	R^2 Standard : > 0.75	0.49	0.62	0.61	0.7

Table 4.15 Maximum Difference of Verification Results

	A 2050	A 2031	A 2020	A 2010
Maximum Difference of Air Temperature (C)	1.8	0.6	1.0	0.4
Maximum Difference of Relative Humidity (%)	10.8	13.9	11.3	18.0

4.2 Macroclimate of Surabaya

According to Indonesia Statistic Bureau (2017), Surabaya is located at 7°21' south latitude and between 112°36' - 112°54' east longitude, with altitude between 3 - 6 m above the sea level, except the south area of Surabaya which has altitude of 25 – 50 m above sea level. There are three meteorological stations in Surabaya, Perak Harbor I, Perak Harbor II both located in the north area of Surabaya, and Juanda Airport, located in Sidoarjo area, next to borderline of Surabaya east area. In this study, the climate analysis data is taken from Juanda Airport because it is the closet meteorological station to the sample building of this study (Bale Hinggil Apartment).

Table 4.16 Monthly Climate Data of Surabaya

Month	Temperature	RH (%)	Sunshine Duration (%)	Rainy Days
January	27.5	83	46	29
February	27.7	82	51	24
March	27.9	81	55	24
April	28.2	81	64	21
May	28.6	75	91	10
June	27.9	77	75	16
July	27.5	74	88	3
August	27.3	71	96	0
September	28.3	69	88	0
October	29.8	69	49	3
November	28.2	79	49	17
December	28	80	46	26

In 2017, the lowest recorded temperature was 20.7 °C in August, and the highest recorded temperature was 35.9 °C in October. The average monthly

temperatures range from 27.3 – 29.8 °C. The lowest average temperature was in August, and the highest average temperature was in October. During 2017, relative humidity in Surabaya range from 28 – 99%. However, the average relative humidity was above 65% throughout the year. The highest average relative humidity was recorded in January, and the lowest average relative humidity was in September and October 2017.

According to the climate data of Juanda in 2017, January was the coolest month, while October was the hottest moth. Although the lowest average temperature was recorded in August 2017, January had 46% sunshine duration compared to August with 96% sunshine duration. January also had the most rainy days in 2017. The combination of temperature, relative humidity, sunshine duration, and rainy days showed that January was the coolest month. In addition, according to Henni (2018), during 2013 – 2017, January is considered as the coolest month, while October is considered the hottest month in Surabaya.

The wind data of Juanda Airport in 2017 showed that the dominant wind direction came from the east and west direction. The average wind speed recorded was between 3.6 – 4.9 m/s. During the coolest month and the hottest month in 2017, the dominant wind direction came from the east.

Table 4.17 Dominant Monthly Wind Direction in Surabaya

Month	Mostly Directional	Average Wind Speed	
		Knot	m/s
January	East	8.8	4.5
February	West	9.5	4.9
March	West	7	3.6
April	West	6.5	3.3
May	East	7.5	3.9
June	East	8	4.1
July	East	7	3.6
August	East	8.3	4.3
September	East	8.5	4.4
October	East	7.7	4.0
November	East	7	3.6
December	West	7.7	4.0

4.2.1 The Coolest Month : January

In January 2017, the lowest average air temperature was 25.3 °C and was recorded at 04:00 in the morning. The highest average temperature recorded was 31.2 C at 12:00 in the afternoon. The average hourly Global Horizontal Irradiance (GHI) was 181.2 kWh/m². GHI is the amount of shortwave radiation received by a horizontal plane. GHI is the sum of Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance, and ground-reflected radiation.

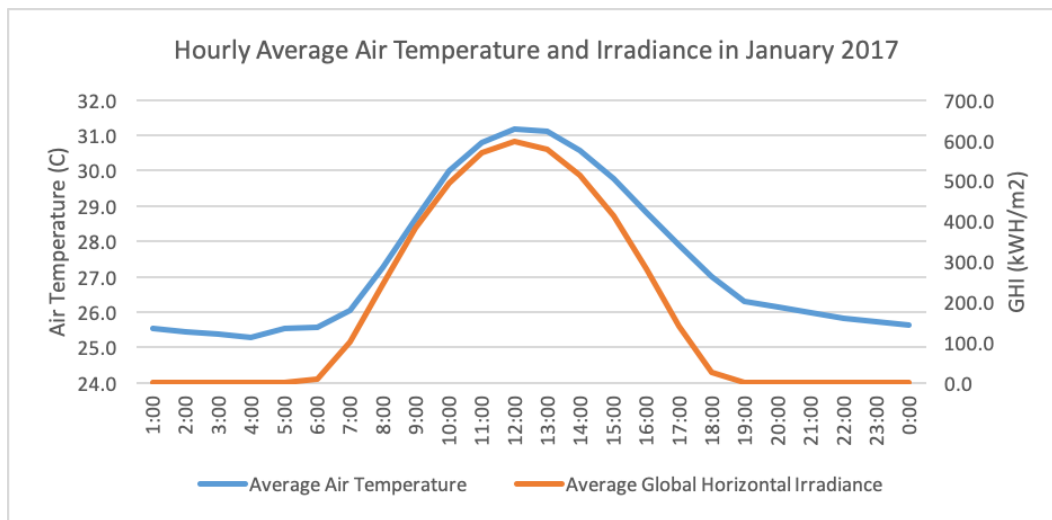


Figure 4.15 Hourly Average Air Temperature and Irradiance of Surabaya in January 2017

Table 4.18 Climate Data of Surabaya in January 2017

Hour	January		
	Average Air Temperature (°C)	Average Relative Humidity (%)	Average Global Horizontal Irradiance (kWh/m ²)
1:00	25.5	90.5	0.0
2:00	25.5	91.0	0.0
3:00	25.4	91.4	0.0
4:00	25.3	91.9	0.0
5:00	25.5	90.9	0.0
6:00	25.6	91.1	10.5
7:00	26.1	88.9	102.5
8:00	27.2	83.1	244.2
9:00	28.6	76.9	381.3
10:00	30.0	71.2	494.8
11:00	30.8	68.1	568.1

12:00	31.2	66.7	596.7
13:00	31.1	67.1	576.5
14:00	30.6	69.3	514.6
15:00	29.8	72.6	412.6
16:00	28.8	76.8	282.2
17:00	27.9	80.7	139.3
18:00	27.0	84.4	26.3
19:00	26.3	87.6	0.0
20:00	26.2	88.1	0.0
21:00	26.0	88.7	0.0
22:00	25.8	89.2	0.0
23:00	25.7	89.8	0.0
0:00	25.6	90.2	0.0

4.2.2 The Hottest Month : October

In October 2017, the lowest average air temperature was 25.9 °C and was recorded at 04:00 in the morning. The highest average temperature recorded was 33.6 °C during 12:00 – 13:00 in the afternoon. The average hourly Global Horizontal Irradiance (GHI) was 237.7 kWh/m². In average, October 2017 had higher temperature of 2.3 °C recorded, but had lower relative humidity value of 14.3% in average than January 2017.

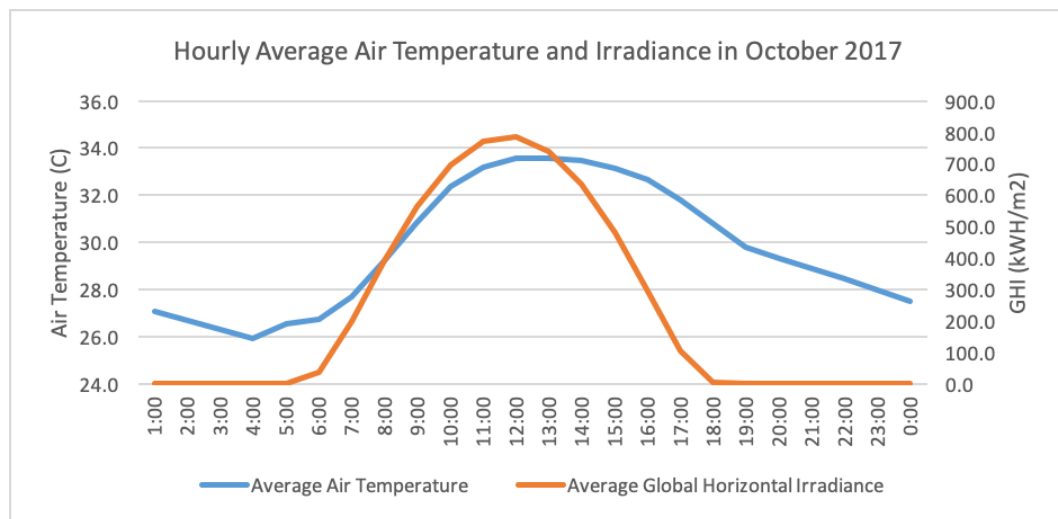


Figure 4.16 Hourly Average Air Temperature and Irradiance of Surabaya in October 2017

Table 4.19 Climate Data of Surabaya in October 2017

Hour	October		
	Average Air Temperature (°C)	Average Relative Humidity (%)	Average Global Horizontal Irradiance (kWh/m ²)
1:00	27.1	81.1	0.0
2:00	26.7	82.6	0.0
3:00	26.3	84.0	0.0
4:00	25.9	85.5	0.0
5:00	26.5	82.5	0.0
6:00	26.8	81.1	37.5
7:00	27.7	76.8	197.4
8:00	29.2	70.1	390.1
9:00	30.9	63.4	564.0
10:00	32.4	57.5	695.7
11:00	33.2	54.4	771.3
12:00	33.6	52.8	786.9
13:00	33.6	52.5	739.1
14:00	33.5	52.1	635.3
15:00	33.1	52.5	481.6
16:00	32.7	53.9	294.5
17:00	31.8	57.8	106.3
18:00	30.8	62.8	5.3
19:00	29.8	68.5	0.0
20:00	29.3	70.3	0.0
21:00	28.9	71.9	0.0
22:00	28.5	73.7	0.0
23:00	28.0	76.1	0.0
0:00	27.5	78.7	0.0

4.3 Heat Gains of Model Experiments

As explained in 2.1.2 about heat transfer mechanism, a building is a thermal system and constantly react to its surrounding thermal environment. During the simulation there are four different heat gains that contribute to the model experiment's cooling energy. There are two different heat loss by cooling process

which result in building energy consumption, sensible cooling and latent cooling. Sensible cooling accounts for cooling caused by sensible heat gain, while total cooling accounts for both sensible and latent cooling.

Sensible heat gain from the simulation process is divided into four category as follows :

1. Fabric heat gain accounts for heat gain generated by the building envelope, such as wall, window, floor, ceiling, and roof. Heat gain from both conduction and convection process are included in the fabric heat gain, expect heat gain from window solar radiation.
2. Solar heat gain accounts for heat gain caused by window solar radiation.
3. Infiltration heat gain accounts for heat gain caused by exchange of air through cracks from inside and outside as well as exchange air between two different rooms.
4. Internal heat gain accounts for heat gain generated by building occupants, lighting and electronic appliances. In this experiment, building internal gain is one of the control variable, thus difference range between model experiments internal heat gain is about 0.1 kW/m².

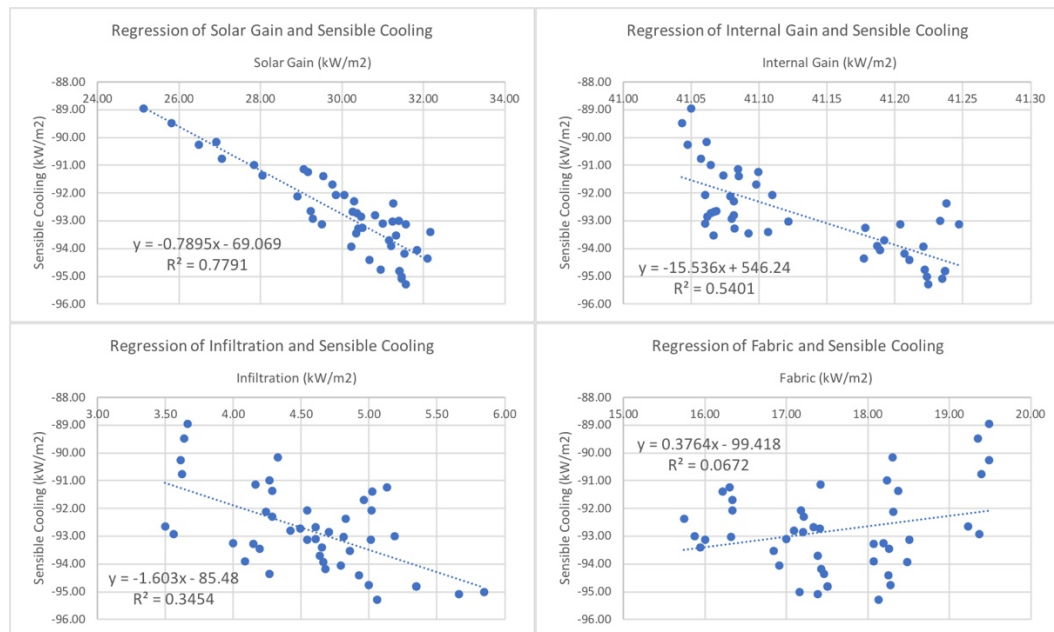


Figure 4.17 Regression of Heat Gain and Sensible Cooling Load

Regression analysis of each building heat gain and building sensible cooling load are conducted, in order to evaluate correlation between these variables. The

result showed that solar gain has the highest correlation with building sensible cooling load with R^2 of 0.78, followed by internal gain, infiltration, and fabric with R^2 value of 0.54, 0.35, and 0.07 respectively.

4.3.1 Solar Heat Gain

Solar heat gain of model experiments vary between 32.18 – 25.12 kW/m^2 , with difference range of 7.05 kW/m^2 . U shape building have both the highest and lowest solar heat gain than the other building geometries. The highest solar gain is generated when U shaped building with courtyard L/W of 1 are oriented toward north south (32.18 kW/m^2). On the other hand, the lowest solar gain is generated when U shaped building with courtyard L/W of 2 are oriented toward west east (25.12 kW/m^2).

a. Effect of Building Geometry on Solar Gain

In general, U geometry generates the lowest solar gain in different courtyard L/W of northwest - southeast and west - east orientation. However, when the building has courtyard L/W of 1 elongated alongside north south axis, Double L geometry generates the lowest solar gain of 29.06 kW/m^2 , while U geometry generate the highest solar gain of 32.18 kW/m^2 . U geometry has only one courtyard opening compared to the others geometry, U geometry can generate more self-shading for the building in different orientation and courtyard aspect ratio. Other than U geometry, H geometry generates slightly higher solar gain compared to the other three geometries.

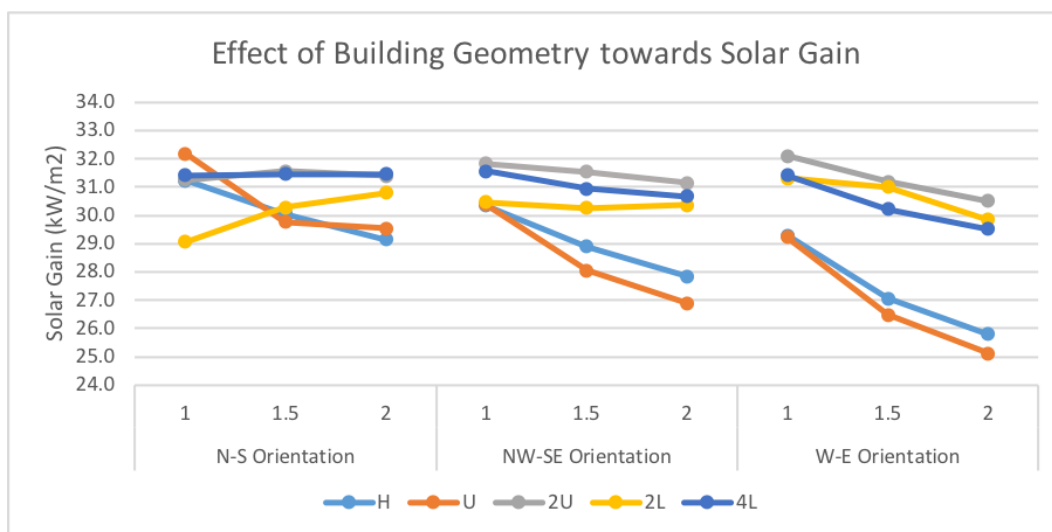


Figure 4.18 Effect of Building Geometry on Solar Gain

b. Effect of Courtyard L/W on Solar Gain

In general, increasing the courtyard L/W could reduce solar gain of model experiments, especially for U and H geometries. Increasing courtyard L/W from 1 to 2 of H geometry could reduce solar gain about 2.08 – 3.48 kW/m² in three different orientation, and for U geometry could reduce solar gain about 2.63 – 4.10 kW/m². Effect of increasing the courtyard L/W of Double U, Double L, and Quadruple L could reduce solar heat gain about 0.1 – 1.90 kW/m².

Increasing the courtyard L/W will result in more impact when the building is oriented toward west-east, in which all building geometries has lower solar gain as the courtyard is longer. On the other hand, increasing the courtyard L/W of Double U, Double L, and Quadruple L oriented towards north-south will increase the solar heat gain, with Double L geometry has the highest heat gain of 1.75 kW/m², followed by Double U, and Quadruple L geometries, with heat gain of 0.32 kW/m², and 0.11 kW/m², respectively.

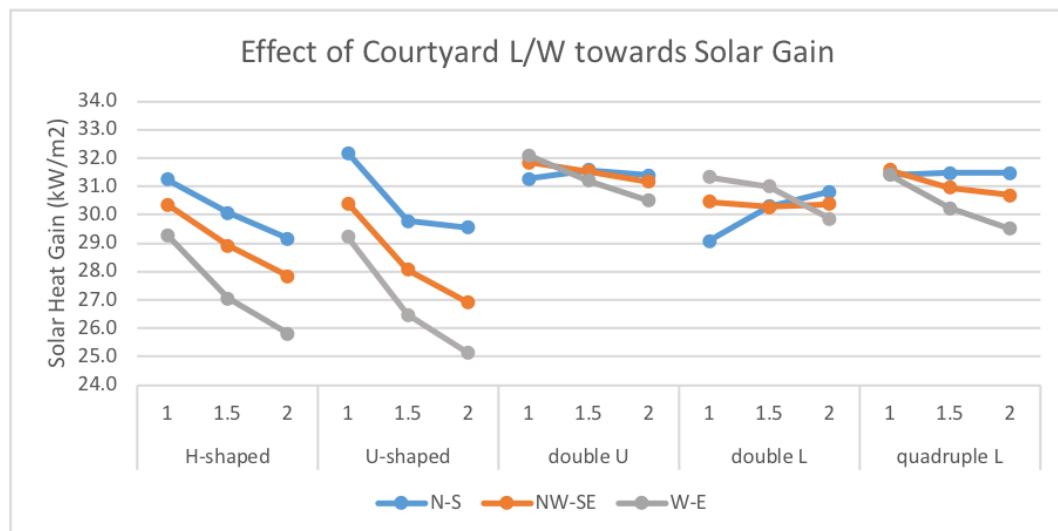


Figure 4.19 Effect of Courtyard L/W on Solar Gain

c. Effect of Building Orientation on Solar Gain

Similar with the previous subject about effect of courtyard L/W on solar gain, impact of building orientation play more important role for solar heat gain of U and H geometry, in which orienting the building form north-east to west-east could reduce solar gain of 1.07 – 3.35 kW/m² of H geometry, and 2.95 – 4.42 kW/m² of U geometry. For Double U, Double L, and Quadruple L geometries changing the building orientation form north-east to west-east could reduce solar

heat gain about $0.37 - 1.95 \text{ kW/m}^2$. On the other hand, orienting the building form north-east to west-east of Double U, Double L, and Quadruple L with courtyard L/W of 1 will increase the solar heat gain, with Double L geometry has the highest heat gain of 2.26 kW/m^2 , followed by Double U, and Quadruple L, with heat gain of 0.84 kW/m^2 , and 0.16 kW/m^2 , respectively.

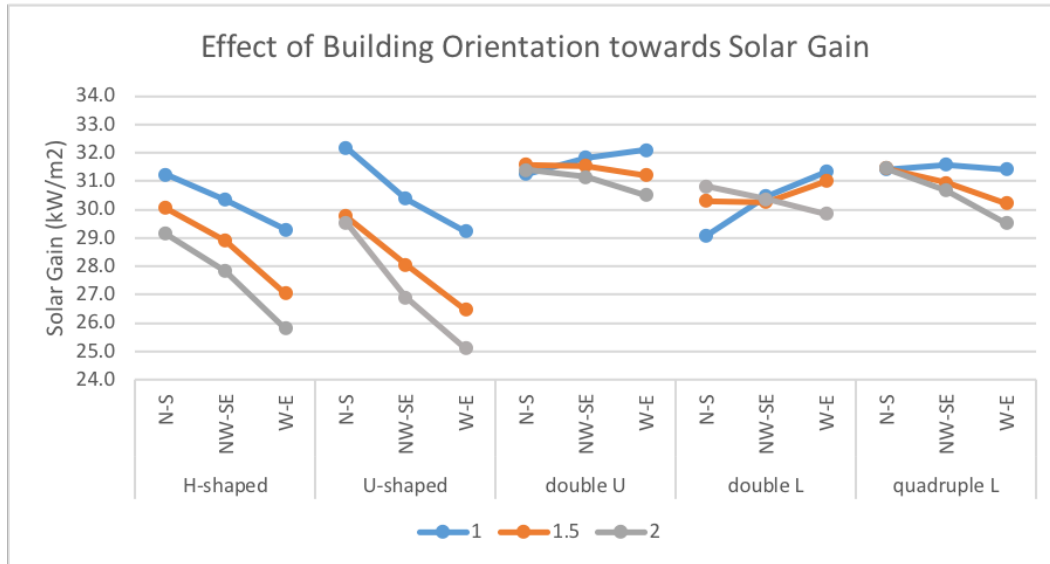


Figure 4.20 Effect of Building Orientation on Solar Gain

4.3.2 Heat Gain by Infiltration

Compared to the other heat gains, value of heat gain caused by infiltration is much smaller, with range between $3.5 - 5.85 \text{ kW/m}^2$. Quadruple L geometry with courtyard L/W of 2 elongated alongside north-south axis generates the highest heat gain by infiltration (5.85 kW/m^2), while U geometry with courtyard L/W of 1 facing west-east orientation generate the lowest heat gain by infiltration (3.5 kW/m^2)

a. Effect of Building Geometry on Infiltration Heat Gain

Double L geometry generate the lowest infiltration gain than the other geometries, when the building is elongated alongside north-south axis. For northwest-southeast, and west-east orientation U and H geometry generate the lowest amount of infiltration gain, with almost similar value. On the other hand, Quadruple L geometry has the highest infiltration heat gain in all orientation and courtyard L/W. Higher surface to volume ratio of Quadruple L geometry, makes the building geometry more susceptible from solar radiation and upcoming wind.

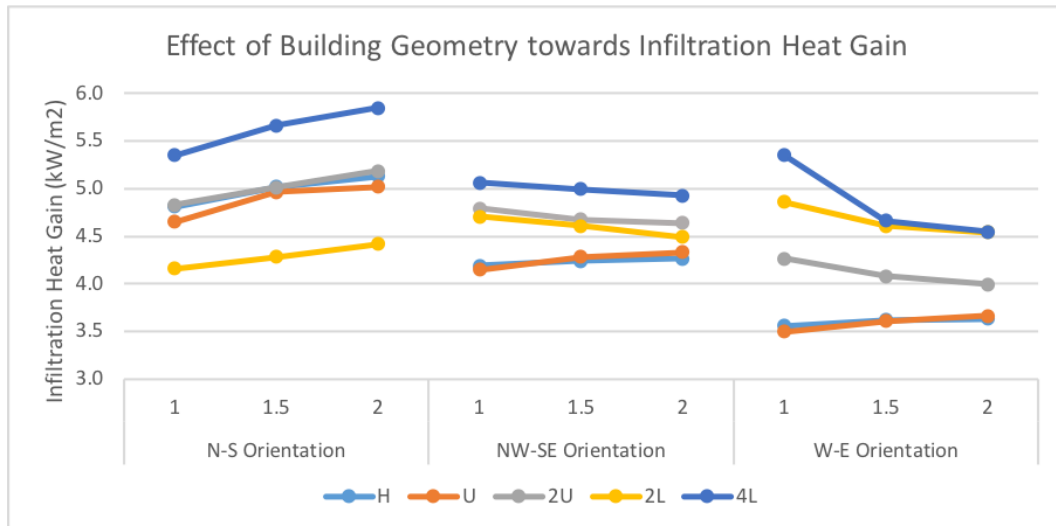


Figure 4.21 Effect of Building Geometry on Infiltration Heat Gain

b. Effect of Courtyard L/W on Infiltration Heat Gain

Increasing the courtyard L/W from 1 to 2 in three different orientation, will result in slightly higher infiltration gain for H and U geometries about 0.07 – 0.37 kW/m². However, increasing the courtyard L/W from 1 to 2 elongated alongside northwest – southeast and west - east axis will decrease infiltration gain about 0.15 – 0.8 kW/m² for Double U, Double L, and Quadruple L geometries, but will increase infiltration heat gain up to 0.5 kW/m² when the building is oriented towards west-east. Increasing the courtyard L/W of Double U, Double L, and Quadruple L geometries on north-south orientation, will increase the apartments units facing west and east, which are the source of wind direction in Surabaya.

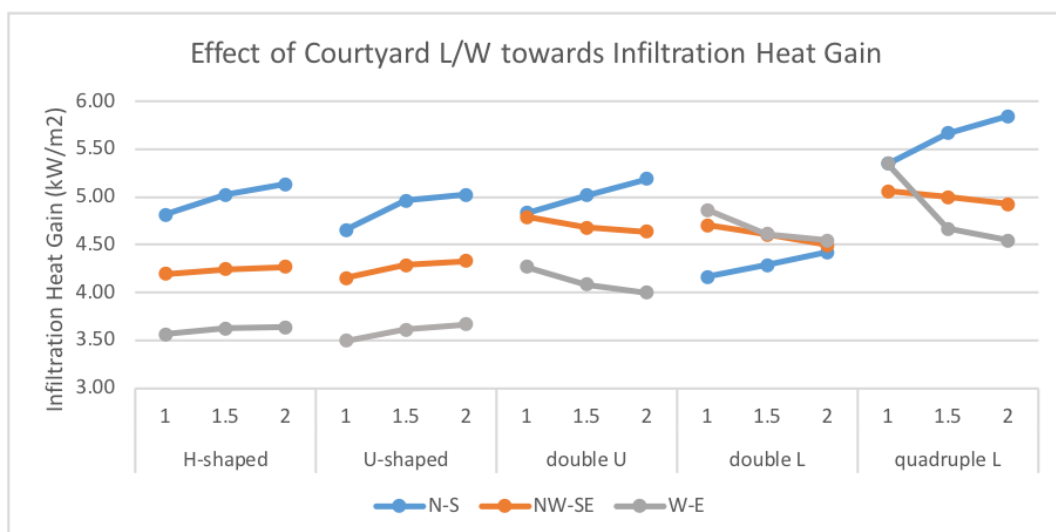


Figure 4.22 Effect of Courtyard L/W on Infiltration Heat Gain

c. Effect of Building Orientation on Infiltration Heat Gain

H, U, and Double U, as well as Quadruple L geometries with courtyard L/W of 1.5 and 2 generate the lowest infiltration heat gain when the building is oriented towards west-east. On the other hand, orienting the building form north-east to west-east will increase infiltration heat gain of Double L geometry. Quadruple L with courtyard L/W of 1 generate the lowest infiltration heat gain on northwest-southeast orientation.

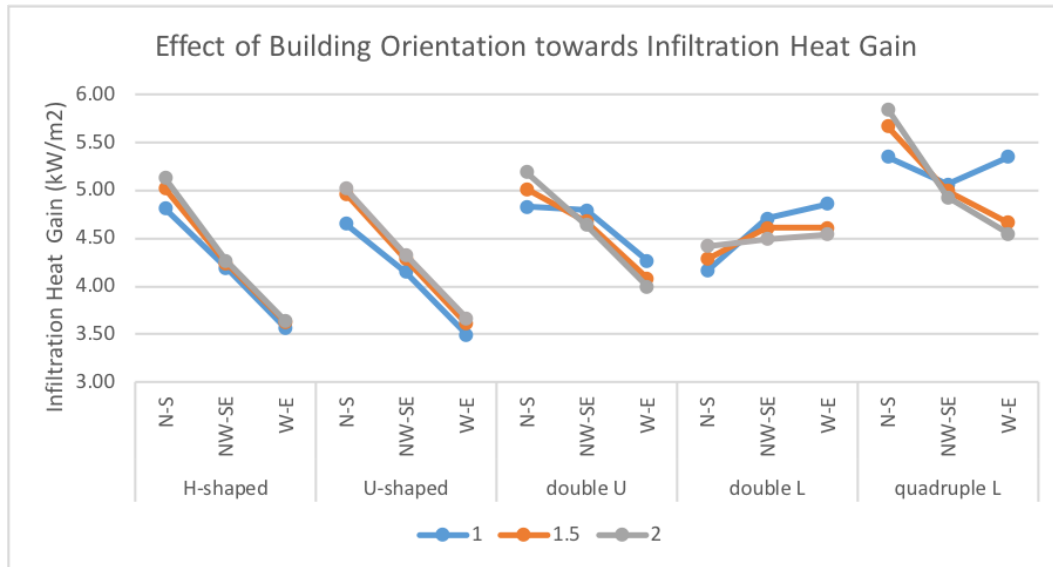


Figure 4.23 Effect of Building Orientation on Infiltration Heat Gain

4.3.3 Fabric Heat Gain

Fabric heat gain generated by model experiments range between 15.7 – 19.5 kW/m². U geometry with courtyard L/W of 2 elongated to west-east axis has the highest fabric heat gain (19.5 kW/m²). On the other hand, Double U geometry with courtyard L/W of 1 oriented to north-south generate the lowest fabric heat gain (15.7 kW/m²).

a. Effect of Building Geometry on Fabric Heat Gain

Double U and Double L geometry tend to generate lower fabric heat gain than the other geometries. For north-south orientation, Double U geometry generate the lowest fabric heat gain. For northwest-southeast both Double U and Double L geometry generate lower fabric heat gain than the others geometries. For west-east orientation Double L geometry generate the lowest fabric gain.

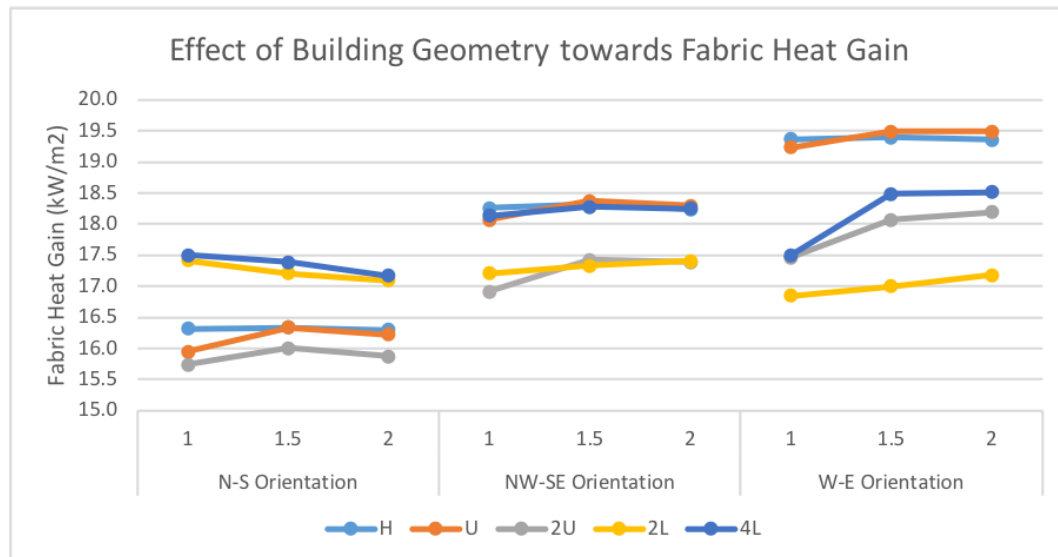


Figure 4.24 Effect of Building Geometry on Fabric Heat Gain

c. Effect of Courtyard L/W on Fabric Heat Gain

Increasing the courtyard L/W from 1 to 2 in three different orientation, will result in slightly higher infiltration gain for H and U geometries about 0.07 – 0.37 kW/m². Similar with the other three geometries, the impact of increasing the courtyard L/W is not significant.

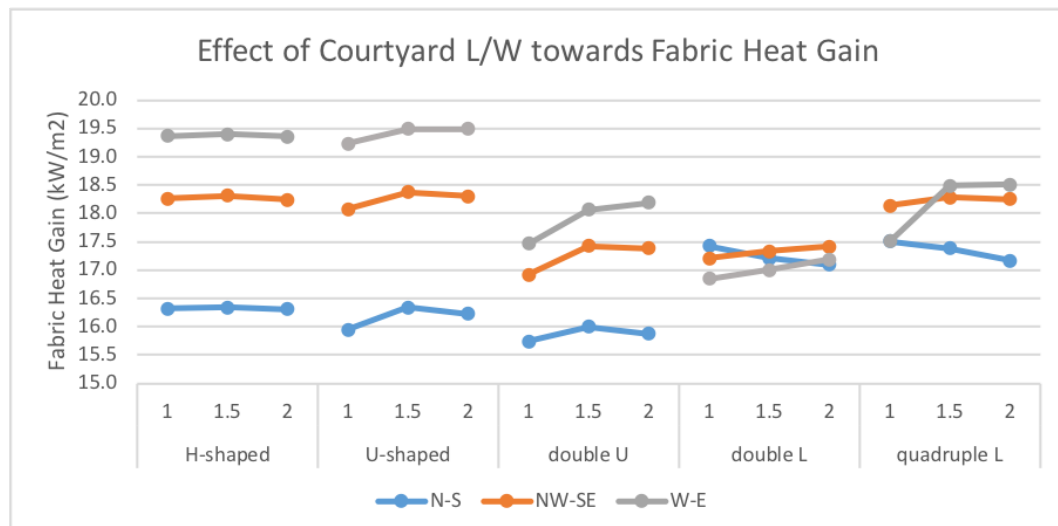


Figure 4.25 Effect of Courtyard L/W on Fabric Heat Gain

c. Effect of Building Orientation on Fabric Heat Gain

In general changing the building orientation from north-south to west-east will increase fabric heat gain of model geometries except Double L geometry. H, U geometries are more sensitive toward the change of orientation, which result in increase of fabric heat gain about 3.05 – 3.19 kW/m². Double U geometry generates

higher fabric gain about 1.72 – 2.32 kW/m² with similar change in orientation, followed by Quadruple L geometry which generate about 0.63 – 1.34 kW/m². On the other hand, changing the building orientation from north-south to west-east will decrease fabric heat gain generated by Double L geometry about 0.21 – 0.57 kW/m².

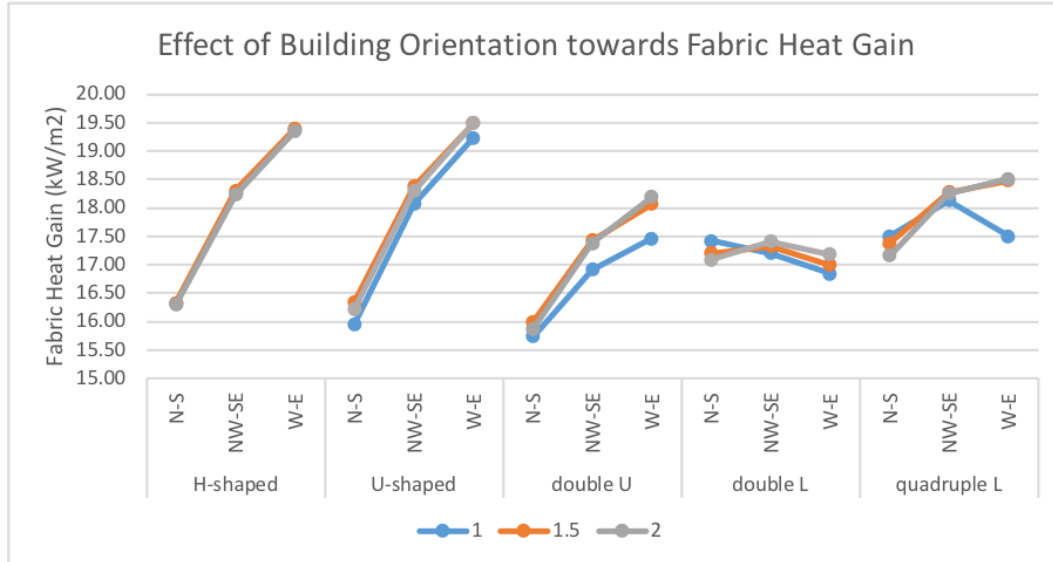


Figure 4.26 Effect of Building Orientation on Fabric Heat Gain

4.4 Cooling Load of Model Experiments

As previously explained, there are two different cooling process which result in building energy consumption, sensible cooling and latent cooling. Sensible cooling accounts heat quantity required to be removed in order to achieve desired temperature, while latent cooling accounts for heat quantity required in order to lower the moisture content. Cooling energy is the sum of energy required for sensible and latent cooling processes.

As explained in 3.7.4, Design Builder presents heat loss by cooling process in the negative value on the contrary with building heat gains, which presented in positive value. In conditioned building, the lower cooling value of a building, the more heat should be removed in order to meet desired thermal condition. Therefore, the lower heat loss by cooling a building, the higher cooling load of a building. For example, when Double U Geometry has sensible cooling of -93.4 kWh/m², while H Geometry has -93.0 kWh/m², means that Double U Geometry generates higher sensible cooling load than H geometry, because the amount of sensible heat needed to be removed is 93 kWh/m².

4.4.1 Sensible Cooling Load

Sensible cooling load are influenced by heat gain such as solar heat gain, fabric, infiltration, and internal heat gain. In this research, internal heat gain is one of the control variables.

a. Effect of Building Geometry on Sensible Cooling Load

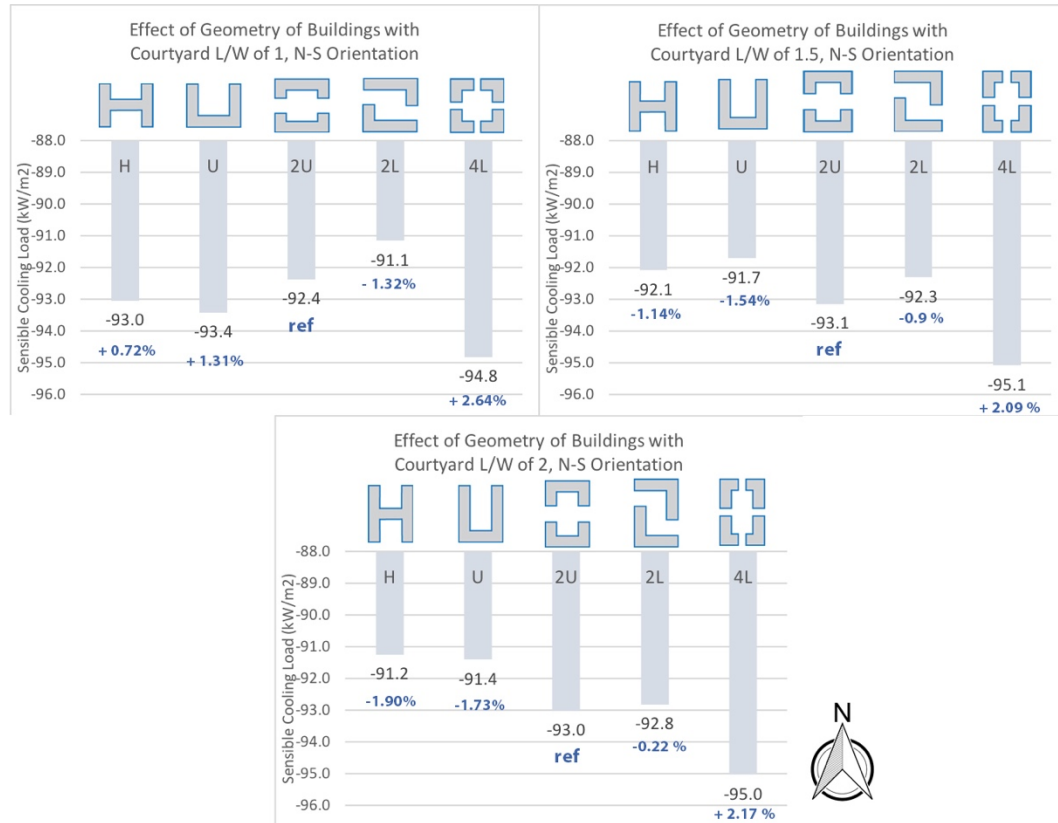


Figure 4.27 Effect of Building Geometry on Sensible Cooling Load, North- South Orientation

Double U Geometry is the geometry reference while evaluating the impact of building geometry on sensible cooling load. Double U Geometry is chosen because the base case geometry in this study is Double U Geometry. When the building is elongated to north-south axis, with courtyard L/W of 1, Double L geometry generate the lowest cooling load (91.1 kWh/m²). Changing Double U geometry to Double L geometry will decrease building sensible cooling load of 1.32%. When the courtyard L/W is increased into 1.5 and 2, U geometry and H generate the lowest cooling load with value of 91.7 kWh/m², 91.2 kWh/m² respectively. On north-south orientation with three different courtyard L/W,

Quadruple L geometry generate the highest sensible cooling load, and will increase the sensible cooling load up to 2.64%.

For northwest-southeast and west-east axis, U geometry generate the lowest sensible cooling load in courtyard L/W of 1 and 1.5. Changing Double U geometry to U geometry will decrease building sensible cooling load of 3.77% on courtyard building with L/W ratio 2, elongated alongside northwest-southeast axis. When the building has courtyard L/W of 1 elongated towards northwest-southeast axis, Double L geometry generate the lowest cooling load and generate lower sensible cooling load of 1.28%. On the other hand, Quadruple L geometry generate the highest sensible cooling load northwest-southeast orientation with three different courtyard L/W, which increase the sensible cooling load up to 1.32%.

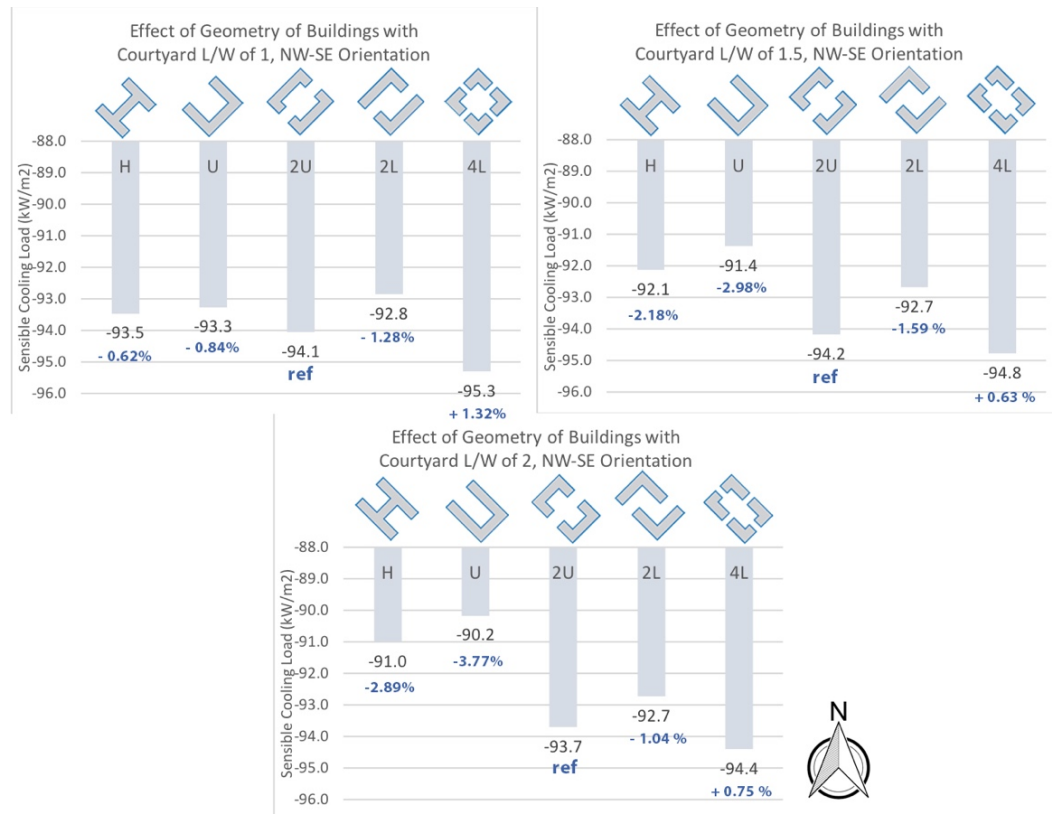


Figure 4.28 Effect of Building Geometry on Sensible Cooling Load, Northwest - Southeast Orientation

On west-east orientation with courtyard L/W of 1 and 1.5, Quadruple L geometry generate highest sensible cooling load, and increase the sensible cooling load of 0.495 and 0.04%, respectively. for courtyard L/W of 2 west-east, Double U

geometry generate the highest cooling load. For building with courtyard L/W of 2 west-east orientation, Double U geometry generate the highest cooling load. On the other hand U geometry generate lower sensible cooling load, when the building is elongated alongside west-east axis. . Changing Double U geometry to U geometry will decrease building sensible cooling load of 4.61% on courtyard building with L/W ratio 2.

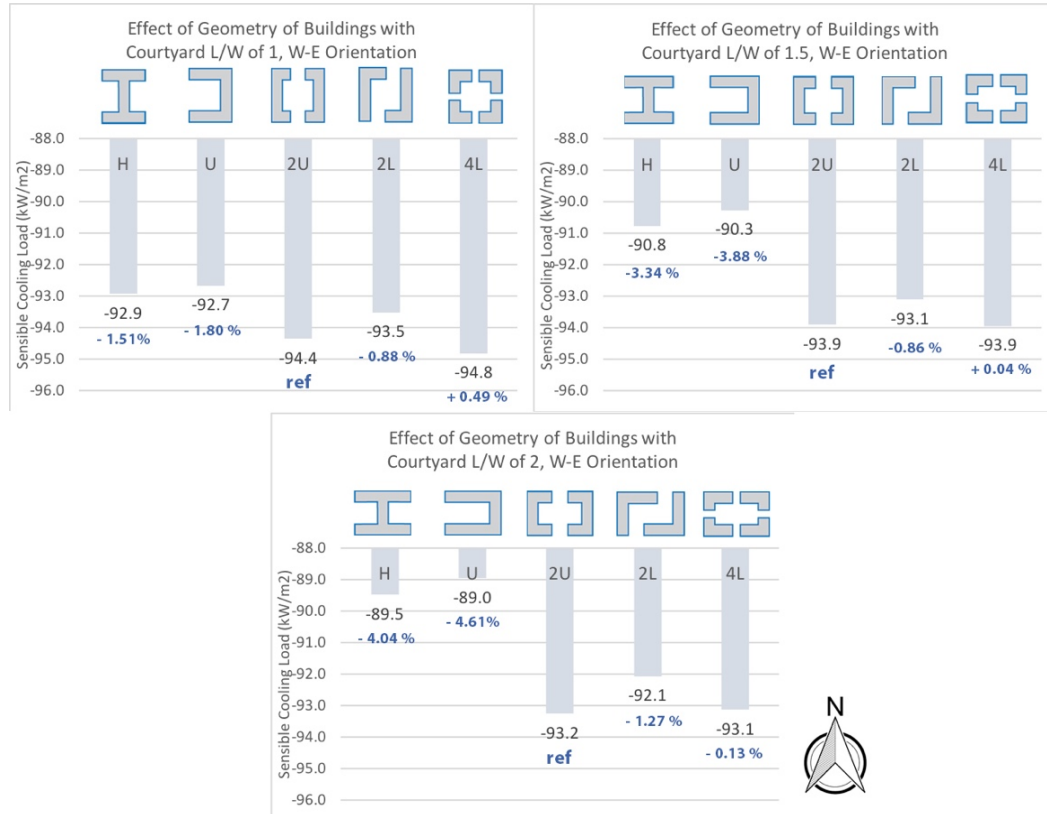


Figure 4.29 Effect of Building Geometry on Sensible Cooling Load, West-East Orientation

b. Effect of Courtyard L/W on Sensible Cooling Load

In general, changing the courtyard L/W from 1 to 2 will lower the sensible cooling load up to 4%. However, when Double U, Double L, and Quadruple L geometries are elongated alongside north-south axis, sensible cooling load will increase up to 1.82%. According to the result of sensible cooling load, H and U geometries are more sensitive when the courtyard is elongated, than the other three geometries. Increasing courtyard L/W from 1 to 2 in all orientation, could decrease sensible cooling load of H and U geometries up to 3.45 kWh/m² and 3.71 kWh/m²,

respectively, which is 4% lower sensible cooling load than H and U geometries with courtyard L/W of 1.

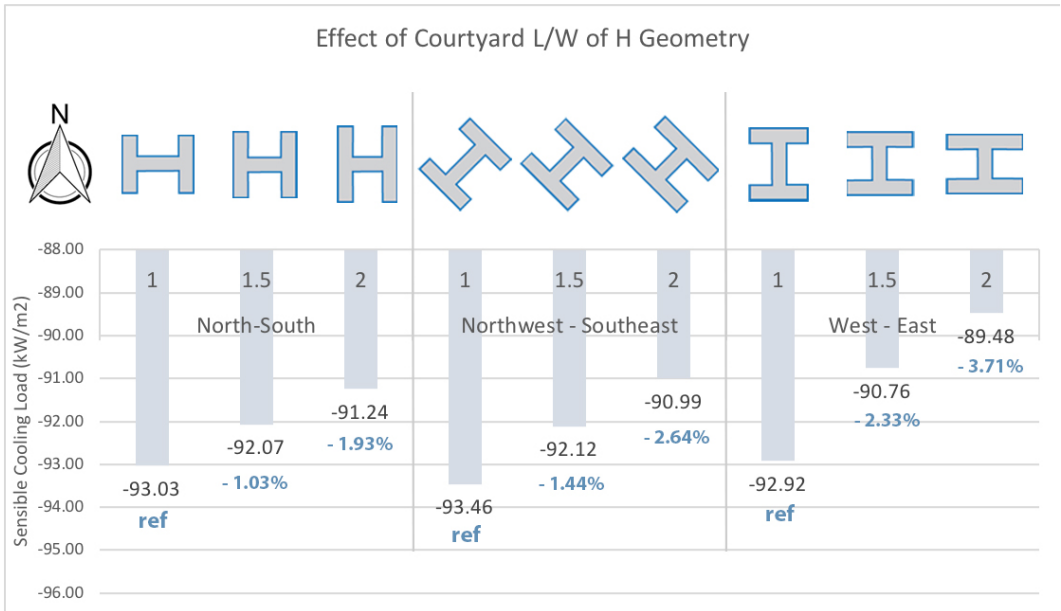


Figure 4.30 Effect of Courtyard L/W on Sensible Cooling Load, H Geometry

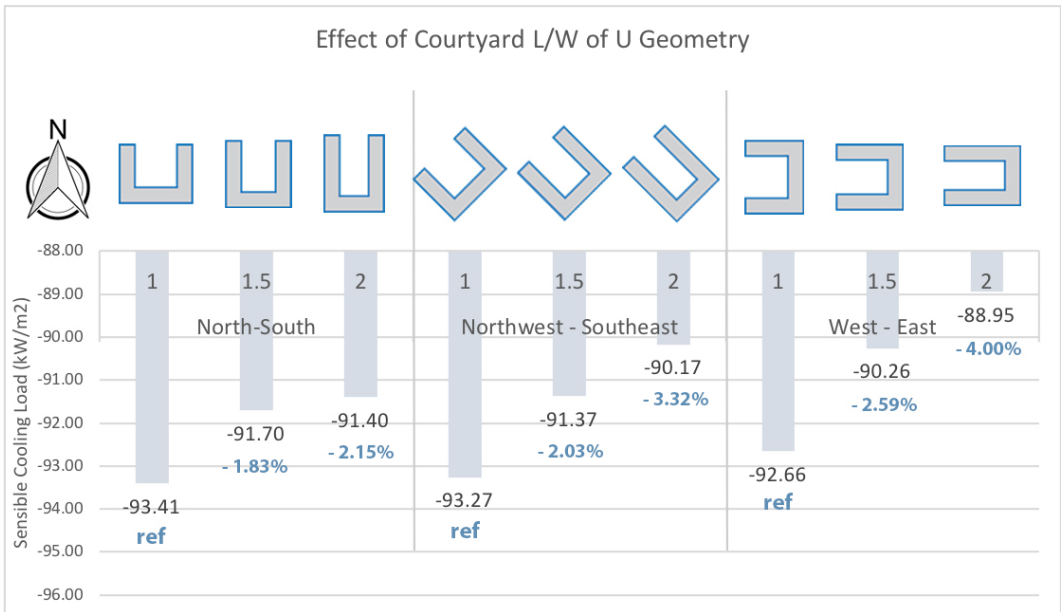


Figure 4.31 Effect of Courtyard L/W on Sensible Cooling Load, U Geometry

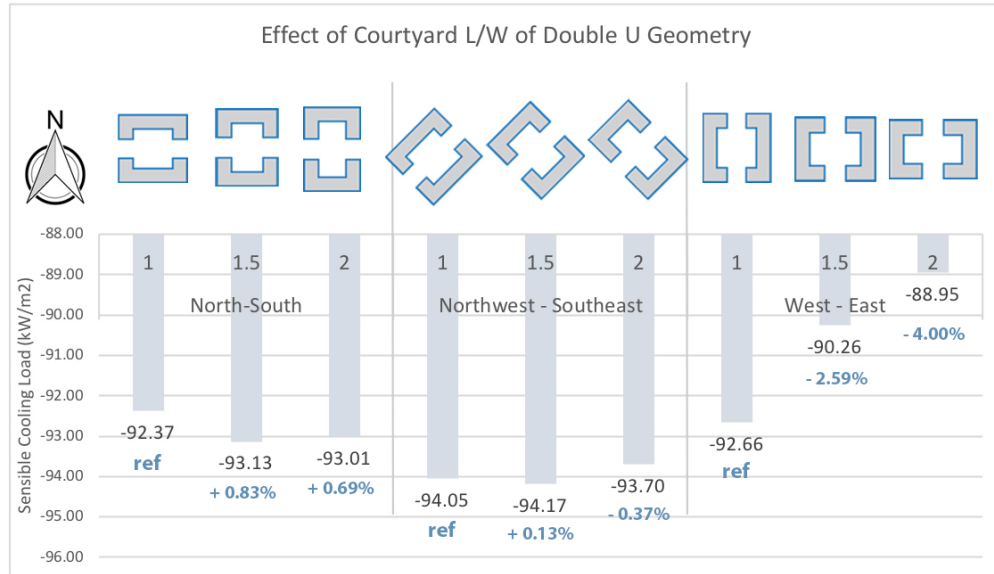


Figure 4.32 Effect of Courtyard L/W on Sensible Cooling Load, Double U Geometry

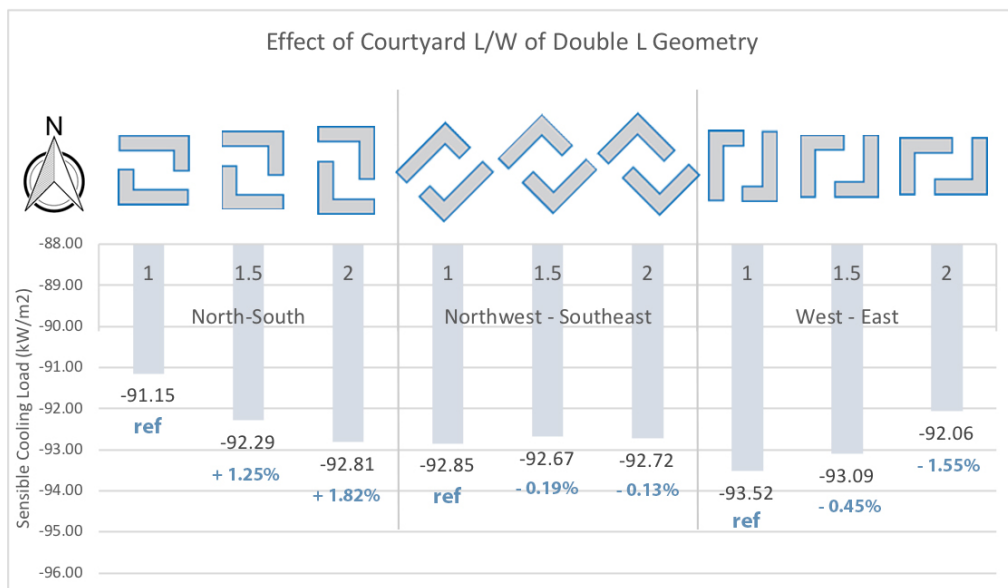


Figure 1 Effect of Courtyard L/W on Sensible Cooling Load, Double L Geometry

On the other hand, increasing courtyard L/W from 1 to 2 will decrease sensible cooling load of Double U, Double L, and Quadruple L geometries in northwest-southeast and west-east orientation, but increasing the sensible cooling load in north-south orientation. However, the impact of elongating the courtyard for Double U, Double L, and Quadruple L geometries are not much compared to H and U geometries. Increasing courtyard L/W from 1 to 2, could decrease sensible cooling load of Double U up to 4% (3.71 kWh/m²) when the building is elongated alongside west-east axis. However increasing courtyard L/W of Double U geometry

has lower impact on northwest-southeast orientation, which reduce sensible cooling load about 0.19% only. Similar with Double U, increasing courtyard L/W of Double L, and Quadruple L geometries on west-east orientation generate higher reduction of sensible cooling load of 1.55% and 1.77%, respectively.

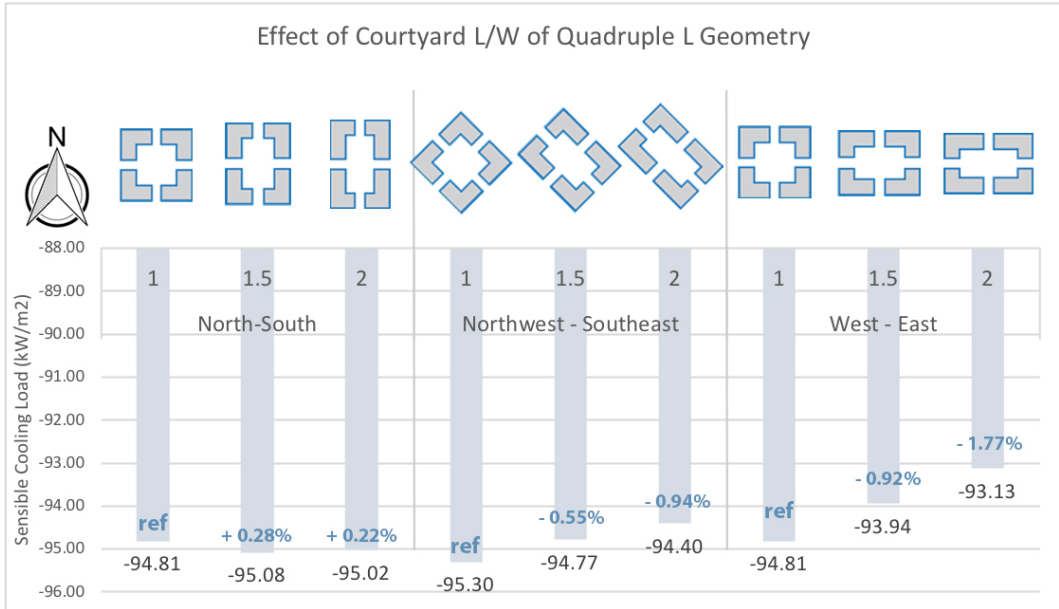


Figure 4.34 Effect of Courtyard L/W on Sensible Cooling Load, Quadruple L Geometry

c. Effect of Building Orientation on Sensible Cooling Load

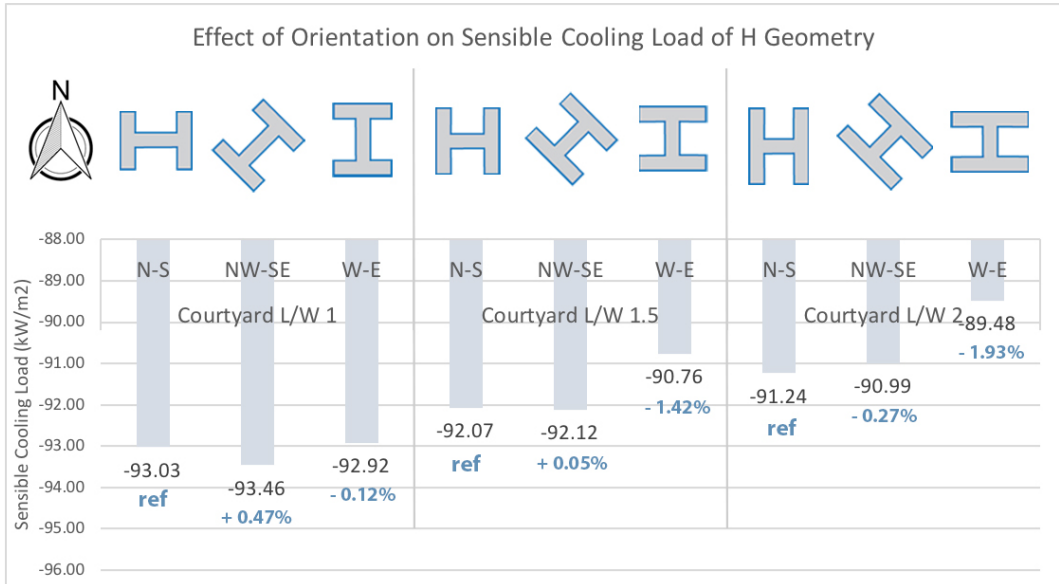


Figure 4.35 Effect of Building Orientation on Sensible Cooling Load, H Geometry

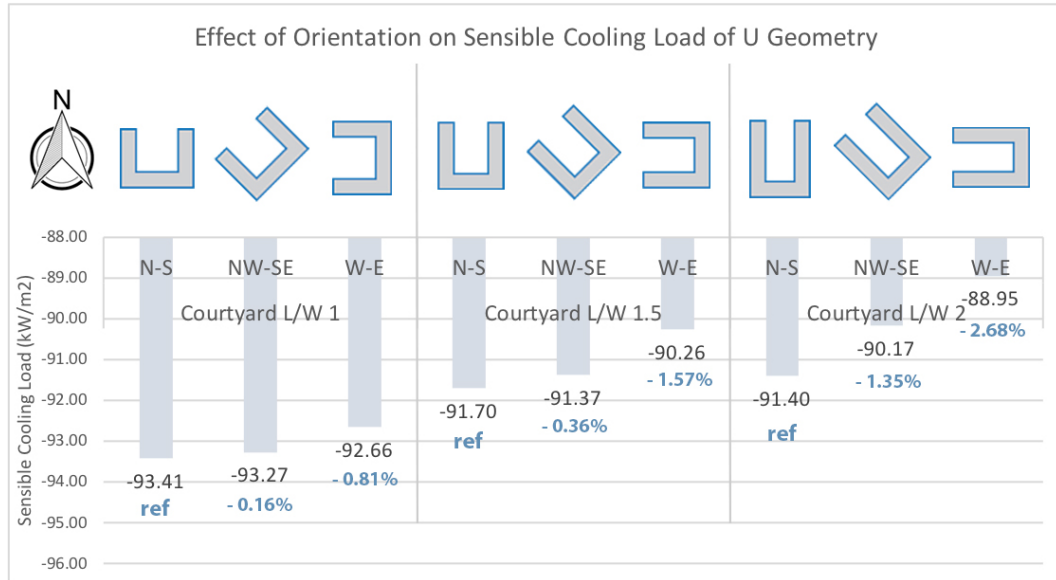


Figure 4.36 Effect of Building Orientation on Sensible Cooling Load, U Geometry

The impact of changing the building orientation is different in five different geometries, however H and U geometries show almost similar pattern. When the building orientation is changed from north-south to west-east, the building sensible cooling load decrease for H and U geometries in different courtyard aspect ratio. The highest reduction of changing orientation from north-south to west-east is shown by H and U geometries with courtyard L/W of 2, which reduce sensible cooling load of 1.93% (1.76 kWh/m²) and 2.68% (2.45 kWh/m²), respectively.

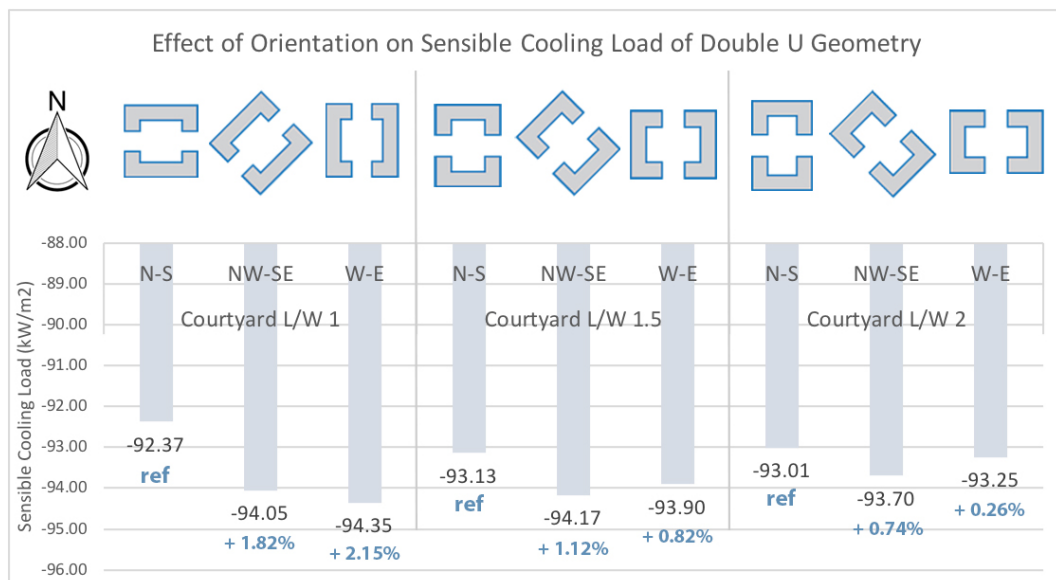


Figure 4.37 Effect of Building Orientation on Sensible Cooling Load, Double U Geometry

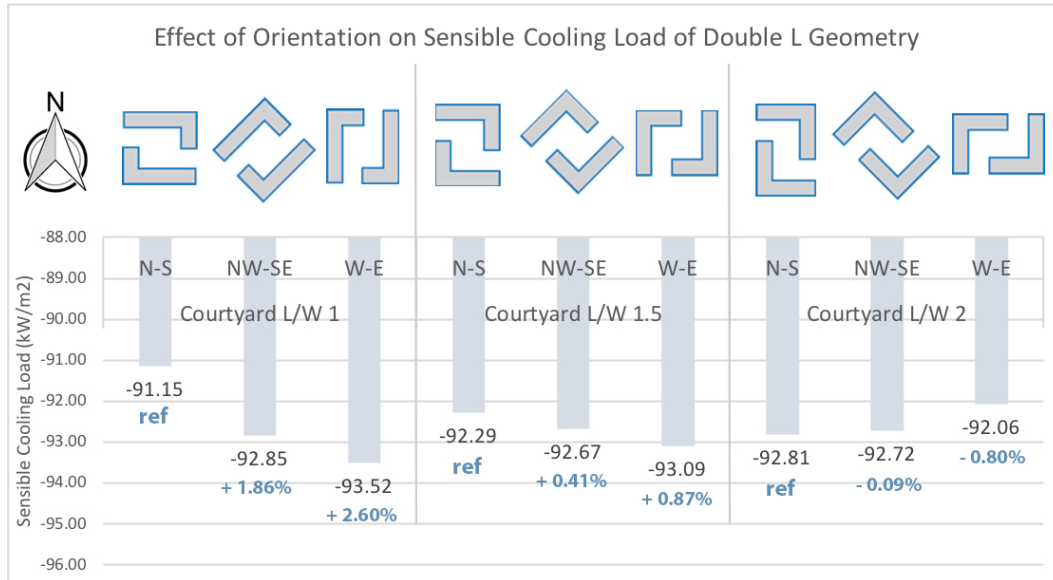


Figure 4.38 Effect of Building Orientation on Sensible Cooling Load, Double L Geometry

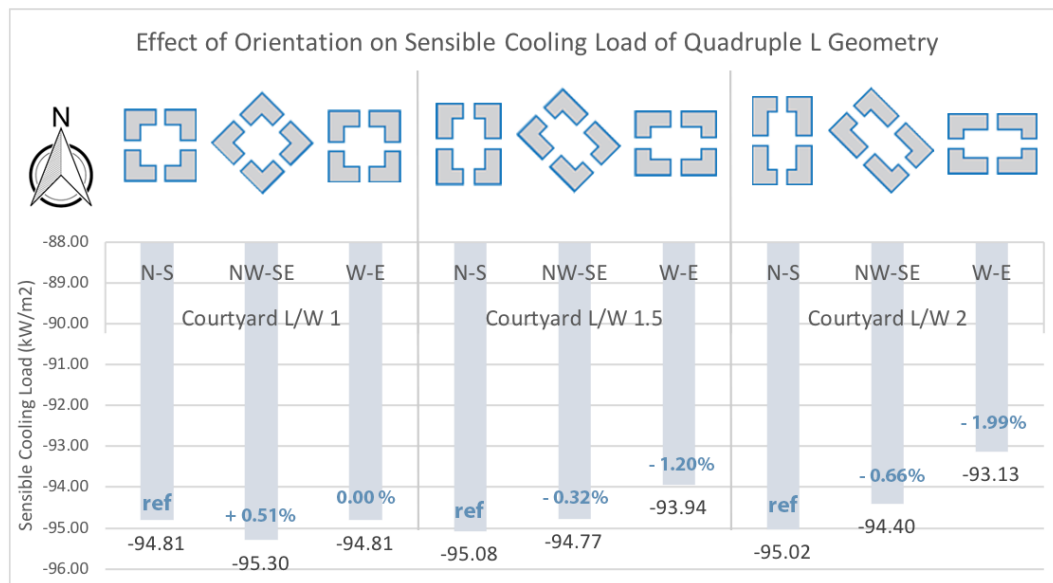


Figure 4.39 Effect of Building Orientation on Sensible Cooling Load, Quadruple L Geometry

For Double U and Double L geometries, changing the building orientation from north-south to west-east will have the highest impact when the building has a courtyard L/W of 1, which increases the sensible cooling load by 2.15% (1.98 kWh/m²) and 2.6% (2.37 kWh/m²), respectively. Changing orientation for Double U with a courtyard L/W of 1.5 and 2 will slightly increase the sensible cooling load. For Double L building, changing the building orientation from north-south to west-east will increase the sensible cooling load by 0.87%, when the building has

courtyard L/W of 1.5, and decrease the sensible cooling load of 0.80%, when the building has courtyard L/W of 2. In addition, shifting the building orientation from north-south to west-east will decrease the sensible cooling load of Quadruple L geometry with courtyard L/W of 1.5 and 2, about 1.2% (1.14 kWh/m²) and 1.99% (1.89 kWh/m²), respectively.

4.4.2 Latent Cooling Load

Latent cooling load is cooling load related to latent heat, which is not related to the changing of temperature unlike sensible heat. Latent cooling load is influenced by volume flow or air, and moisture content of the air. Therefore, one of the factors that influence the latent heat load is infiltration gain. According to the linear regression analysis, latent cooling load has highest relationship with infiltration gain when the building is elongated alongside north-south axis. Based on the climate data of Surabaya, the wind flow are mostly come from west or east side. When the building is elongated alongside north-south axis, the longest side of the building are facing west and east side, thus increasing the exposure of upcoming wind. As a result, as explained in 4.3.2, infiltration heat gain on north-south orientation is higher than the other orientation.

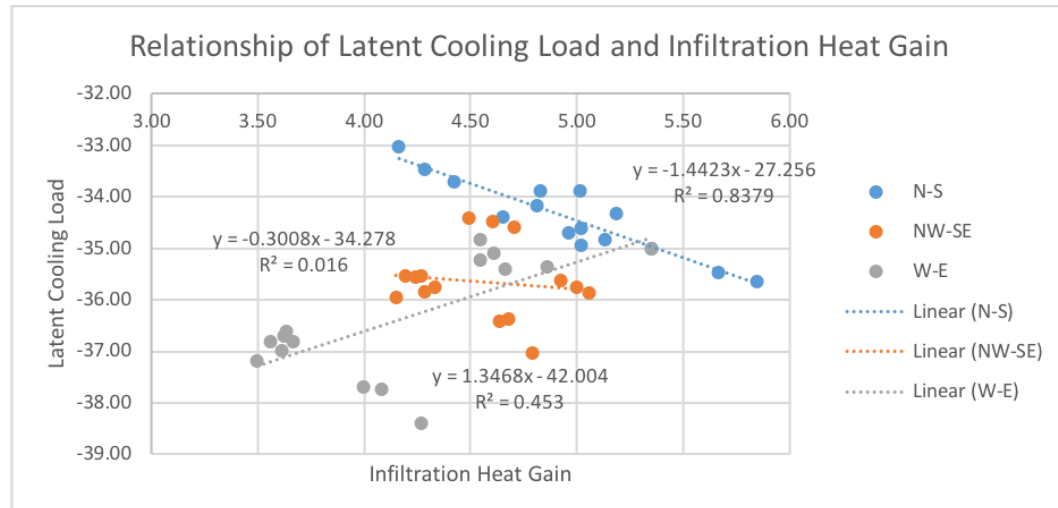


Figure 2 Relationship of Latent Cooling Load and Infiltration Heat Gain

Similar with sensible cooling load, results of Design Builder simulation mark latent cooling load in negative number, and heat gain in positive number. Annual cooling energy is the sum of sensible and latent cooling load, in the form

of absolute value. Therefore, the lower latent cooling load of a building, the annual cooling energy will increase

a. Effect of Building Geometry on Latent Cooling Load

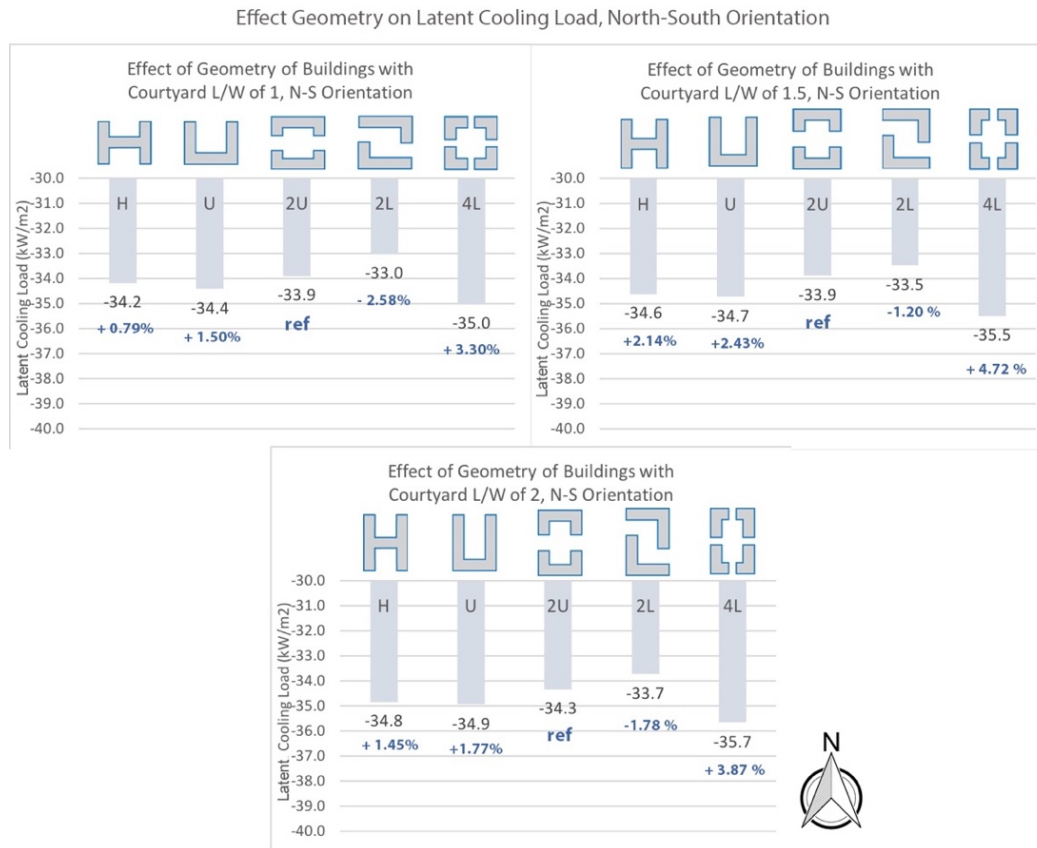


Figure 4.41 Effect of Building Geometry on Latent Cooling Load, North-South Orientation

Among five building geometries investigated, Double L geometries tend to generate the lowest latent cooling load in three different orientation and courtyard L/W, except when building with courtyard L/W is elongated alongside west-east axis, Quadruple L building has slightly lower latent cooling load. Changing from Double U geometry to Double L geometry could reduce latent cooling load up to 2.58%, 6.62%, and 7.91% in north south, northwest-southeast, and west-east orientation respectively. Effect of reducing latent cooling load of Double L geometry is the highest when the building has courtyard L/W of 1.

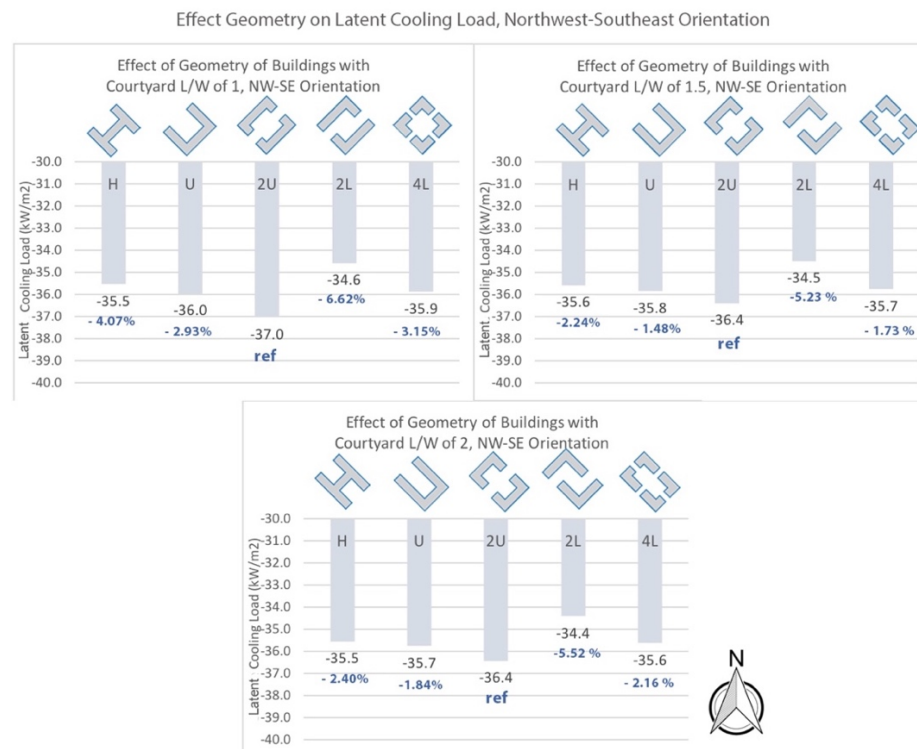


Figure 4.42 Effect of Building Geometry on Latent Cooling Load, Northwest-Southeast Orientation

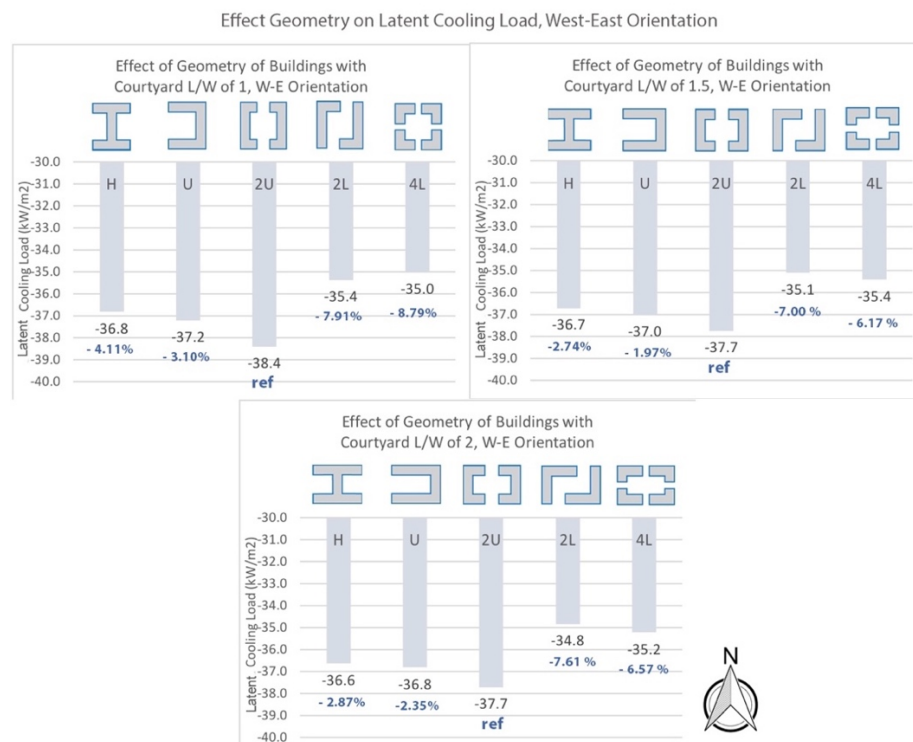


Figure 4.43 Effect of Building Geometry on Latent Cooling Load, West-East Orientation

Quadruple L building generate the highest latent cooling energy on north-south orientation with three different courtyard aspect ratio. Changing from Double U geometry to Quadruple L geometry could increase latent cooling load up to 4.72%, when the building is elongated alongside north-south axis. For northwest-southeast and west-east orientation, Double U geometry generate the highest latent cooling energy in three different courtyard aspect ratio.

a. Effect of Courtyard L/W on Latent Cooling Loads

Effect of increasing courtyard L/W on latent cooling load is small compared to effect of changing building orientation on latent cooling load. Increasing courtyard L/W from 1 to 2 of five different geometries studied has the highest impact when the building is elongated alongside north-south axis, except Double U geometry which has the highest impact on west-east orientation, which reduce latent cooling load of 1.79%. For H, U, Double L, and Quadruple L, increasing courtyard L/W from 1 to 2 on north-south orientation will increase 1.94%, 1.56%, 2.11%, and 1.84% latent cooling load, respectively.

On the contrary with elongating the courtyard on north-south orientation, increasing courtyard L/W from 1 to 2 in west-east and northwest-southeast orientation, will decrease latent cooling load of four geometries studied about 0.3% up to 1.79% (0.04 – 0.69 kWh/m²), except Quadruple L geometry elongated alongside west-east axis, and H geometry elongated alongside northwest-southeast axis, which result in increasing 0.6% , and 0.03% latent cooling load.

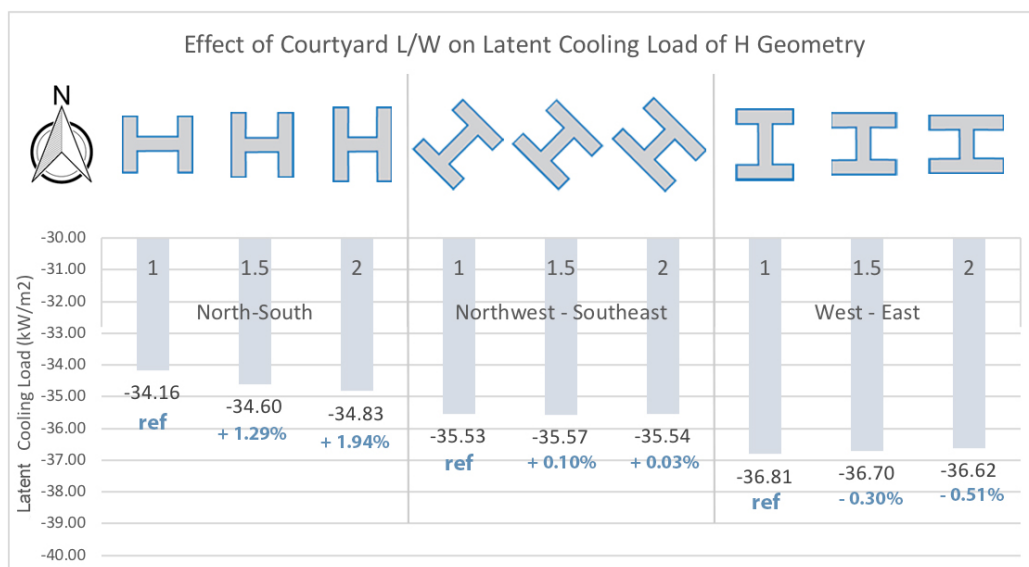


Figure 4.44 Effect of Courtyard L/W on Latent Cooling Load, H Geometry

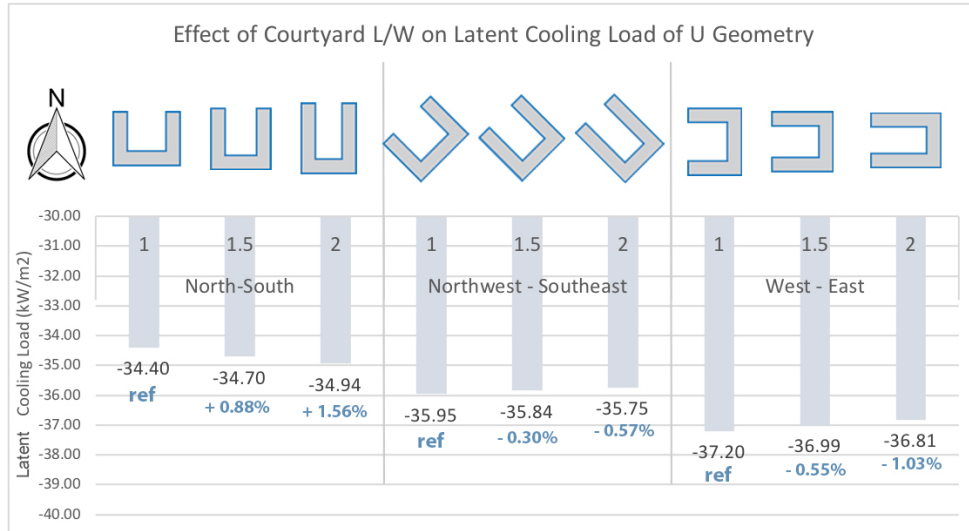


Figure 4.45 Effect of Courtyard L/W on Latent Cooling Load, U Geometry

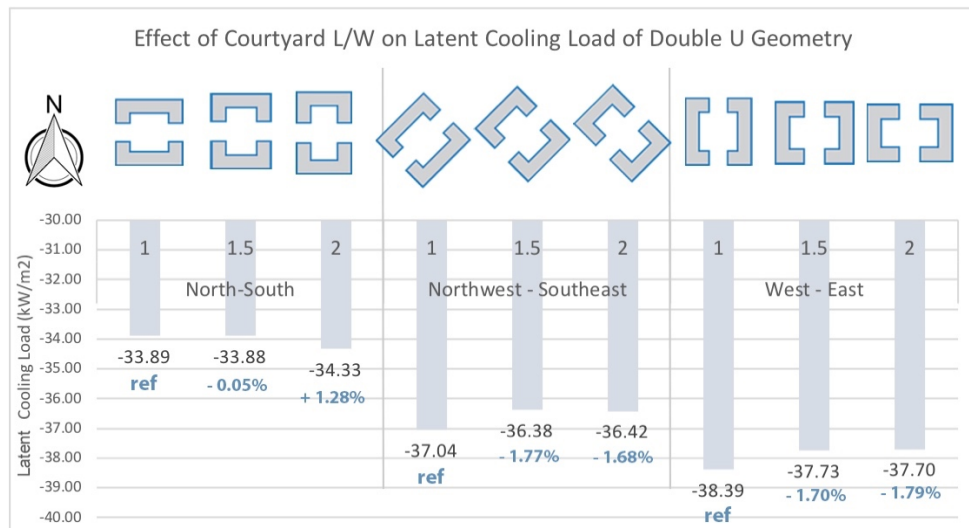


Figure 4.46 Effect of Courtyard L/W on Latent Cooling Load, Double U Geometry

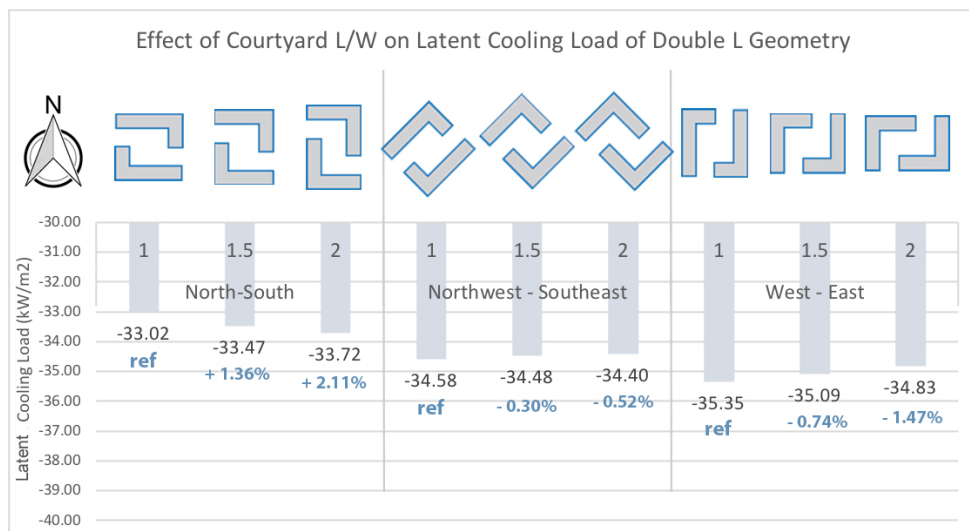


Figure 4.47 Effect of Courtyard L/W on Latent Cooling Load, Double L Geometry

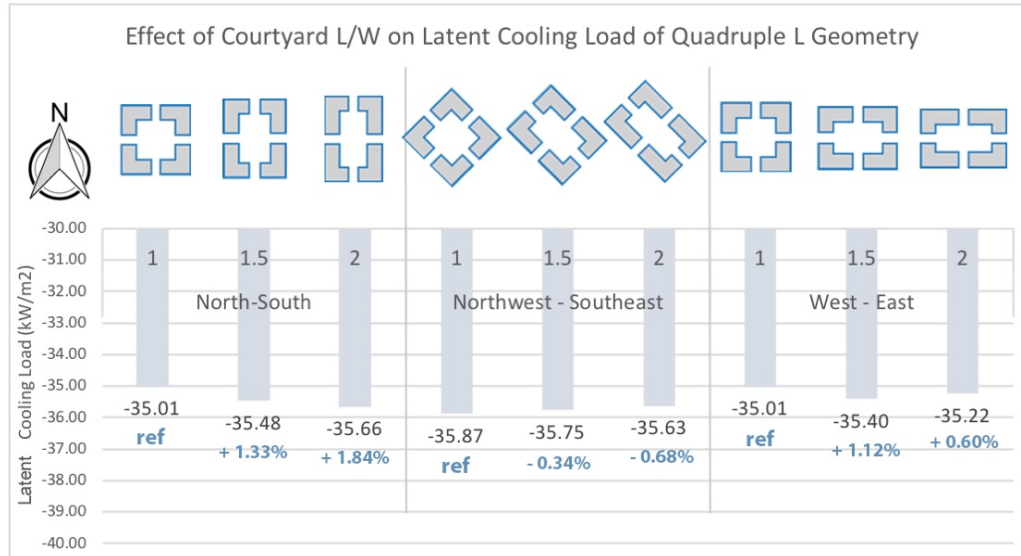


Figure 4.48 Effect of Courtyard L/W on Latent Cooling Load, Quadruple L Geometry

a. Effect of Building Orientation on Latent Cooling Load

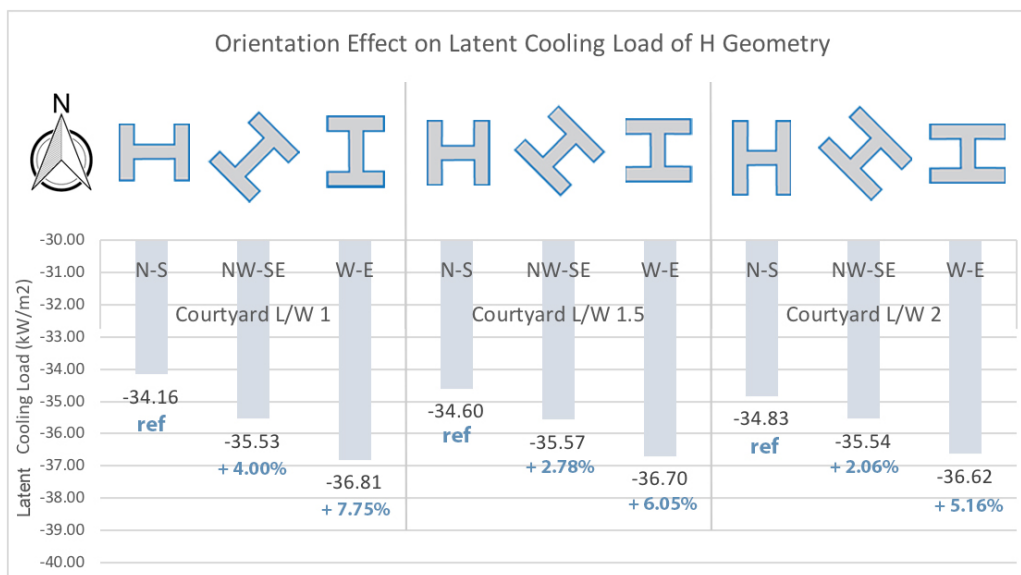


Figure 4.49 Effect of Building Orientation on Latent Cooling Load, H Geometry

Similar with the result of infiltration gain of model experiments, the impact of changing the building orientation is much higher compared to the impact of increasing the courtyard aspect ratio for building latent cooling load. Changing the building orientation from north-south to west-east will increase latent cooling load of all geometries, except Quadruple L geometry, in which the latent cooling load decreases. Double U geometry experiences the highest change when the building orientation is changed from north-south to west-east, increasing latent cooling load

up to 13.25% (3.37 – 4.49 kWh/m²). followed by U, H, and Double L geometries with increasing latent cooling load up to 8.13% (1.88 – 2.80 kWh/m²), 7.75% (1.80 – 2.65 kWh/m²), and 7.06% (1.12 – 2.33 kWh/m²), respectively. The impact of changing orientation of H, U, Double U, and Double L geometries has the highest rate of latent cooling load, when these geometries have courtyard aspect ratio of 1.

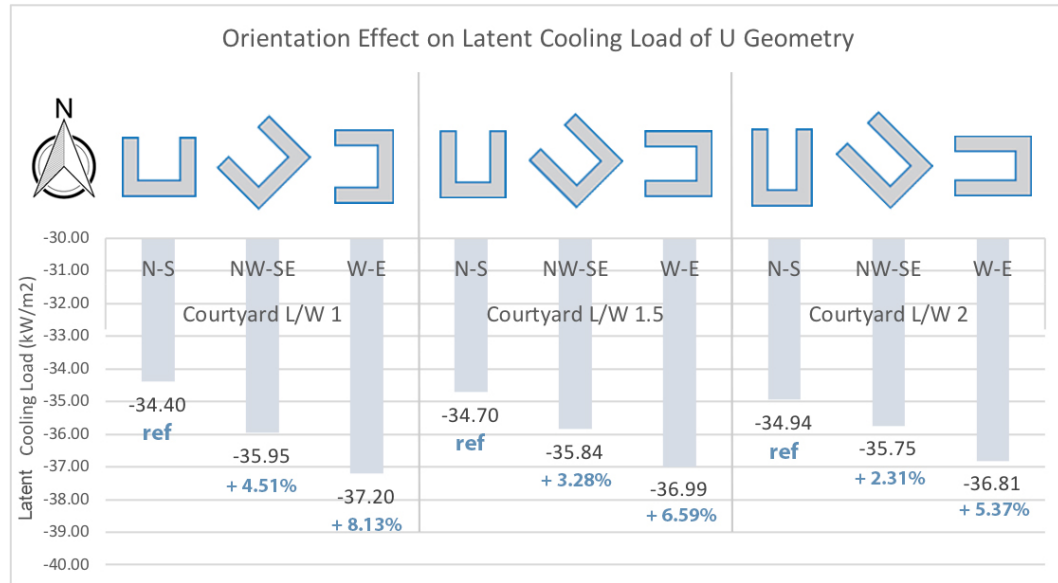


Figure 4.50 Effect of Building Orientation on Latent Cooling Load, U Geometry

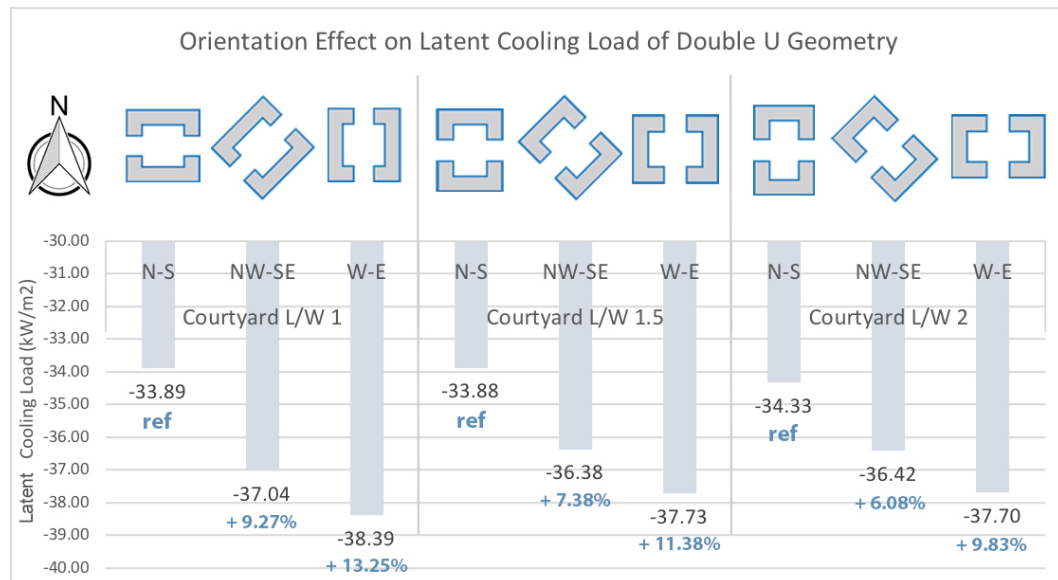


Figure 4.51 Effect of Building Orientation on Latent Cooling Load, Double U Geometry

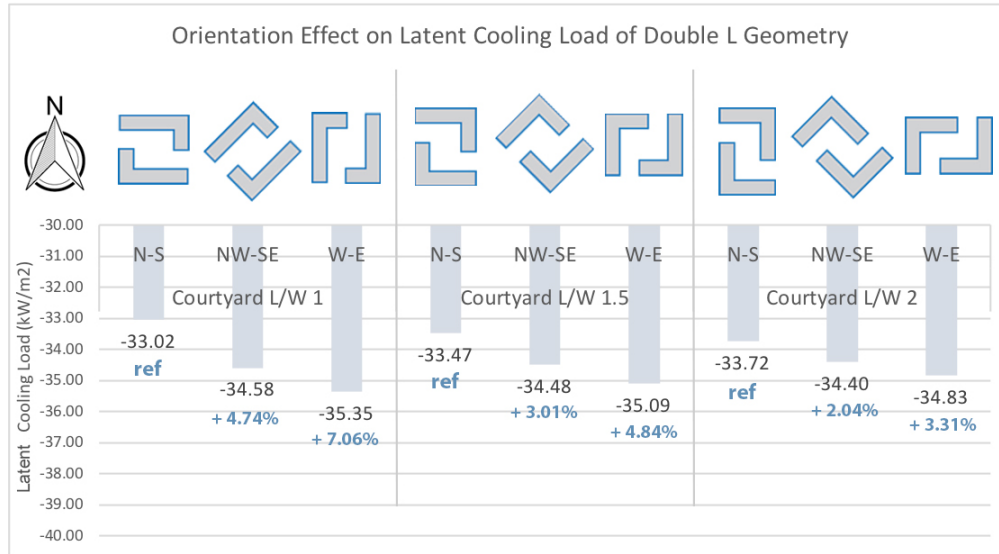


Figure 4.52 Effect of Building Orientation on Latent Cooling Load, Double L Geometry

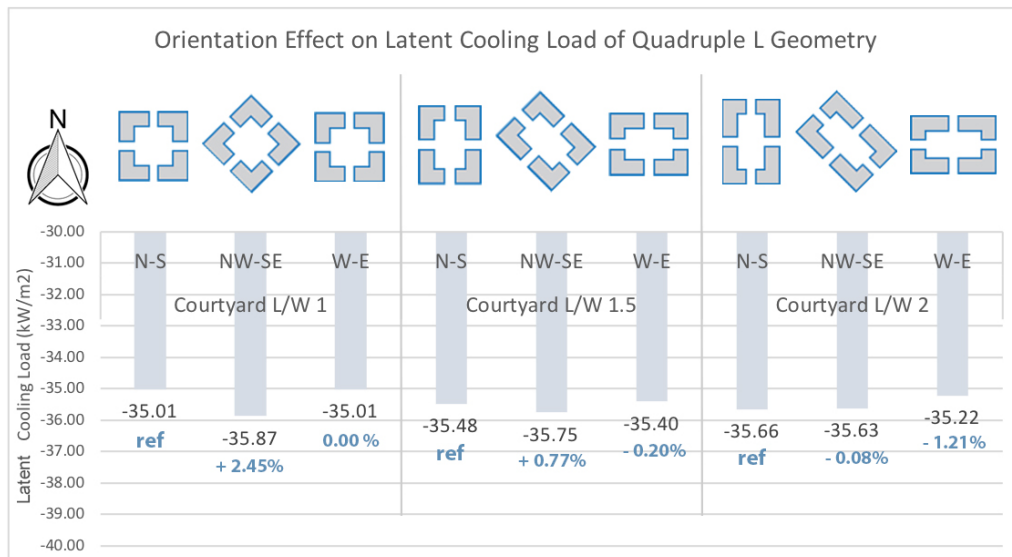


Figure 4.53 Effect of Building Orientation on Latent Cooling Load, Quadruple L Geometry

On the other hand, changing the building orientation from north-south to west-east of Quadruple L geometry will decrease latent cooling load up to 1.21%. ($0.34 - 0.86 \text{ kWh/m}^2$). The impact of changing orientation of Quadruple L geometry with courtyard aspect ratio of 1 and 1.5, will increase the latent cooling load of 2.45%, and 0.77% respectively, when the building is elongated alongside northwest-southeast axis. Changing orientation of Quadruple L geometry with courtyard L/W of 2, will decrease the latent cooling load on both northwest-southeast and west-east orientation.

4.5 Annual Cooling Energy of Model Experiments

Shape	Courtyard L/W	Annual Cooling Energy (kWh/m ² /yr)		
		N-S	NW-SE	W-E
H-shaped	1	127.19	128.99	129.73
	1.5	126.67	127.68	127.46
	2	126.06	126.54	126.1
U-shaped	1	127.81	129.22	129.85
	1.5	126.4	127.21	127.25
	2	126.34	125.91	125.76
double U	1	126.26	131.09	132.74
	1.5	127.01	130.55	131.63
	2	127.34	130.12	130.95
double L	1	124.17	127.43	128.87
	1.5	125.76	127.15	128.18
	2	126.53	127.13	126.9
quadruple L	1	129.82	131.17	129.82
	1.5	130.55	130.52	129.34
	2	130.68	130.03	128.35

According to annual cooling energy simulation, the Model Experiments consume cooling energy between 124.17 – 132.74 kWh/m²/yr. Model experiment with lowest annual cooling energy, reduce the energy consumption of 8.57 kWh/m² annually, which is 6.46% lower than the model with highest annual cooling energy. Model Double L with courtyard L/W of 1 elongated from north – south axis has the lowest annual cooling energy. On the other hand, model experiment which produce the highest cooling energy is model Double U with courtyard L/W of 1, elongated from west – east axis.

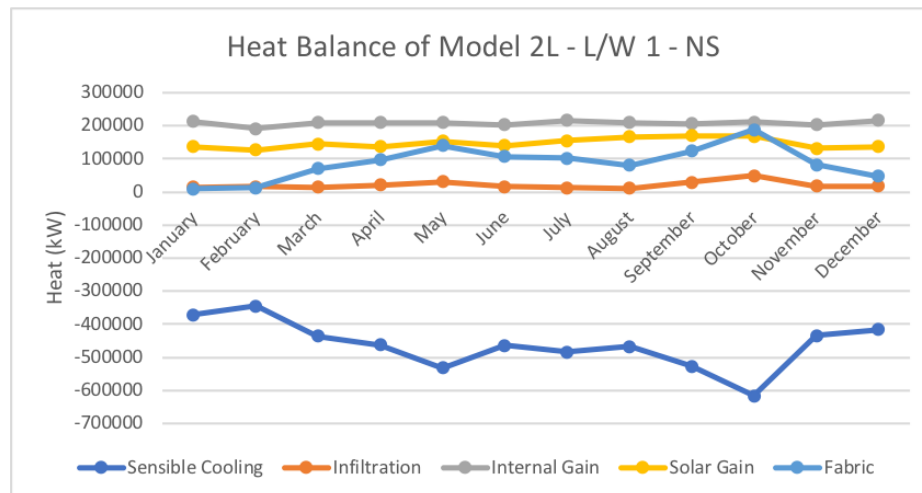


Figure 4.54 Heat Balance of Model Double L, Courtyard L/W 1, North South

Orientation

According to heat transfer figure of model 2L-1-NS and 2U-1-WE, heat gain from the building fabric greatly influence building cooling energy. Building fabric include the building element such as, glazing, walls, partition, ceiling, and roof. Heat gain from the building fabric reach its peak in October and fall down to its lowest point in January similar with hottest and coolest month of Surabaya during 2017.

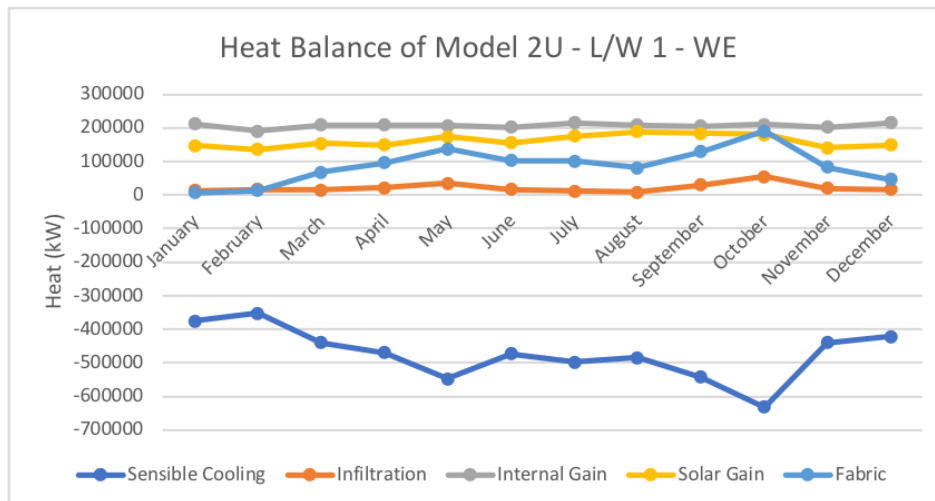


Figure 4.55 Heat Transfer of Model Double U, Courtyard L/W 1, West East Orientation

4.5.1 Performance of Base Case Model

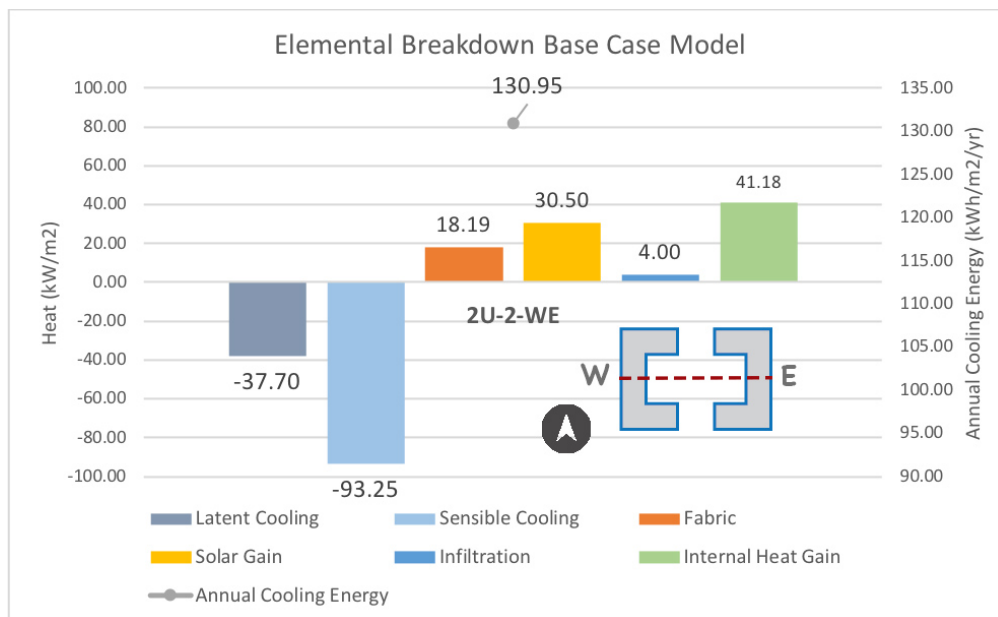


Figure 4.56 Elemental Breakdown of Base Case Model

Double U geometry with courtyard L/W of 2 elongated alongside west east axis (2U-2-WE) is chosen as the base case model in this study, because it has similar building characteristic, such as courtyard aspect ratio, building orientation, and building height just like Bale Hinggil Apartment. Annual cooling energy of base case model is 130.95 kWh/m² yr.

4.5.2 Effect of Building Geometry on Annual Cooling Energy

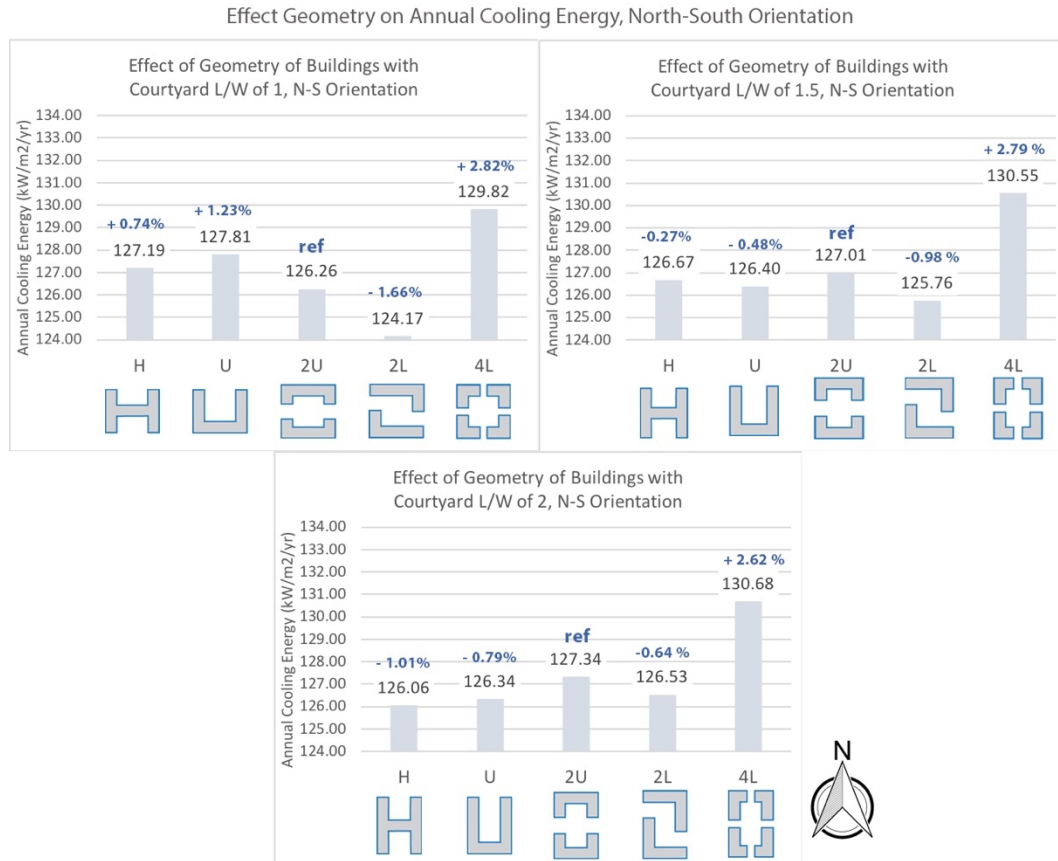


Figure 4.57 Effect of Building Geometry on Annual Cooling Energy, North-South Orientation

Among five different building geometries investigated, Double U and Quadruple L Geometries tend to have higher annual cooling energy than the other three geometries. Among five different geometries elongated along north-south axis, Quadruple L has the highest cooling energy consumption than the other geometries. Changing building geometry of Double U to Quadruple L on north-south orientation will increase the annual energy consumption up to 2.82%. On the other hand, Double U geometries generate the highest cooling energy consumption, when the model experiments are elongated alongside west-east axis. Among five

different building geometries elongated alongside north-south axis, Double L geometry generates the lowest annual cooling energy when the courtyard L/W is 1, and 1.5. H geometry generate the lowest annual cooling energy when the courtyard L/W is 2, north south orientation, with reduction of 1.01% annual cooling energy.

Similar with geometries on north south orientation, Quadruple L geometry with courtyard L/W of 1 and 1.5 generate the highest cooling energy consumption when the building is elongated alongside northwest-southeast axis, and Double U geometry has the highest annual cooling energy demand with courtyard L/W of 2. However in this orientation, Quadruple L and Double U geometries generate almost similar annual energy consumption. Quadruple L geometry generate only up to 0.06% higher, and 0.07% lower annual cooling energy compared to Double U geometry.

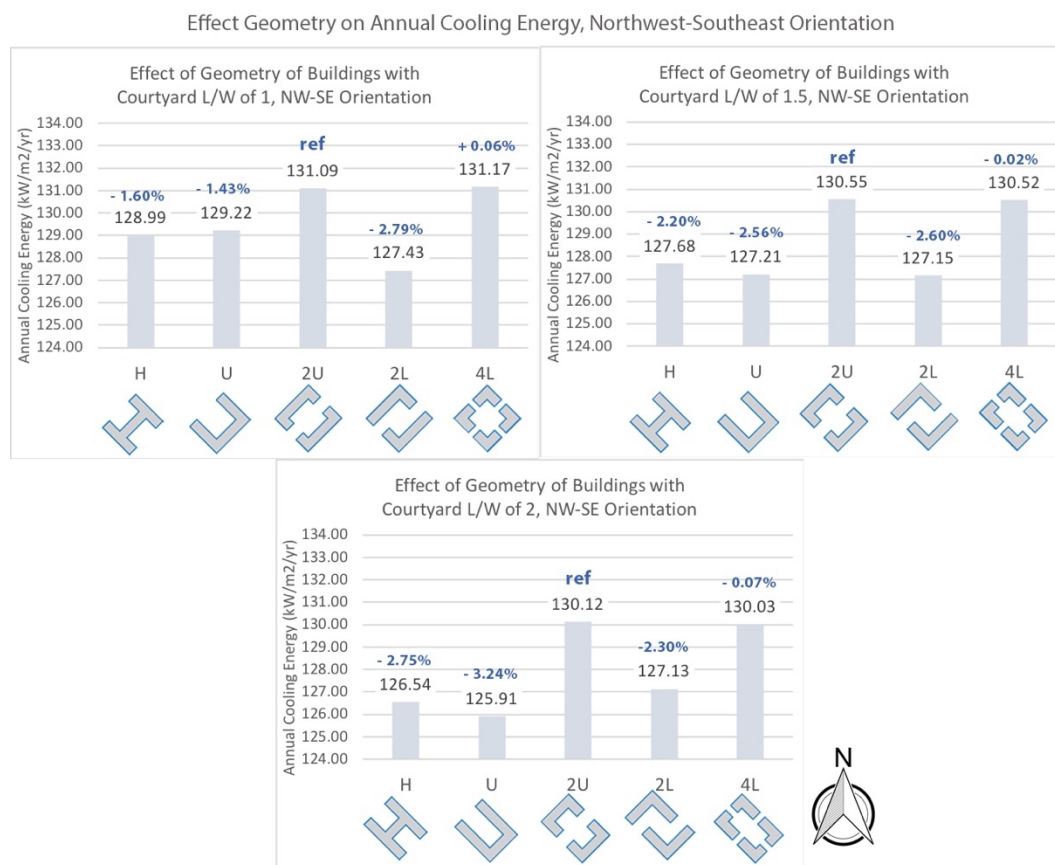


Figure 4.58 Effect of Building Geometry on Annual Cooling Energy, Northwest-Southeast Orientation

When building with courtyard L/W of 2 is elongated alongside northwest southeast axis, U Geometry generates minimum annual cooling energy with

courtyard L/W of 2. Changing building geometry of Double U to U geometry with courtyard L/W of 2 on north-south orientation will decrease the annual energy consumption up to 3.24%. Double L geometry generate the lowest annual cooling energy with courtyard L/W of 1, and 1.5 on north-south orientation, with reduction of annual cooling energy of 2.79%, and 2.6% respectively.

For buildings elongated alongside west-east axis, Double U geometry generate the highest annual cooling energy with three different courtyard aspect ratio. On the other hand, U Geometry, elongated alongside west-east axis, generates minimum annual cooling energy when the courtyard L/W is 1.5, and 2, with reduction of annual cooling energy of 3.33% and 3.96% respectively compared to Double U geometry.

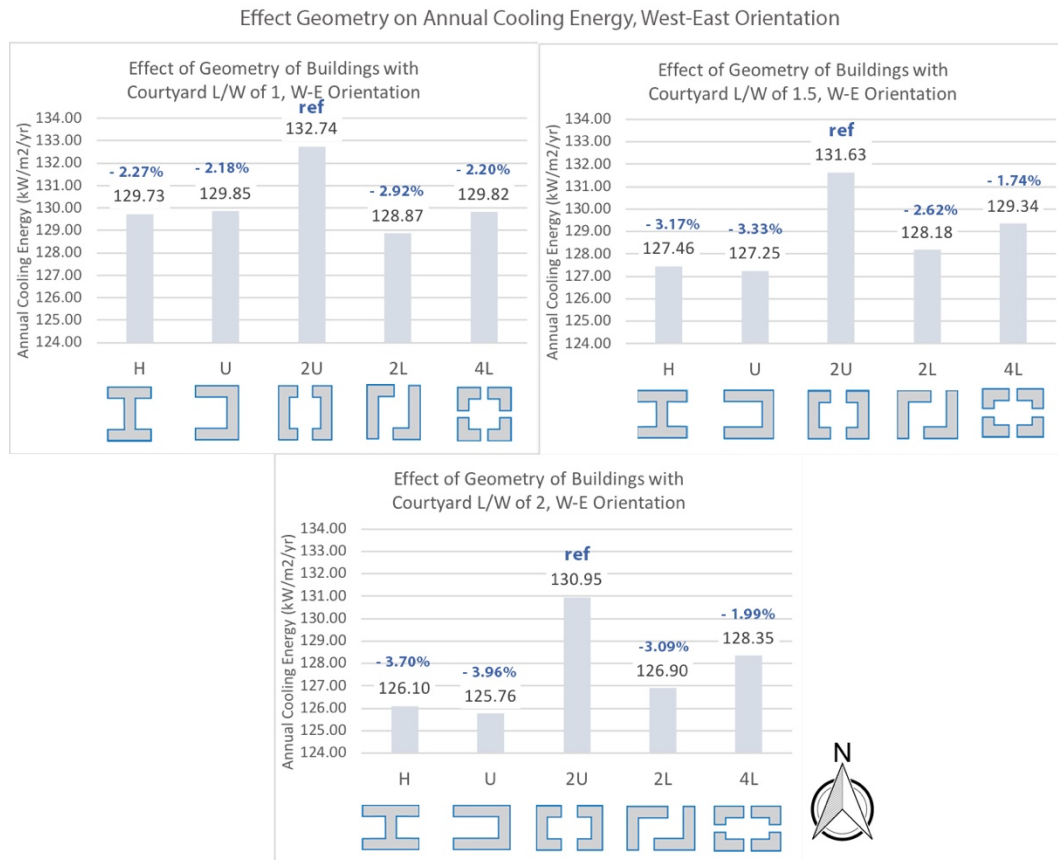


Figure 4.59 Effect of Building Geometry on Annual Cooling Energy, West-East Orientation

4.5.3 Effect of Courtyard L/W on Cooling Energy

In general, courtyard with L/W of 2 result in lower annual cooling energy of buildings. Influence of courtyard L/W is significant on H and U geometries

oriented to west east, which could reduce cooling energy consumption up to 2.8% (3.63 kWh/m² yr) and 3.15% (4.09 kWh/m² yr) respectively. However, there are some cases where longer courtyard result in higher energy consumption. Increasing courtyard length of Double U, Double L, and Quadruple L geometries with north south orientation could increase cooling energy consumption up to 0.86%, 1.9%, and 0.66%, respectively. In addition, the effect of higher courtyard L/W is not significant on double L geometry oriented to northwest – southeast, which could reduce the cooling energy consumption only about 0.24%.

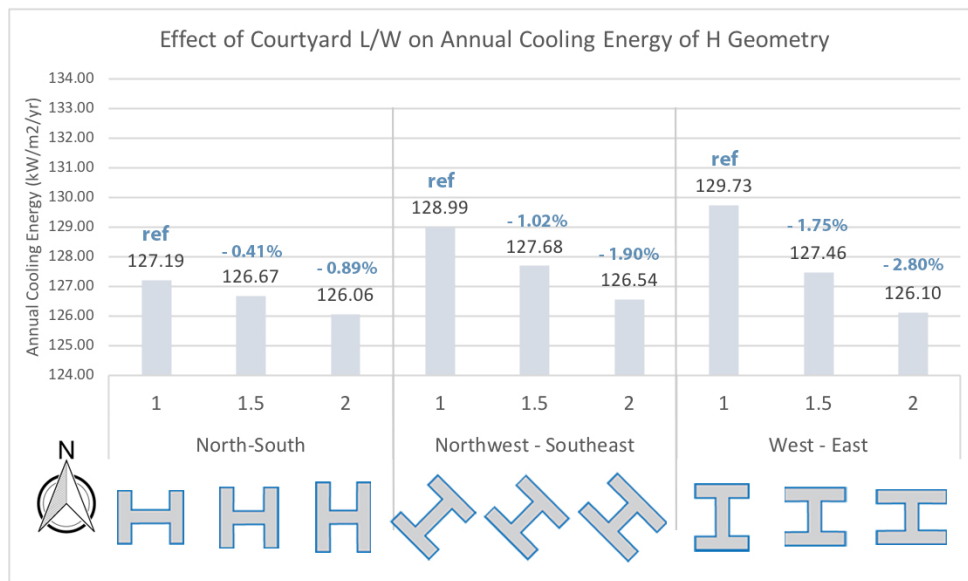


Figure 4.50 Effect of Courtyard L/W on Annual Cooling Energy, H Geometry

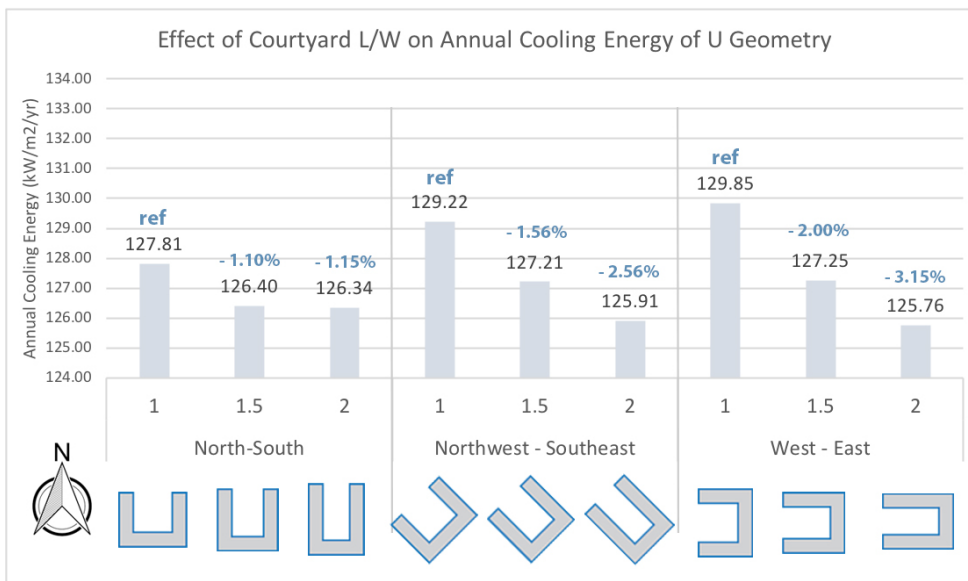


Figure 4.51 Effect of Courtyard L/W on Annual Cooling Energy, U Geometry

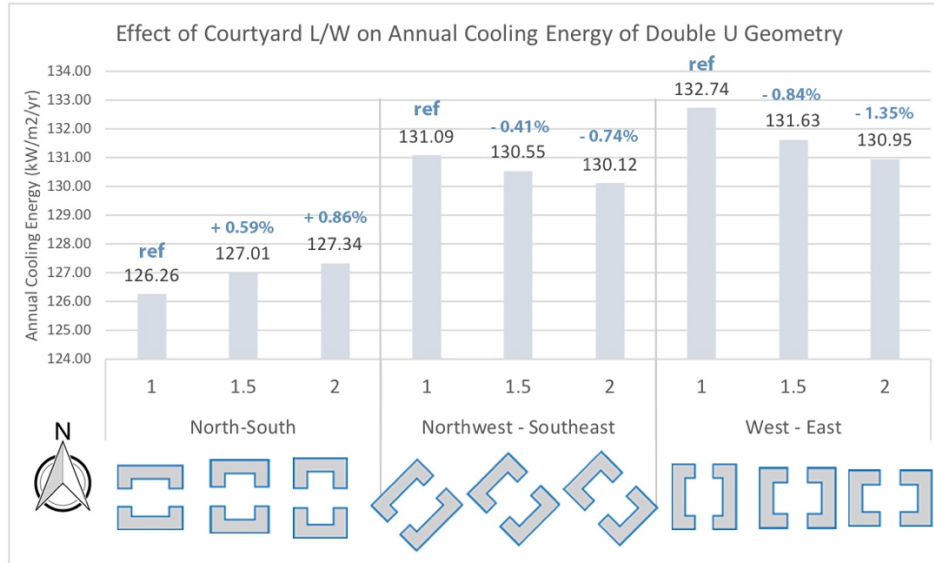


Figure 4.52 Effect of Courtyard L/W on Annual Cooling Energy, Double U Geometry

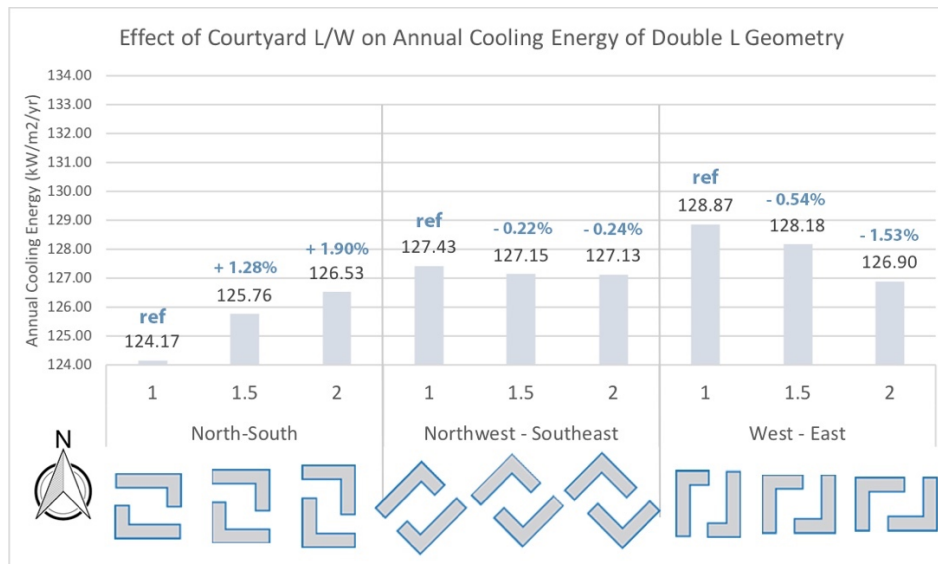


Figure 4.53 Effect of Courtyard L/W on Annual Cooling Energy, Double L Geometry

On the contrary with general result that elongating the courtyard will reduce annual cooling energy, in the case of Double U, Double L, and Quadruple L geometries with north south orientation, higher courtyard L/W result in higher annual cooling energy. This phenomenon could be the result of courtyard gaps present in Double U, Double L, and Quadruple L geometries are facing east and west side, allowing the solar radiation penetrating the courtyard area. On the other hand, for U and H geometries the open-ended courtyards are facing north and south,

similar with the building orientation. Courtyard of H and U geometries, which facing south and north receive less solar radiation than courtyard with opening facing west or east. In addition, for building geometries which consist of several blocks, such as Double U, Double L, and Quadruple L geometries, courtyard aspect ratio determine how close one tower toward the others, as a result courtyard L/W of 1, create more self-shading area than the longer courtyard.

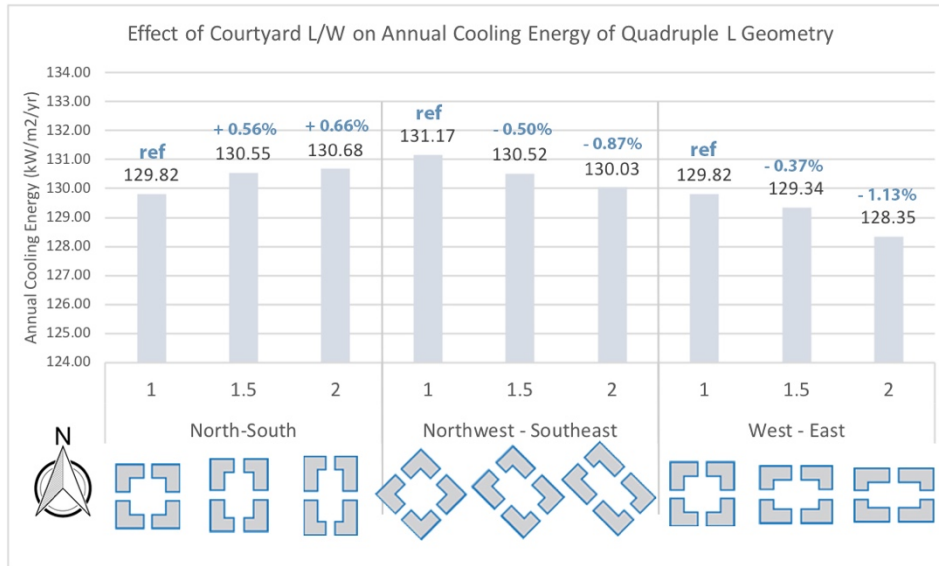


Figure 4.54 Effect of Courtyard L/W on Annual Cooling Energy, Double L Geometry

In order to investigate the impact of courtyard L/W on each building geometry, elemental breakdown of building heat gain and loss will be investigated according to the most significant orientation. As each building geometry with different courtyard L/W is simulated in three different orientation, there are significant orientation in which generate the most impact when the building courtyard is elongated. Each building geometry with its significant orientation is listed in the table below. Investigation of elongating the courtyard will be analysed in the Chapter 5.

Table 4.20 The Highest Change of Annual Cooling Energy When Courtyard is Elongated

Geometry	Orientation*	Impact of Increasing
		Courtyard L/W from 1 to 2
H	West-East	Reduce cooling energy up to 2.80%
U	West-East	Reduce cooling energy up to 3.15%

Double U	West-East	Reduce cooling energy up to 1.35%
Double L	North-South	Increase cooling energy up to 1.90%
Quadruple L	West-East	Reduce cooling energy up to 1.13%

*orientation which highest change of annual cooling energy occurs, when the courtyard L/W is changed from 1 to 2.

4.5.4 Effect of Building Orientation on Cooling Energy

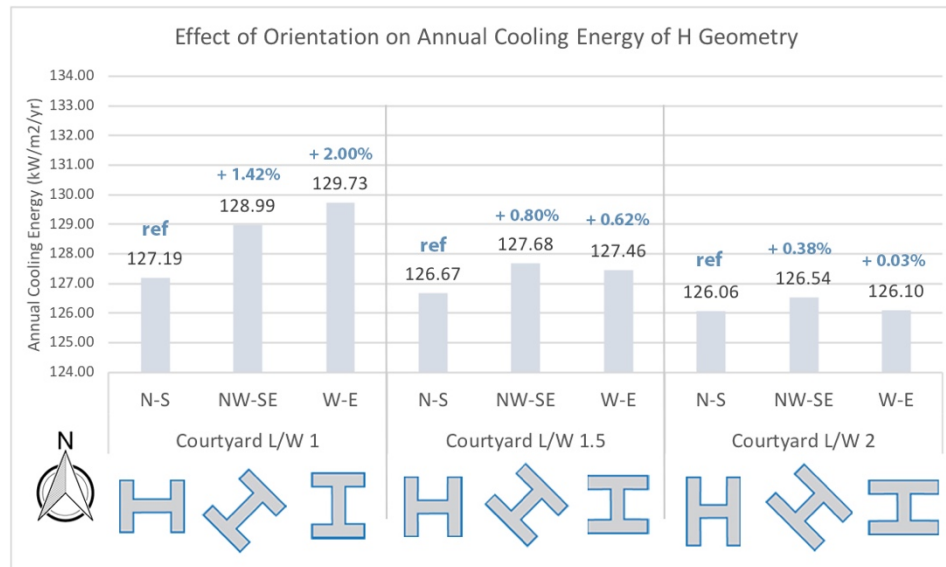


Figure 4.55 Effect of Building Orientation on Annual Cooling Energy, H Geometry

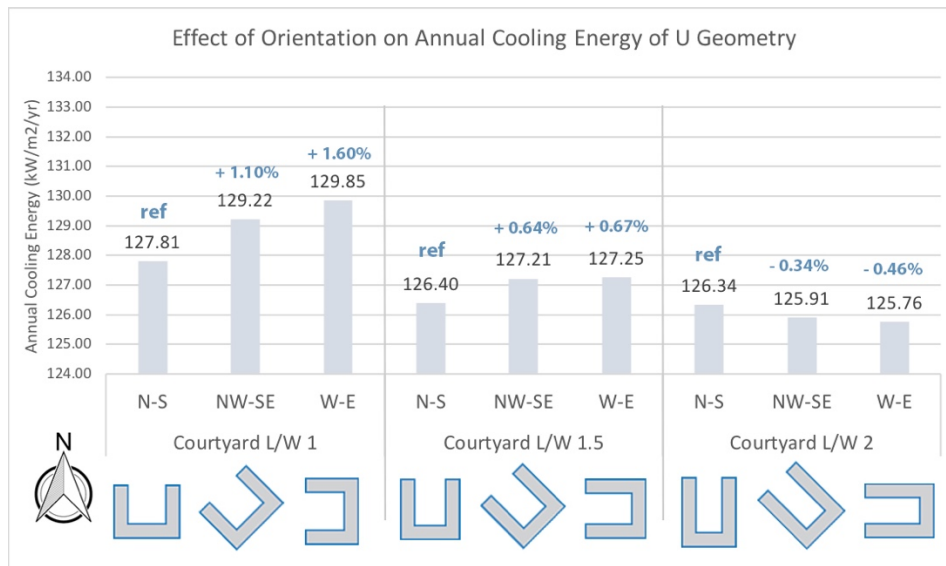


Figure 4.56 Effect of Building Orientation on Annual Cooling Energy, U Geometry

In general, all building geometries with courtyard L/W of 1 is more sensitive to the change of orientation rather than geometries with courtyard L/W of 2. Transforming the building orientation from north south to west east orientation will

result in higher cooling energy consumption, except for Quadruple L geometry which has lower cooling energy when oriented to west east. Double U geometry is the most sensitive geometry when it comes to building orientation. Transform building orientation from north south to west east orientation of Double U geometry, with courtyard L/W of 1, 1.5, and 2, could increase the building cooling energy consumption up to 6.48 kWh/m² yr, 4.62 kWh/m² yr, and 3.61 kWh/m² yr respectively.

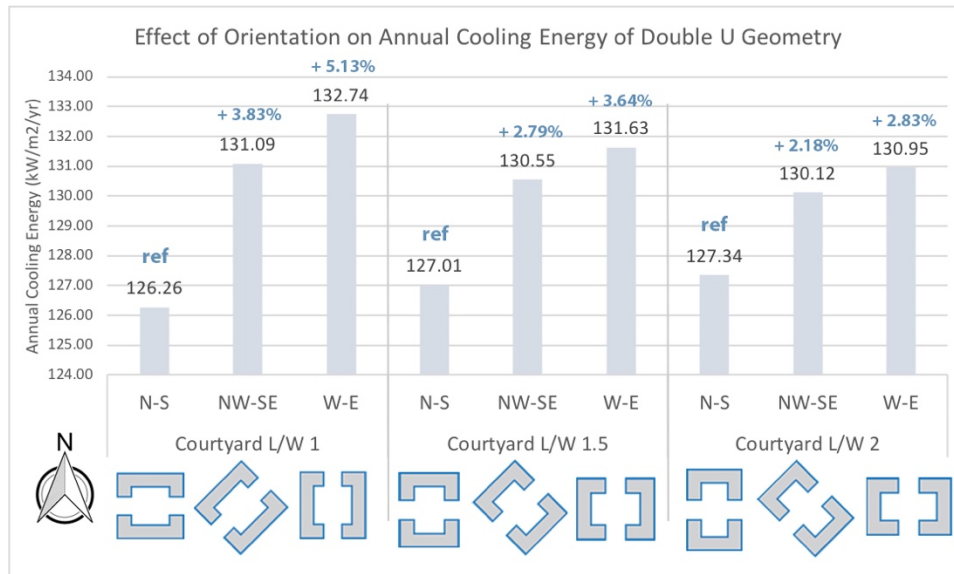


Figure 4.57 Effect of Building Orientation on Annual Cooling Energy, Double U Geometry

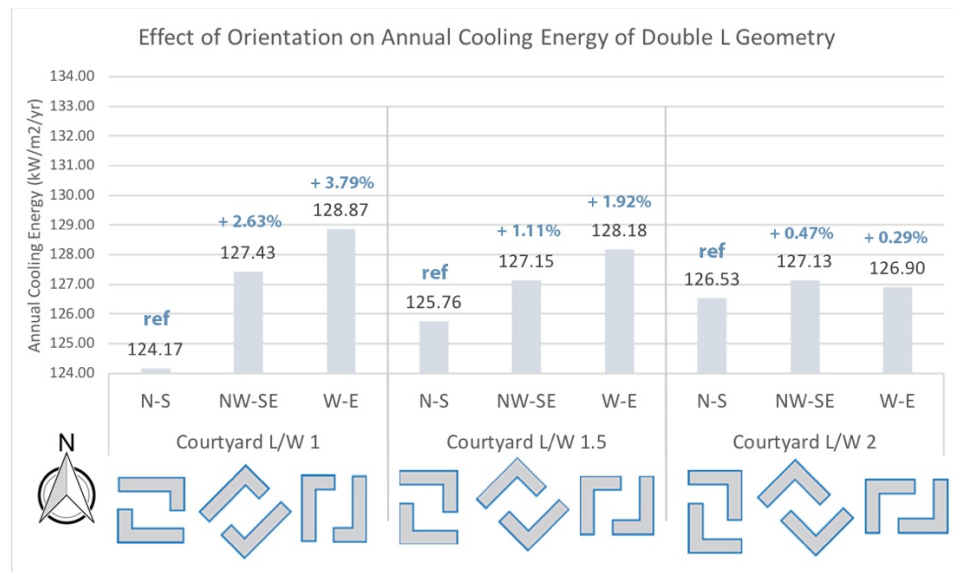


Figure 4.58 Effect of Building Orientation on Annual Cooling Energy, Double L

Geometry

In order to investigate the impact of orientation on each building geometry, elemental breakdown of building heat gain and loss will be investigated according to the most significant courtyard L/W. As each building geometry with different courtyard L/W is simulated in three different orientation, there are significant courtyard L/W in which generate the most impact when the building orientation is transformed. Each building geometry with its significant courtyard L/W is listed in the table below.

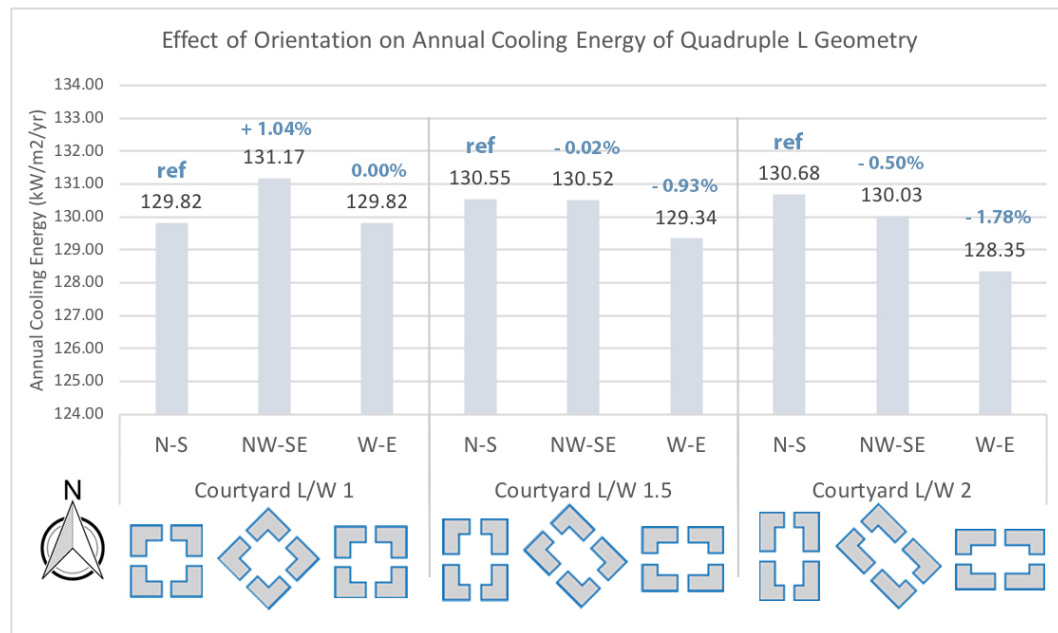


Figure 4.59 Effect of Building Orientation on Annual Cooling Energy, Quadruple L Geometry

Table 4.21 The Highest Change of Annual Cooling Energy When Building Orientation is Changed

Geometry	Courtyard L/W*	Impact of Changing Orientation from NS to WE
H	1	Increase cooling energy up to 2.00%
U	1	Increase cooling energy up to 1.60%
Double U	1	Increase cooling energy up to 5.13%
Double L	1	Increase cooling energy up to 3.79%
Quadruple L	2	Reduce cooling energy up to 1.78%

*courtyard L/W in which highest change of annual cooling energy occurs, when the building orientation is changed from north south to west east.

4.6 Performance Evaluation of Each Building Geometry

Different geometries have their own optimum cooling energy performance with different courtyard L/W and building orientation. In addition, different geometries also reach differently to the transformation of courtyard L/W and building orientation.

4.6.1 H Geometry

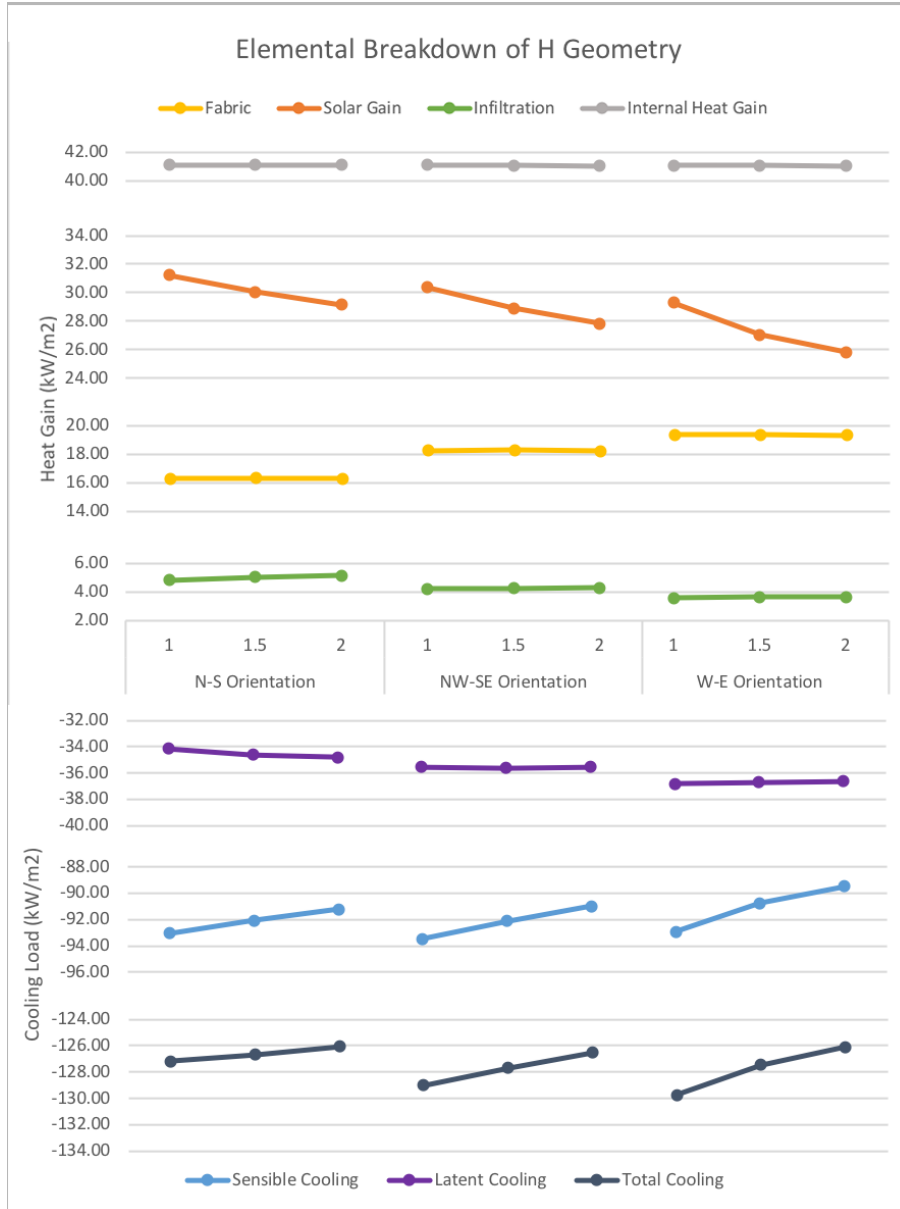


Figure 4.60 Elemental Breakdown of H Geometry in Different Courtyard L/W and Building Orientation

Minimum cooling energy of H geometry ($126.06 \text{ kWh/m}^2 \text{ yr}$) is obtained when the courtyard L/W is 2, and the building is oriented to north south axis.

Increase courtyard L/W of H geometry could reduce annual cooling energy consumption of 1.13 kWh/m² yr for north south orientation, 2.45 kWh/m² yr for northwest southeast orientation, and 3.63 kWh/m² yr for west east orientation. The effect of building orientation is different on H geometry with different courtyard L/W. Transform H geometry with courtyard L/W of 1 from north south orientation to west east orientation will increase building cooling energy of 2.54 kWh/m² yr. Transform building orientation of H geometry with courtyard L/W of 1.5 and 2 from north south orientation to northwest southeast orientation will increase building cooling energy of 1.01 kWh/m² yr and 0.48 kWh/m² yr respectively.

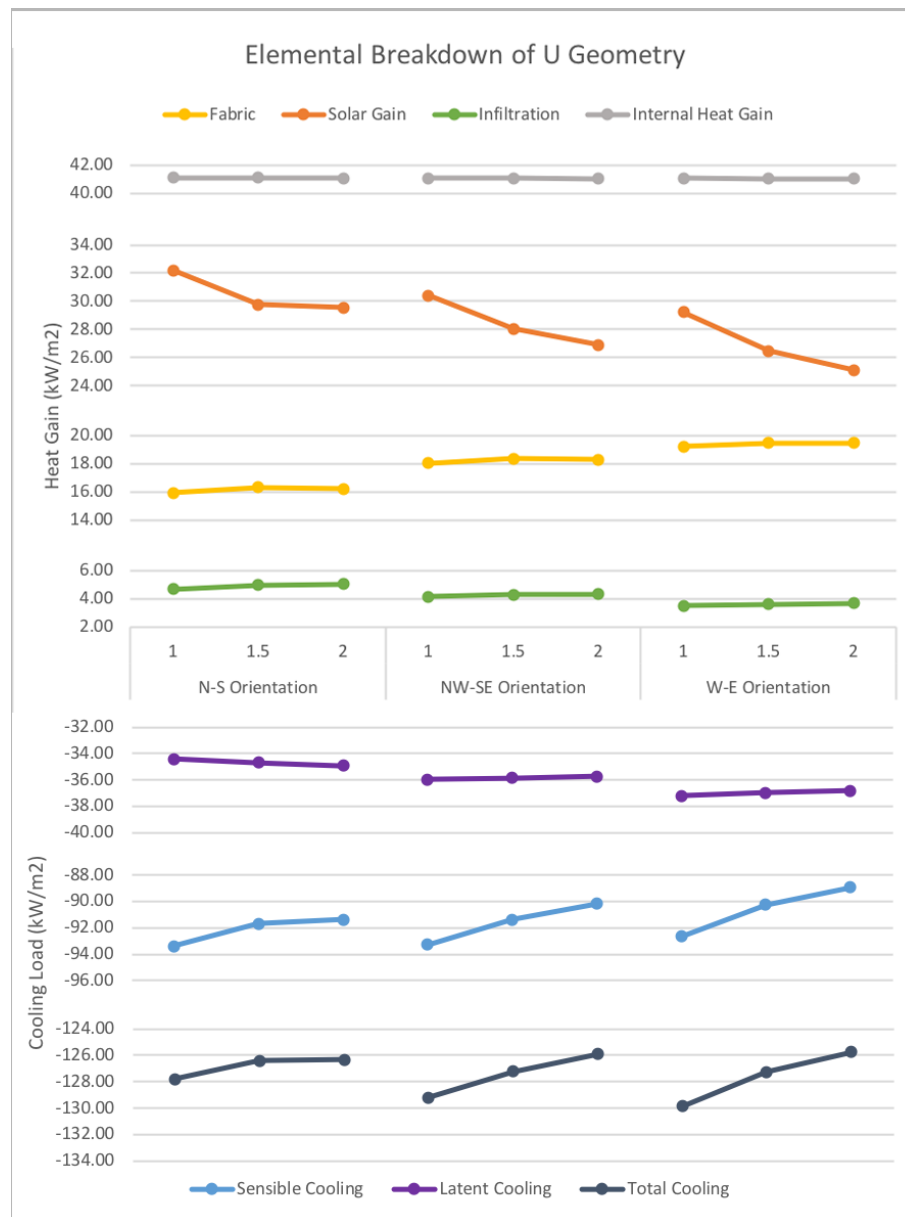


Figure 4.61 Elemental Breakdown of U Geometry in Different Courtyard L/W and

Building Orientation

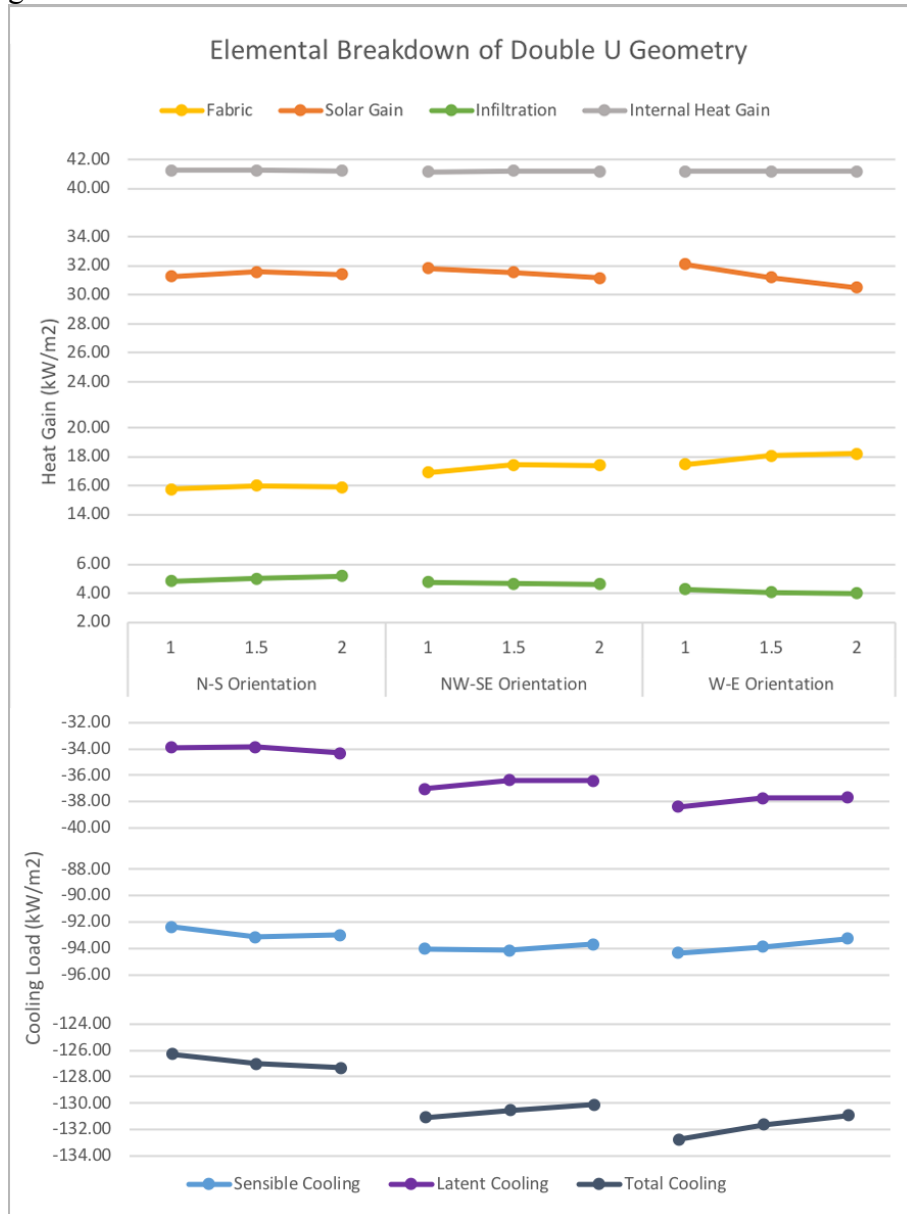


Figure 4.62 Elemental Breakdown of Double U Geometry in Different Courtyard L/W and Building Orientation

4.6.2 U Geometry

Minimum cooling energy of U geometry ($125.76 \text{ kWh/m}^2 \text{ yr}$) is obtained when the courtyard L/W is 2, and the building is oriented to west east axis. Increase courtyard L/W of H geometry could reduce annual cooling energy consumption of $1.47 \text{ kWh/m}^2 \text{ yr}$ for north south orientation, $3.31 \text{ kWh/m}^2 \text{ yr}$ for northwest southeast orientation, and $4.09 \text{ kWh/m}^2 \text{ yr}$ for west east orientation. The effect of building orientation is different on U geometry with different courtyard L/W. Transform

building orientation of U geometry with courtyard L/W of 1 and 1.5 from north south orientation to west east orientation will increase building cooling energy of 2.04 kWh/m² yr and 0.85 kWh/m² yr respectively. On the other hand, transform building orientation of U geometry with courtyard L/W of 2 from north south to west east orientation will decrease building cooling energy of 0.58 kWh/m² yr.

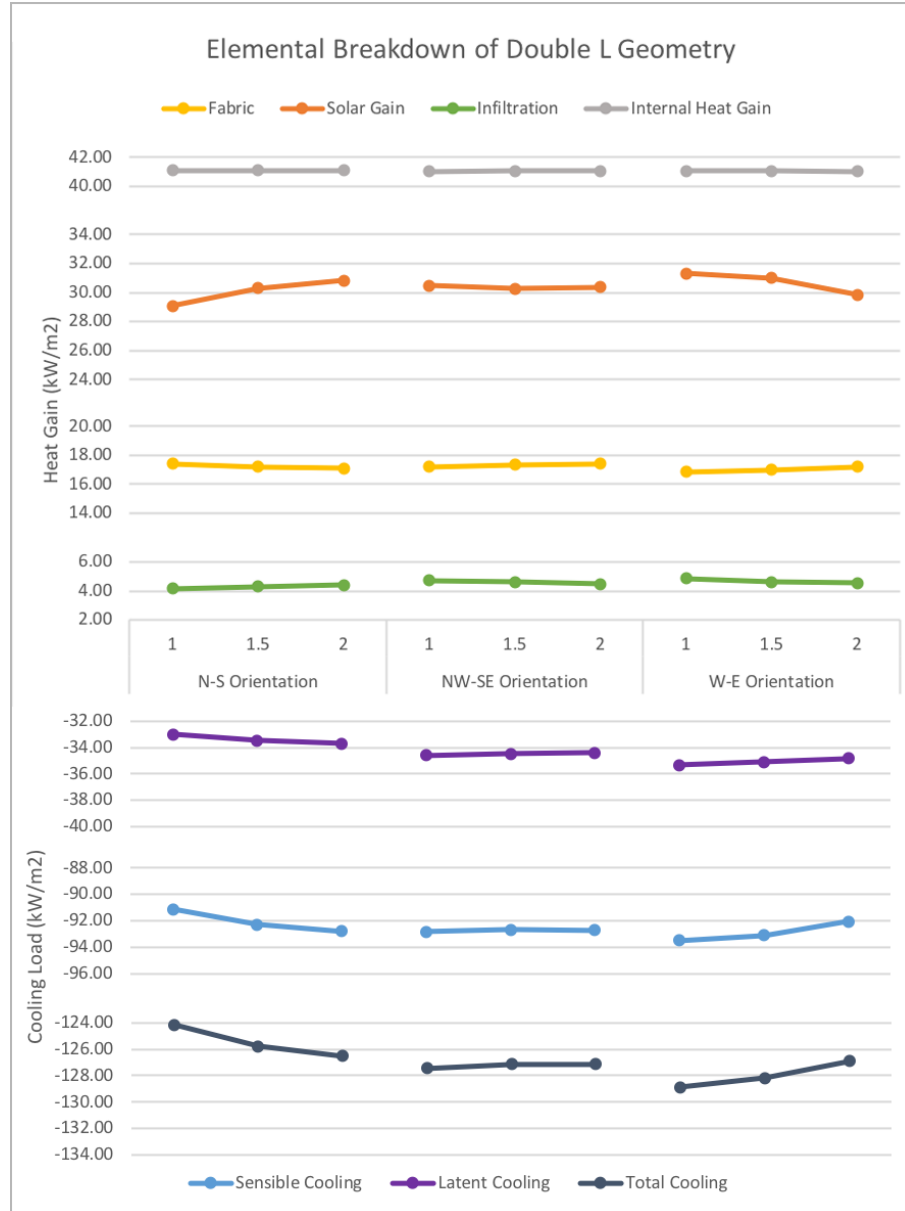


Figure 4.63 Elemental Breakdown of Double L Geometry

4.6.3 Double U Geometry

Minimum cooling energy of Double U geometry (126.26 kWh/m² yr) is obtained when the courtyard L/W is 1, and the building is oriented to north south

axis. Increase courtyard L/W of Double U geometry building will decrease building cooling energy of 0.97 kWh/m² yr for northwest southeast orientation, and 1.79 kWh/m² yr for west east orientation, but will increase the cooling energy up to 1.08 kWh/m² yr for north south orientation. Double U geometry is the most sensitive geometry when it comes to building orientation. Transform building orientation from north south to west east orientation of Double U geometry, with courtyard L/W of 1, 1.5, and 2, could increase the building cooling energy consumption up to 6.48 kWh/m² yr, 4.62 kWh/m² yr, and 3.61 kWh/m² yr respectively.

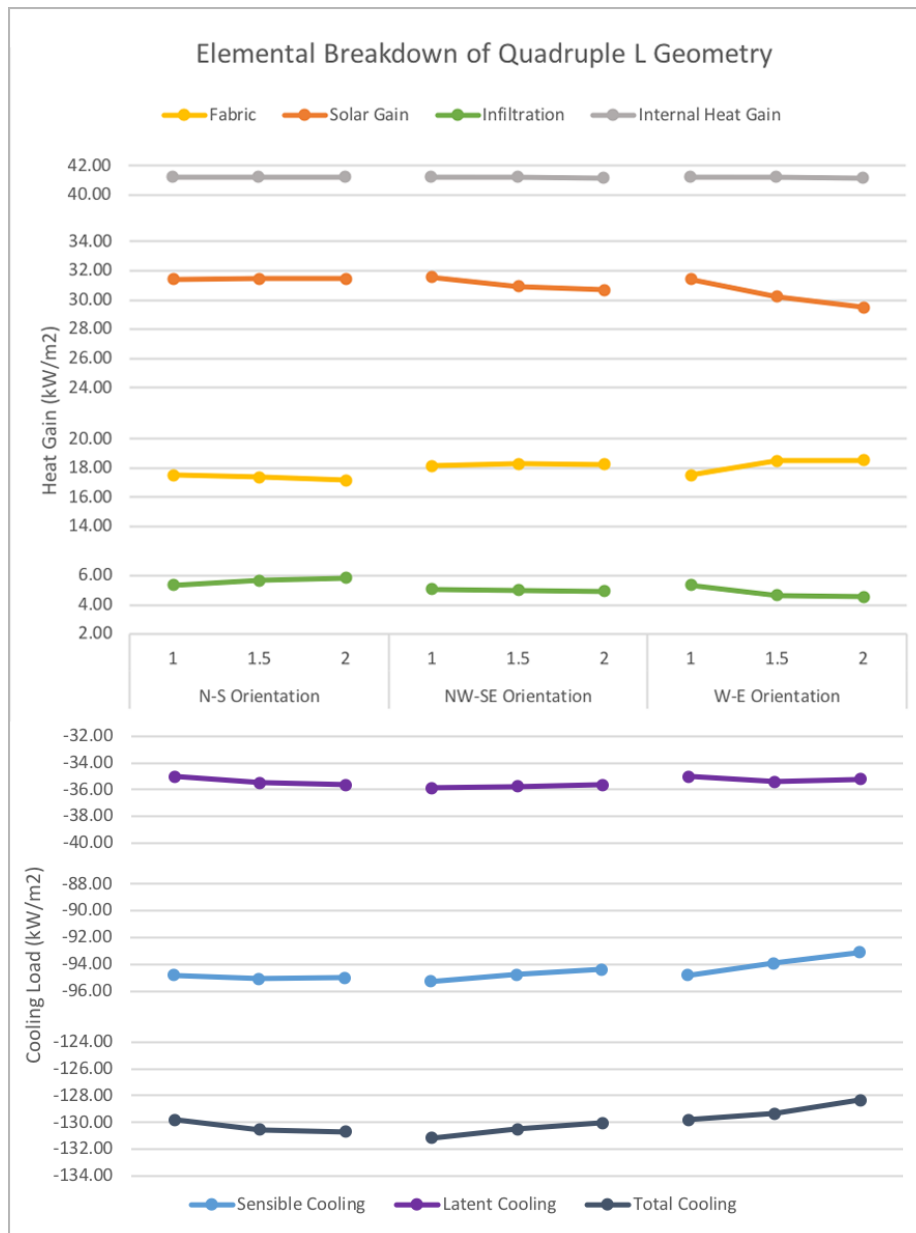


Figure 4.64 Elemental Breakdown of Quadruple L Geometry

4.6.4 Double L Geometry

Minimum cooling energy of Double L geometry ($124.17 \text{ kWh/m}^2 \text{ yr}$) is obtained when the courtyard L/W is 1, and the building is oriented to north south axis. Increase courtyard L/W of Double L geometry building will decrease building cooling energy of $0.3 \text{ kWh/m}^2 \text{ yr}$ for northwest southeast orientation, and $1.97 \text{ kWh/m}^2 \text{ yr}$ for west east orientation, but will increase the cooling energy up to $2.36 \text{ kWh/m}^2 \text{ yr}$ for north south orientation. Transform Double L building orientation from north south to west east of courtyard L/W 1 and 1.5 will increase building cooling energy of $4.7 \text{ kWh/m}^2 \text{ yr}$ and $2.4 \text{ kWh/m}^2 \text{ yr}$ respectively. On the other hand, transform Double L building orientation from north south to northwest southeast with courtyard L/W 2 will increase building cooling energy of $0.6 \text{ kWh/m}^2 \text{ yr}$, but building cooling energy will decrease about $0.23 \text{ kWh/m}^2 \text{ yr}$ when the building orientation is transformed from northwest southeast to west east orientation.

6.4.5 Quadruple L Geometry

Minimum cooling energy of H geometry ($128.35 \text{ kWh/m}^2 \text{ yr}$) is obtained when the courtyard L/W is 2, and the building is oriented to west east axis. Increase courtyard L/W of Quadruple L geometry will decrease building cooling energy of $1.14 \text{ kWh/m}^2 \text{ yr}$ for northwest southeast orientation, and $1.47 \text{ kWh/m}^2 \text{ yr}$ for west east orientation, but will increase the cooling energy up to $0.86 \text{ kWh/m}^2 \text{ yr}$ for north south orientation. Transform Quadruple L building orientation from north south to west east of courtyard L/W 1.5 and 2 will decrease building cooling energy of $1.21 \text{ kWh/m}^2 \text{ yr}$ and $2.33 \text{ kWh/m}^2 \text{ yr}$ respectively. On the other hand, transform Double L building orientation from north south to northwest southeast with courtyard L/W 1 will increase building cooling energy of $1.35 \text{ kWh/m}^2 \text{ yr}$.

CHAPTER 5

DISCUSSION

5.1 Influence of Building Geometry on Cooling Energy

The influence of building geometry on annual cooling energy is analyzed according to the characteristic of five geometries studied. Characteristic of building geometries, such as building shape index, courtyard opening position, and percentage of exposed and shaded window areas, are used to analyze annual cooling energy of a building geometry, and why particular geometries generate lower annual cooling energy than the other geometries.

5.1.1 Characteristics of The Model Experiments

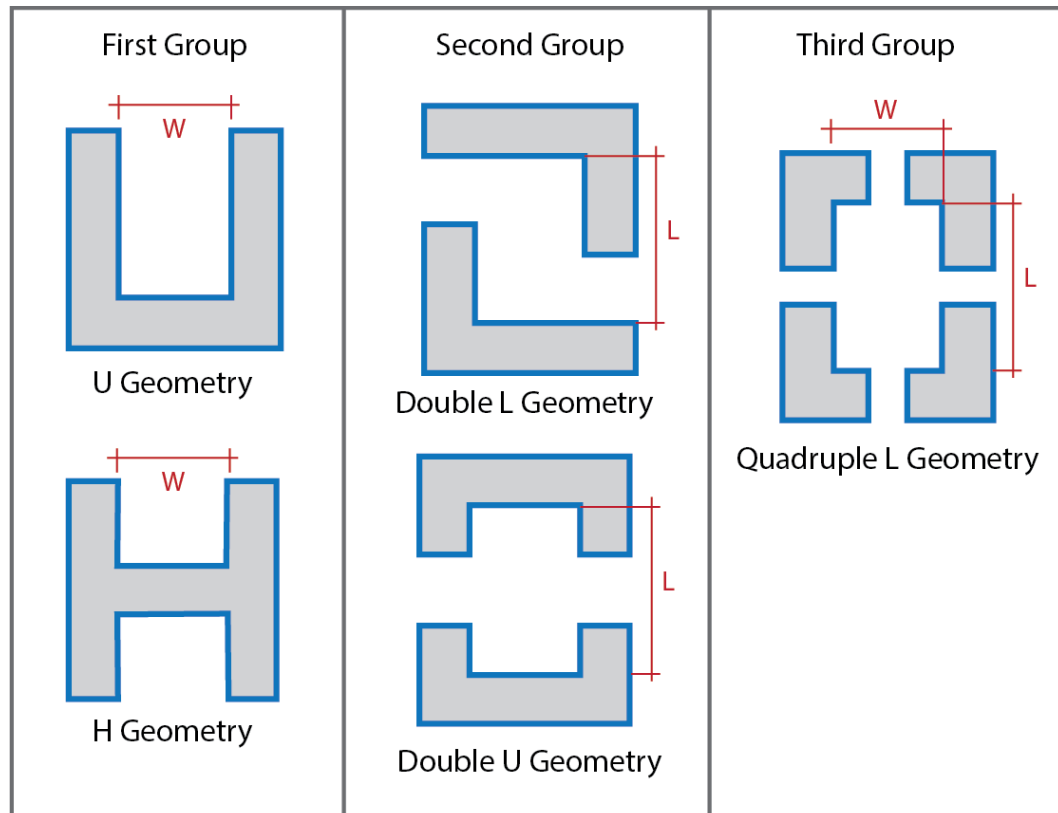


Figure 5.1 Courtyard Opening Position of Building Geometries

According to the simulation result in Chapter 4, five different building geometries with courtyard investigated in this research could be divided into three different group. The first group consist of geometries with single tower such as H and U geometry. These geometries have courtyard opening on the width side of the

building. The second group consist of geometries with twin tower such as Double U and Double L geometry. These geometries have courtyard opening on the elongated side of the building. However, unlike U and H geometries which has fully opened courtyard on one side, the courtyard opening in the second group is partial. The third group consist of Quadruple L geometry, with four similar towers. Courtyard opening of Quadruple L geometry is located on both width and elongated side of the building. Similar with Double U and Double L geometry, courtyard openings of Quadruple L geometry are partial. Geometries within the same group have similar building shape index, if the courtyard L/W are similar. It is important to note the position of courtyard opening, as it will influence self-shading effect of a geometry.

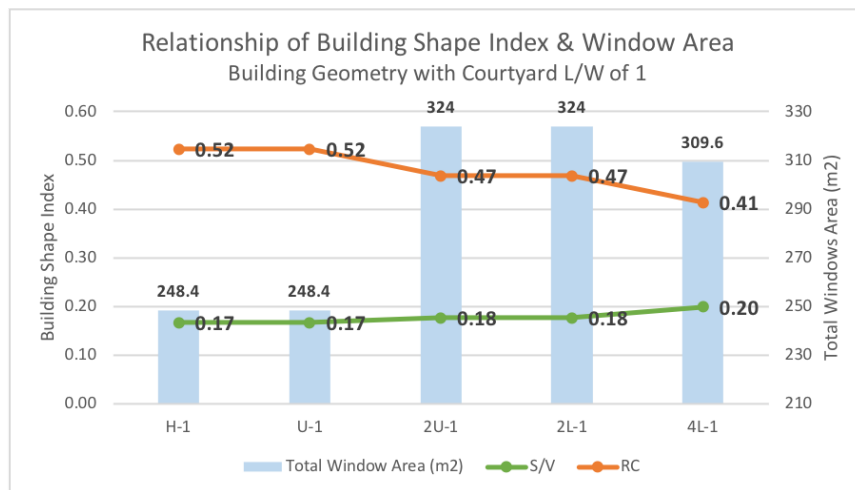


Figure 5.2 Relationship of Building Shape Index (courtyard L/W = 1) and Window Area

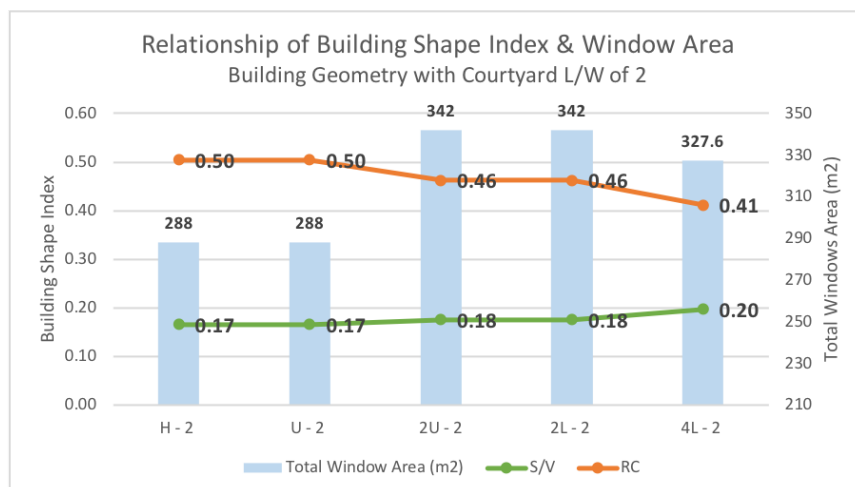


Figure 5.3 Relationship of Building Shape Index (courtyard L/W = 2) and Window Area

According to table 3.17 about characteristics of model experiments, it is important to note that model experiments with similar courtyard L/W and belong to similar group have similar building shape index. Relative Compactness (RC) and surface to volume ratio (S/V) are the most commonly used building shape index which determine the compactness of a building. Building geometry with similar shape index will have similar window area, because all the building geometry have similar WWR area. Higher window area of several geometries are caused by the higher percentage of walls surrounding the courtyard area.

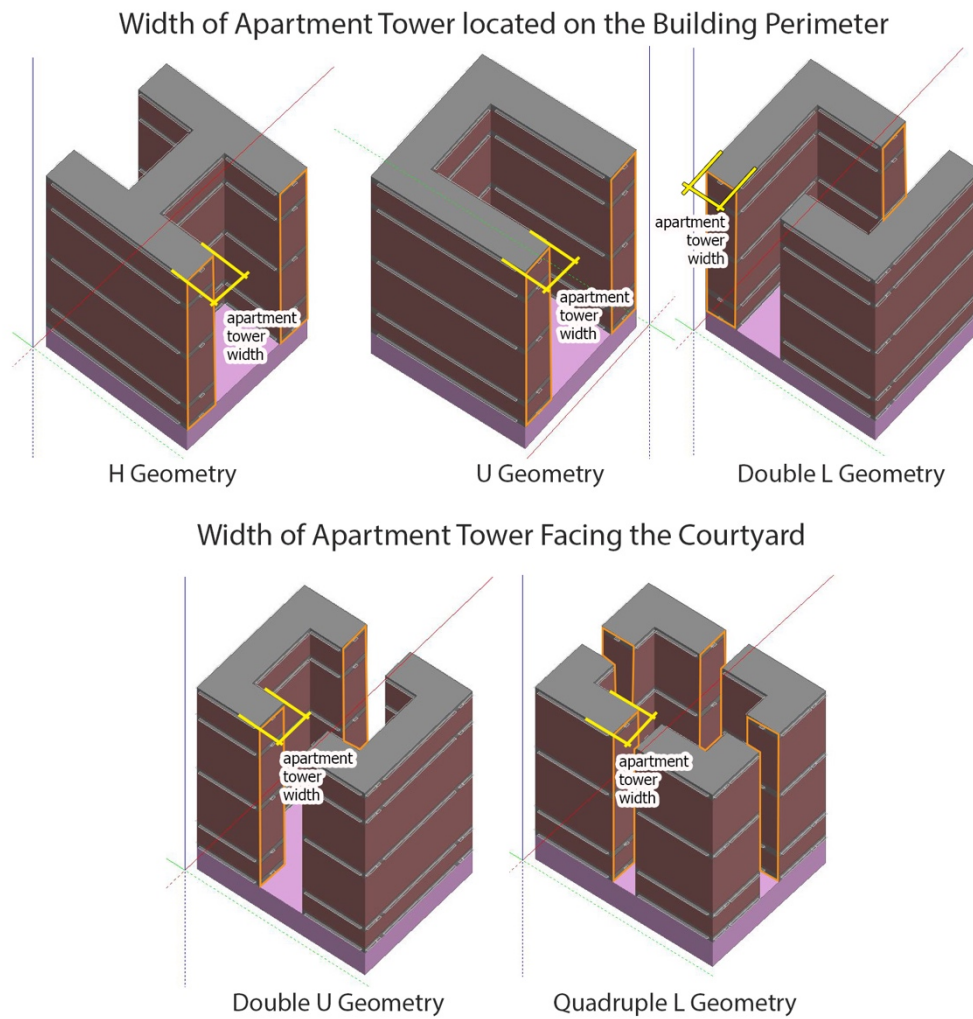


Figure 5.4 Location of Apartment Tower Width of Building Geometries Studied

Another important aspect which define five different geometries studied is the window position related to layout arrangement. In the high rise apartment with courtyard, there are rooms located in the perimeters and rooms facing the courtyard

area. Rooms located in the perimeter area tend to receive more solar radiation than rooms facing the courtyard. Although five different geometries have similar WWR of 30%, on the side of apartment tower width, there is no window at all for the zones of apartment units. H, U, and Double L geometries have side of apartment tower width located in the perimeter of the buildings, apartment tower width of Double U and Quadruple L face the courtyard area. Because apartment tower width have lower WWR than the other area, geometries which have apartment tower width located in the perimeter area have lower windows area on the building perimeter. On the other hand, geometries with apartment tower width facing the courtyard have more window area on the building perimeter.

Although geometries within similar group have similar total window area, due to the position of apartment tower width, geometries with similar window area have different composition of windows area located on the building perimeter, and windows area facing the courtyard. H geometry has the lowest percentage of windows located on the perimeter of the building. On the other hand, Double U geometry has the highest percentage of windows located on the courtyard area.

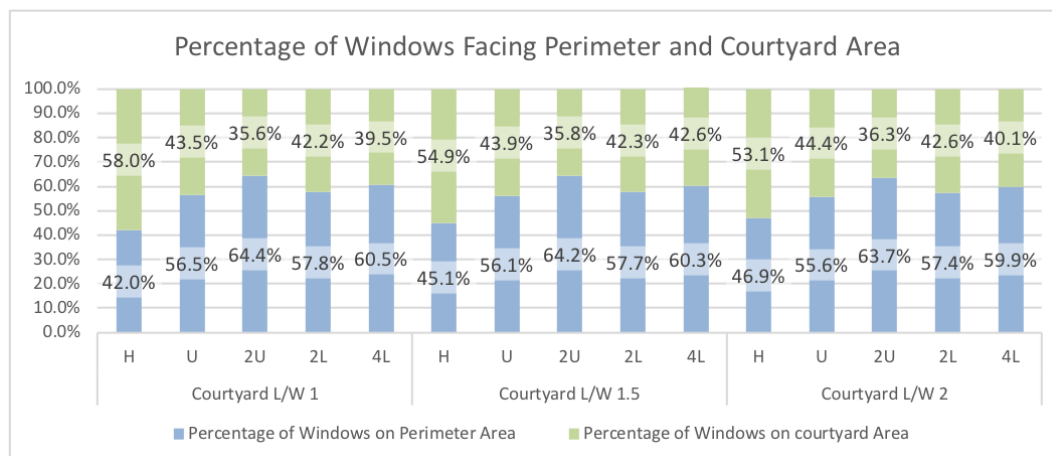


Figure 5.5 Percentage of Windows on Courtyard and Perimeter Area

According to the characteristics of five different geometries studied, the building geometry will influence not only self-shading of a building, but also layout arrangement and window position. Geometries with more windows located on the perimeter area will have less shaded area than geometries with more windows located on the courtyard perimeter. Windows located on the courtyard area, will receive more shading generated by the courtyard thus preventing solar heat gain generated by the window transparent surface.

5.1.1 Building Shape Index and Cooling Energy

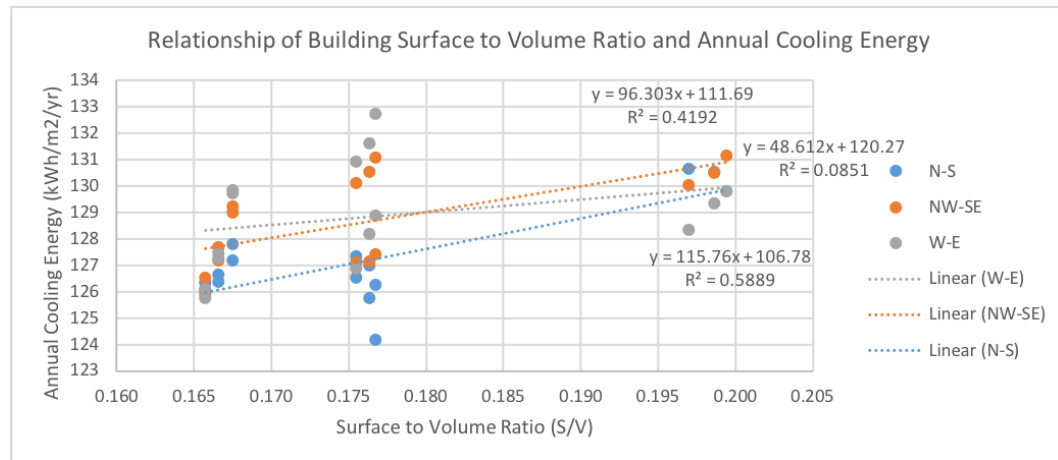


Figure 5.6 Relationship of Building Surface Ratio and Annual Cooling Energy

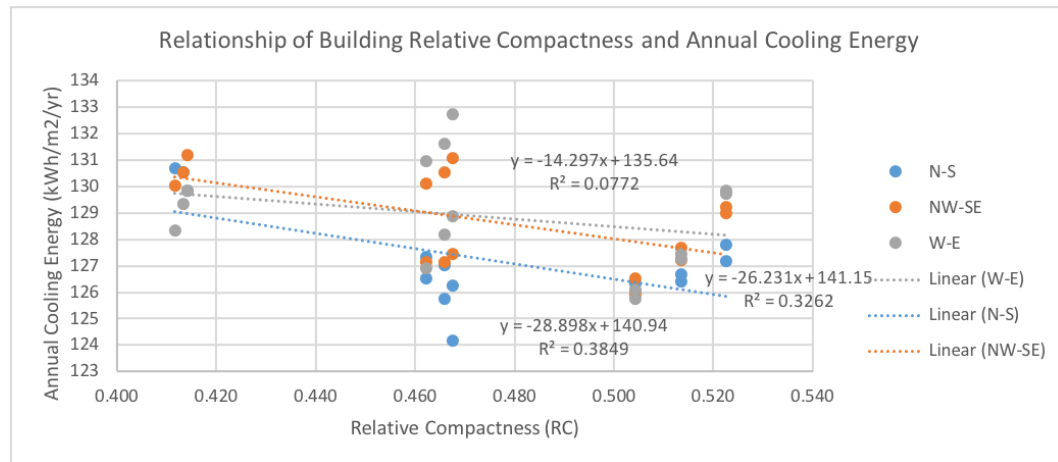


Figure 5.7 Relationship of Building Relative Compactness and Annual Cooling Energy

Building shape index is one of the way to define compactness of a building related to its shape or geometry. Surface to volume ratio (S/V) and relative compactness (RC) are two shape indices which are associated with building cooling energy in previous studies (Rashdi and Embi (2016) and Raji et Al. (2017)). According to regression analysis by comparing building shape index and result of cooling energy, surface to volume ratio (S/V) has slightly higher relationship than relative compactness (RC). In addition, the two indexes has the highest relationship with building cooling energy when the building is elongated towards north-south axis (S/V = 0.58; RC = 0.38), and least correlation when the building is elongated towards north-south axis (S/V = 0.08; RC = 0.07).

As explained previously, five different model experiments studied can be divided into three different group. First group consist of geometries which have courtyard opening on the width side of the building, second group consist of geometries which have courtyard opening on elongated side of the building, and the third group consist of building geometry which has courtyard opening on both width and elongated side of a building. As shown by table 3.17, building geometries within the same group have similar building indexes (relative compactness and surface to volume ratio). According to Rashdi and Embi (2016) building annual cooling energy is directly proportional to building surface to volume ratio. However the result of this experimental research show that building geometries with similar building shape index could result in different value of annual cooling energy. Courtyard building geometries with similar building indexes, could generate different self-shading on the building which result in different value of annual cooling energy. As shown by Figure 5.4 and 5.5, the results of annual cooling energy from five different geometries with courtyard L/W of 1 north-south orientation, and courtyard L/W of 2 west-east orientation showed that building shape index could not determine the result of cooling energy. H and U geometries and Double U and Double L geometries have similar relative compactness and surface to volume ratio but generate different annual cooling energy.

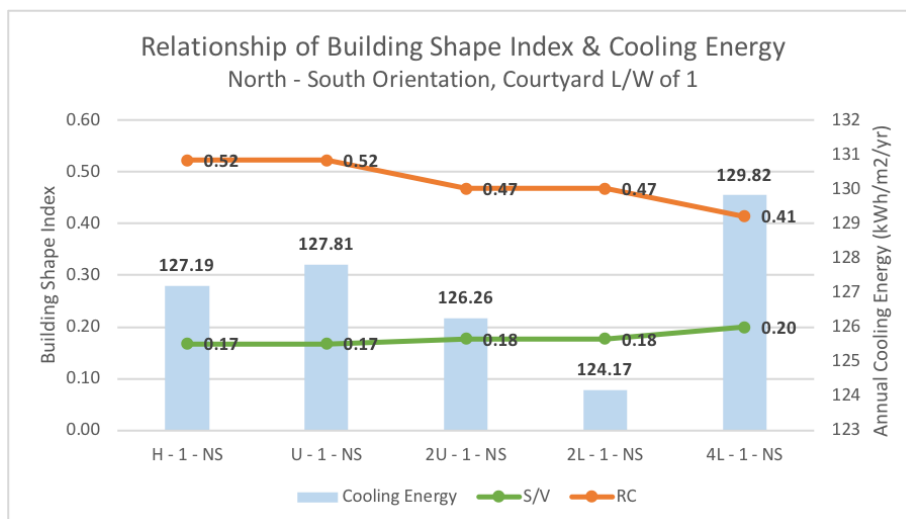


Figure 5.8 Relationship of Building Shape Index and Annual Cooling Energy, Courtyard L/W of 1, North South Orientation

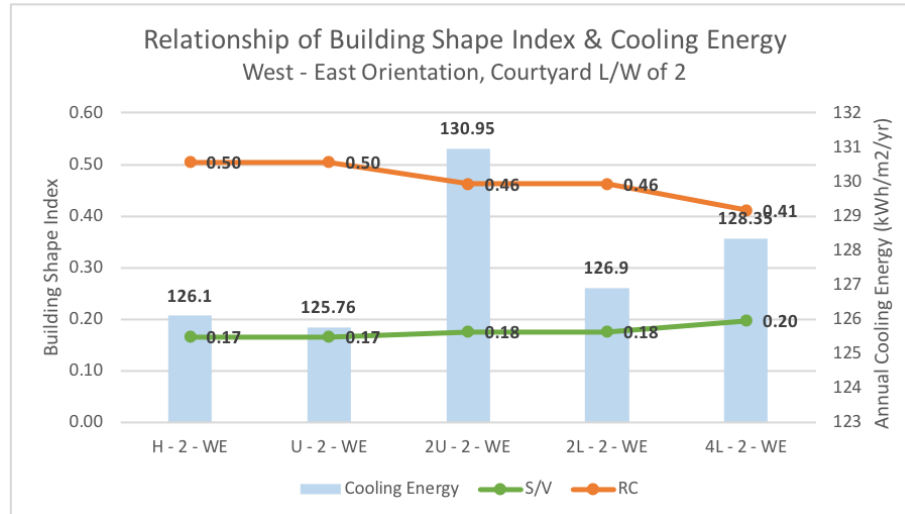


Figure 5.9 Relationship of Building Shape Index and Annual Cooling Energy, Courtyard L/W of 2 West East Orientation

Raji et Al. (2017) mentioned in their studies that building shape index could not determine energy consumption of a building, because building shape indexes do not represent three dimensional geometry of a building, thus diminishing the impact of self-shading by building form. In addition, building transparency ratio (WWR), and building orientation are not included in building shape index, although WWR and building orientation also determine energy consumption of a building.

5.1.2 Elemental Breakdown of Building Geometries

Annual cooling energy of model experiments are combination of building latent load, and sensible load, in which there are many variables that contribute to the cooling load of a building. In order to understand better about how building geometry affect building cooling load, elemental breakdown of some experimental results are investigated.

a. Geometries of Courtyard L/W of 1, North-South Orientation

Among five different geometries studied, when the building has courtyard L/W of 1 and elongated toward north south axis, Double L building generate the lowest annual cooling energy (124 kWh/m²/yr), while Quadruple L geometry generate the highest cooling energy (124 kWh/m²/yr). Changing geometry of Quadruple L to Double L will reduce annual cooling energy of 4.35%. Heat gain of a building determine cooling load and cooling energy of a building. According to linear regression analysis of different heat gain variables and sensible cooling load, solar gain has the highest relationship with sensible cooling load ($R^2 = 0.78$).

However, in this case, solar gain may not be the main contributing factor. Among five different geometries with courtyard L/W of 1 elongated along north-south axis, U geometry has the highest solar gain, but the highest annual cooling energy is generated by Quadruple L geometry.

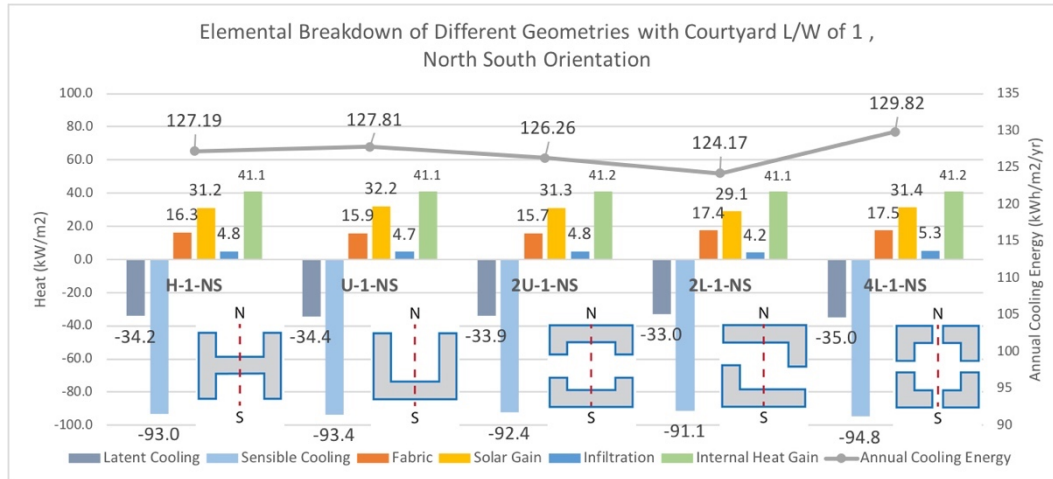


Figure 5.10 Elemental Breakdown of Different Geometries with Courtyard L/W of 1, North South Orientation

According to the elemental breakdown, Quadruple L has the highest fabric and infiltration heat gain which generate the highest sensible cooling load than the other geometries. In addition, Quadruple L geometry also generates the highest latent cooling load. This can be concluded that Quadruple L geometry demands the highest annual cooling energy because of combination of infiltration gain, solar gain, and latent cooling load. Double L geometry, which consume minimum cooling energy, has similar fabric heat gain (17.4 kW/m^2) to Quadruple L building (17.5 kW/m^2), which consume maximum cooling energy. However, Double L geometry generate lowest solar gain, infiltration gain, as well as latent cooling load than the other geometries. As a result, Double L geometry has lower annual cooling energy than the other geometries.

In this case, second group geometries generate lower annual cooling energy than the other group. While, third group geometry generate the highest annual cooling energy. When the buildings is elongated alongside north south axis, second group geometries, which has courtyard opening on the west and east side generate lower annual cooling energy, because the apartment units are elongated alongside west – east axis, minimizing solar radiation and latent cooling load (the dominant

upcoming wind come from west and east side in Surabaya). On the other hand, first group geometries generate higher annual cooling energy than second group geometries, because when the building is elongated alongside north south axis, courtyard opening of first group is facing north and south, and most of apartments units of H and U geometry are oriented towards west east. As a result, latent cooling load of first group geometries are higher than second group geometries, because these H and U geometries expose elongated side of the building towards solar radiation and upcoming wind. Third group geometry, which has the highest annual cooling energy, has higher building surface area than the other geometries. As stated by Yeang (2006), higher surface area of a building could lead to higher exposure of solar radiation. In addition, the higher surface area of a conditioned building, could lead to more wind exposure thus increasing the infiltration gain. As a result, Quadruple L geometry of third group geometry generates both highest sensible cooling load, and latent cooling load than the other geometries.

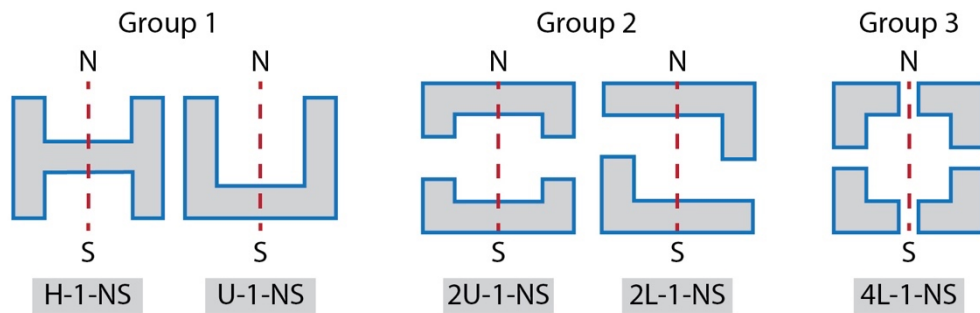


Figure 5.11 Illustration of Building Geometries with Courtyard L/W of 1, North South Orientation

When the buildings is elongated alongside north south axis with courtyard L/W of 1, H and U geometries of Group 1 generate almost similar annual cooling energy, with difference of 0.62 kWh/m²/yr. On the other hand, Double U and geometry generate higher annual cooling energy of 2.09 kWh/m²/yr than Double L geometry, although they belong to the same group. The reason of this is the position of the apartment tower width, which have lower window wall ratio. Two of the apartment tower width sides of Double L geometry are located on the building perimeter, which make Double L geometry has higher percentage of windows facing the courtyard area, thus minimizing the solar gain of the building. Illustration below shows when the building is elongated alongside north south axis, apartment

tower width of Double L geometry is facing the west. On the other hand, apartment tower width of Double U geometry is facing the courtyard area. Absence of the apartment tower width on the west side of Double U geometry is replaced by walls with WWR of 30%. As a result, Double U geometry has more windows area facing east and west side thus increasing exposure towards solar radiation and the upcoming wind. Double U geometry generate higher infiltration gain of 0.6 kWh/m² and higher solar gain of 2.2 kWh/m², which lead to higher latent cooling load of 0.9 kWh/m² and higher sensible cooling load of 1.3 kWh/m² than Double L geometry.

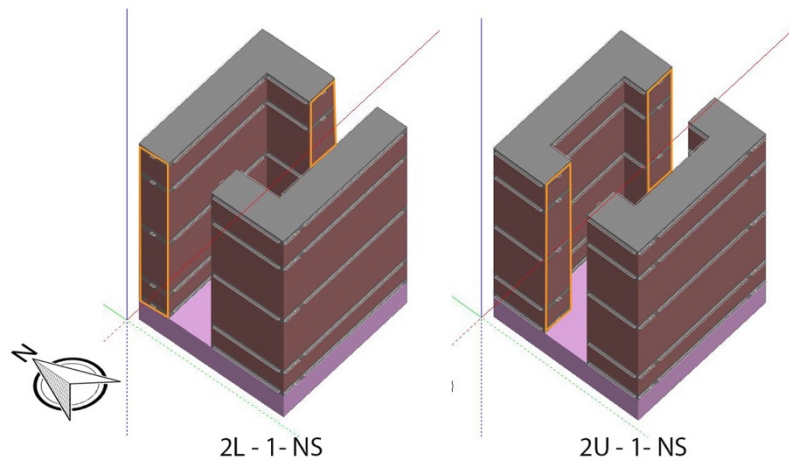


Figure 5.12 Illustration of Apartment Tower Width of Double U and Double L Geometries

The position of apartment tower width is the result of the building layout arrangement, as well as the geometry of the building itself. Building layout arrangement will influence window position, as well as cores of the building. This findings is supported by previous study of Jang et Al. (2015), which mentioned that apartment layout arrangement could influence the building energy demand. Although study of Jang et Al. (2015) focus on heating load of a building.

b. Geometries of Courtyard L/W of 2, West-East Orientation

When courtyard building with L/W of 2 is elongated alongside west-east axis, U geometry consume minimum cooling energy of 125.76 kWh/m² yr and Double U geometry consume maximum cooling energy of 130.95 kWh/m² yr. Changing geometry of Double U to U geometry will reduce annual cooling energy about 3.96 %. In this case, building geometries belong to the first group generate lower annual cooling energy than the other groups, and Double U geometry of

second group generate the highest annual cooling energy. Although Double L belongs to the same group as Double U geometry, annual cooling energy of Double L is slightly higher than first group geometries. Quadruple L of third group geometry has higher annual cooling energy than Double L geometry, but lower than Double U geometry.

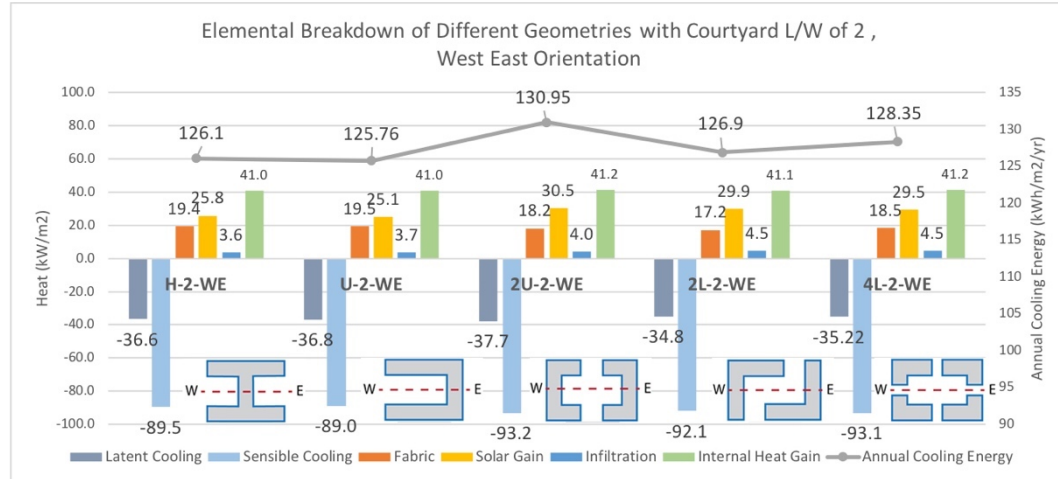


Figure 5.13 Elemental Breakdown of Different Geometries with Courtyard L/W of 2, West East Orientation

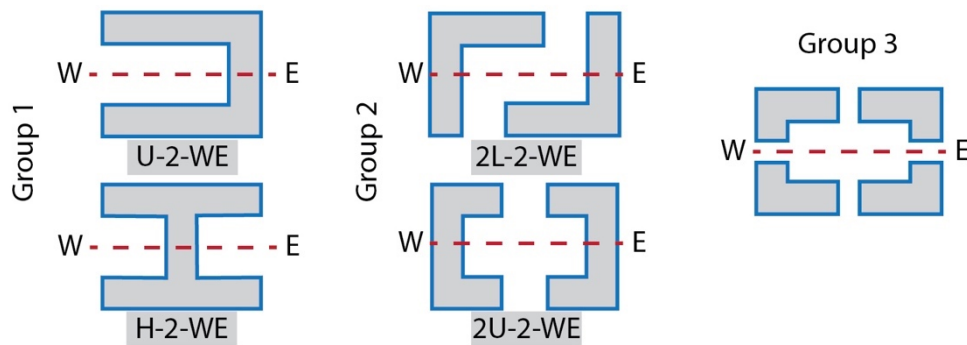


Figure 5.14 Illustration of Building Geometries with Courtyard L/W of 2, West East Orientation

In this case, building geometries belong to the first group generate lower annual cooling energy than the other groups. When the building is elongated alongside west east axis, apartment units of first group geometries are facing north and south thus minimizing the exposure of solar radiation and upcoming winds. As a result, infiltration and solar gain of H and U geometries are lower than the other three geometries. Although U and H building geometries generate fabric and infiltration with almost similar value, U geometry generate less solar gain (25.1 kW/m^2) than H geometry (25.8 kW/m^2), which result in lower sensible cooling load

of 0.5 kW/m^2 than H geometry. Even though U geometry has slightly higher latent cooling load of 0.2 kW/m^2 than H geometry, the impact of sensible cooling load is greater, resulting in lower annual cooling energy of U geometry about $0.34 \text{ kWh/m}^2 \text{ yr}$ than H geometry.

On the other hand, when the building is elongated alongside west east axis, apartment units of second group geometries are facing west east orientation thus increasing the exposure of solar radiation. As a result, Double U and Double L geometries generate the highest solar gain than the other three geometries. Although Double L geometry has higher solar gain of 0.4 kW/m^2 than Quadruple L geometry, annual cooling energy of Quadruple L geometry is higher $1.45 \text{ kWh/m}^2 \text{ yr}$ than Double L geometry, because sensible and latent cooling load of Quadruple L geometry is higher 1 kW/m^2 and 0.42 kW/m^2 than Double L geometry, respectively. Higher fabric gain of Quadruple L geometry contribute to its sensible cooling load. Although, infiltration gain of Double L and Quadruple L geometries are similar (4.5 kW/m^2), Quadruple L geometry has higher latent cooling load, because Quadruple L geometry has higher fabric gain of 1.3 kW/m^2 than Double L geometry. Fabric gain of a building increases temperature of building envelope, thus resulting in evaporation of moisture.

5.1.3 Relationship of Windows Percentage Facing Courtyard and Annual Cooling Energy

As mentioned before, when the building is elongated alongside north-south axis, Double L geometry with courtyard L/W of 1 has lower annual cooling energy than Double U geometry because Double L geometry has higher percentage of windows facing the courtyard area. Building solar exposure can be minimized when more windows area in a building are facing the courtyard which provide self-shading for the building. However, the relationship of windows percentage facing the courtyard and the other building geometries on different orientation need to be analyzed further.

According to the comparison of annual cooling energy and percentage of windows area facing the courtyard, higher percentage of windows facing the courtyard is not directly proportional to the lower annual cooling energy. For geometries with courtyard L/W of 1 elongated alongside north south axis, similar

with cases of Double U and Double L geometries, H geometry has higher percentage of windows facing the courtyard area than U geometry, which result in lower annual cooling energy of H geometry.

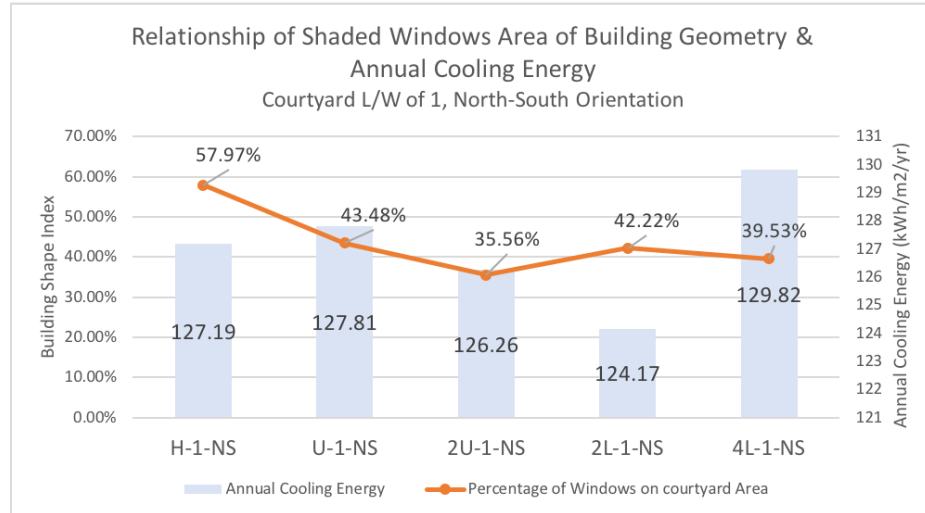


Figure 5.15 Relationship of Windows Percentage Facing the Courtyard and Annual Cooling Energy of Building Geometries with Courtyard L/W of 1, North-South Orientation.

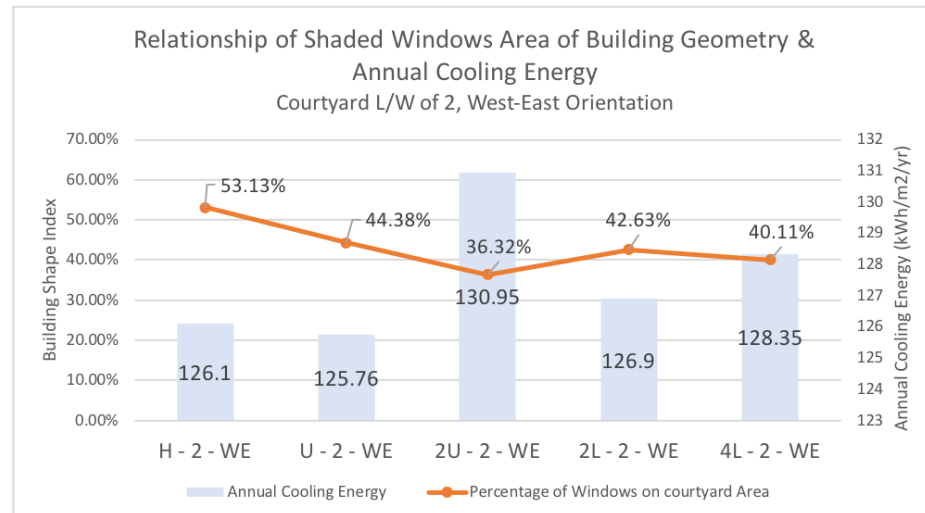


Figure 5.16 Relationship of Windows Percentage Facing the Courtyard and Annual Cooling Energy of Building Geometries with Courtyard L/W of 2, West-East Orientation.

However, when the building orientation is changed from north-south to west-east, and the courtyard L/W become 2, higher percentage of windows facing the courtyard does not determine annual cooling energy of a building. H geometry, with courtyard L/W of 2 elongated alongside west-east axis, has higher annual cooling energy than U geometry, although H geometry has higher percentage of

windows facing the courtyard. H geometry elongated alongside west-east axis has courtyard opening on west and east side of the building, reducing the effect of self-shading by courtyard, while U geometry has longer courtyard with only one opening thus provide more shaded area. On the other hand, Double L geometry with higher percentage of windows facing the courtyard still generate lower annual cooling energy than Double U geometry.

Quadruple L geometry has higher percentage of windows facing the courtyard area than Double U geometry, but lower percentage than H, U, and Double L geometries. Quadruple L geometry with courtyard L/W of 1 elongated alongside north south axis has higher annual cooling energy than Double U geometry. On the other hand, Quadruple L geometry with courtyard L/W of 2 elongated alongside west east axis has lower annual cooling energy than Double U geometry.

In conclusion, percentage of windows facing the courtyard could not determine annual cooling energy of a building geometry. There are many other variables which influence courtyard building annual cooling energy, such as position of courtyard opening, and building orientation.

5.2 Impact of Different Courtyard L/W on Annual Cooling Energy

As explained in 4.3.2, increasing courtyard L/W of 1 to 2, will result in decreasing of annual cooling energy of H and U geometries in all orientation, up to 3.15% less annual cooling energy. Increasing courtyard L/W from 1 to 2 of Double U, Double L, and Quadruple L geometries, will result in decreasing annual cooling energy when the building is oriented alongside northwest-southeast and west-east axis, but annual cooling energy will increase up to 1.90% when the building is oriented alongside north-south axis.

In the case of increasing courtyard L/W of 1 to 2 of all geometries, increasing in solar gain will result in increasing of annual cooling energy, because when the courtyard is elongated, changes of latent cooling load is smaller ($0.04 - 0.7 \text{ kWh/m}^2$) compared to the change of solar gain. However it is important to evaluate the other heat gain factors which contribute to the increasing or decreasing of cooling energy. Elemental breakdown about the impact of increasing courtyard L/W will be divided into two different explanation. The first explanation consist of

elemental breakdown from H and U geometries, and the second explanation consist of Double U, Double L, and Quadruple L geometries. Investigating elemental breakdown of each of this geometries is necessary in order to evaluate which factor that influence energy consumption the most.

a. Effect of Increasing Courtyard L/W on H and U geometries

Increasing courtyard L/W from 1 to 2 of H and U geometries will result in decreasing of cooling energy in three different orientation. For H and U geometries, the impact of elongating the courtyard is the highest when the building is elongated alongside east and west axis. Annual cooling energy consumption of H and U geometry decrease about 2.80% and 3.15%, respectively.

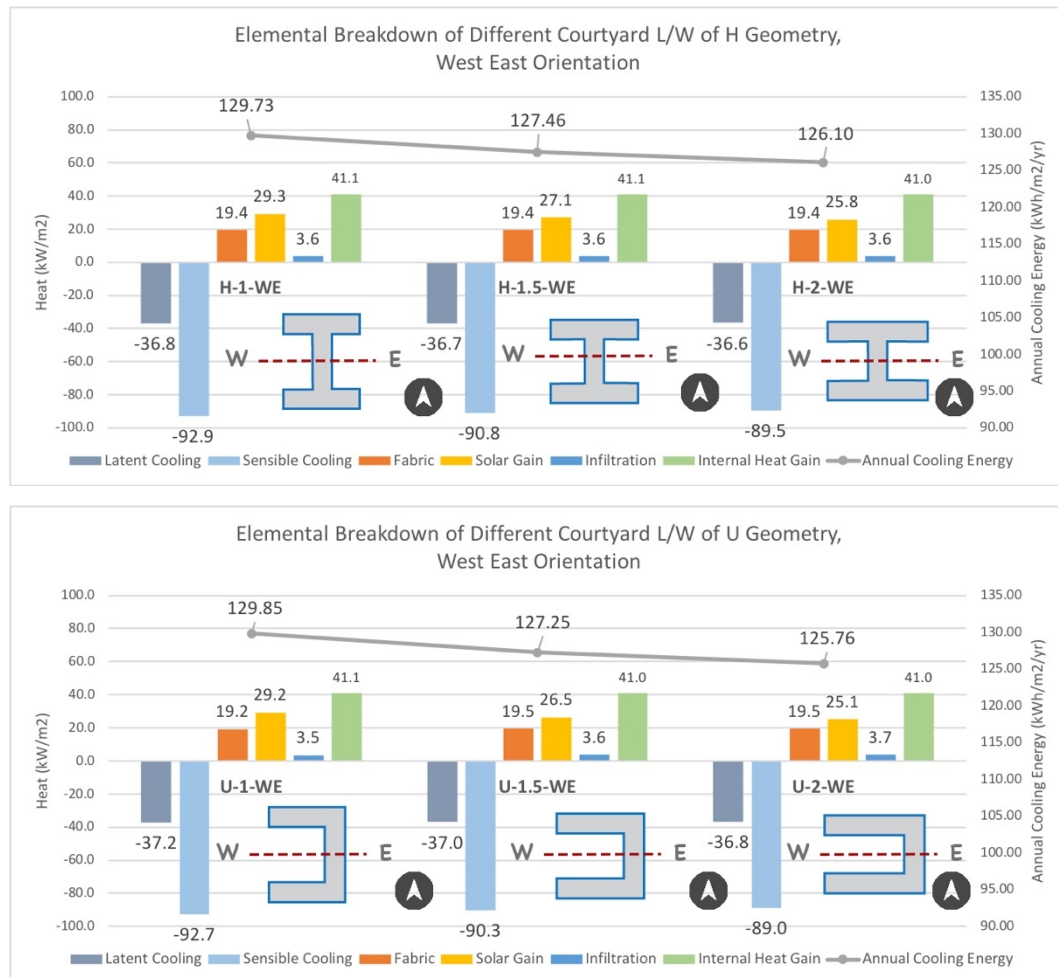


Figure 5.17 Elemental Breakdown of H and U Geometries, West East Orientation

According to the elemental breakdown, increasing courtyard L/W from 1 to 2 of H geometry does not influence fabric gain, and solar gain. Latent cooling load decreases 0.2 kW/m² when the courtyard L/W is 2. Heat gain factor with the highest

change is solar gain, in which increasing courtyard L/W from 1 to 2 will decrease the solar gain 3.48 kW/m².

U geometry shows more changes when the courtyard is elongated, compared with H geometry. Increasing courtyard L/W from 1 to 2 of U geometry will increase the fabric and infiltration gain about 0.3 kW/m² and 0.2 kW/m², respectively. On the other hand, elongating the courtyard will decrease latent cooling load and solar gain will decrease about 0.4 kW/m² and 4.10 kW/m², respectively.

According to both elemental breakdown of H and U geometries, sensible cooling load decreases when solar gain decrease. In the case of U geometry, although fabric and infiltration gain increase when the courtyard L/W is increased from 1 to 2, the sensible cooling load remains decreasing. In addition, latent cooling load in both geometries are decreasing when the courtyard is elongated, thus result in lower total cooling load, because annual cooling energy is the sum of latent and sensible cooling load. According to this analysis, reduction of annual cooling energy of H and U geometries, when the courtyard L/W is increased from 1 to 2, is mainly caused by decreasing of solar heat gain factor.

The study of U and H geometry verify study by Muhaisen and Gadi (2006) which stated that square shaped courtyard generate higher cooling load than rectangular courtyard. This study also mentioned that solar radiation caused rectangular courtyard generate higher cooling load. In addition, Almhafdy et al. (2015) which studied U-shaped courtyard in Malaysia also stated that courtyard with aspect ratio of 1:2 generate more outdoor thermal comfort than U-shaped courtyard with aspect ratio of 1:1.

b. Effect of Increasing Courtyard L/W on Double U, Double L, and Quadruple L Geometries

Double U, Double L, and Quadruple L geometries generate similar reaction when the courtyard L/W is increased from 1 to 2. Elongating courtyard of these geometries will decrease annual cooling energy when the building is elongated alongside northwest-southeast and west-east axis. On the other hand, when the building is elongated alongside north-south axis, the cooling energy will increase. Elemental breakdown of these geometry will be investigated in order to identify

why elongating the courtyard could increasing of cooling energy. Therefore, two orientation from each of Double U, Double L, and Quadruple L geometries will be investigated; north-south orientation which result in increasing of cooling energy, and west-east orientation which result in decreasing of cooling energy.

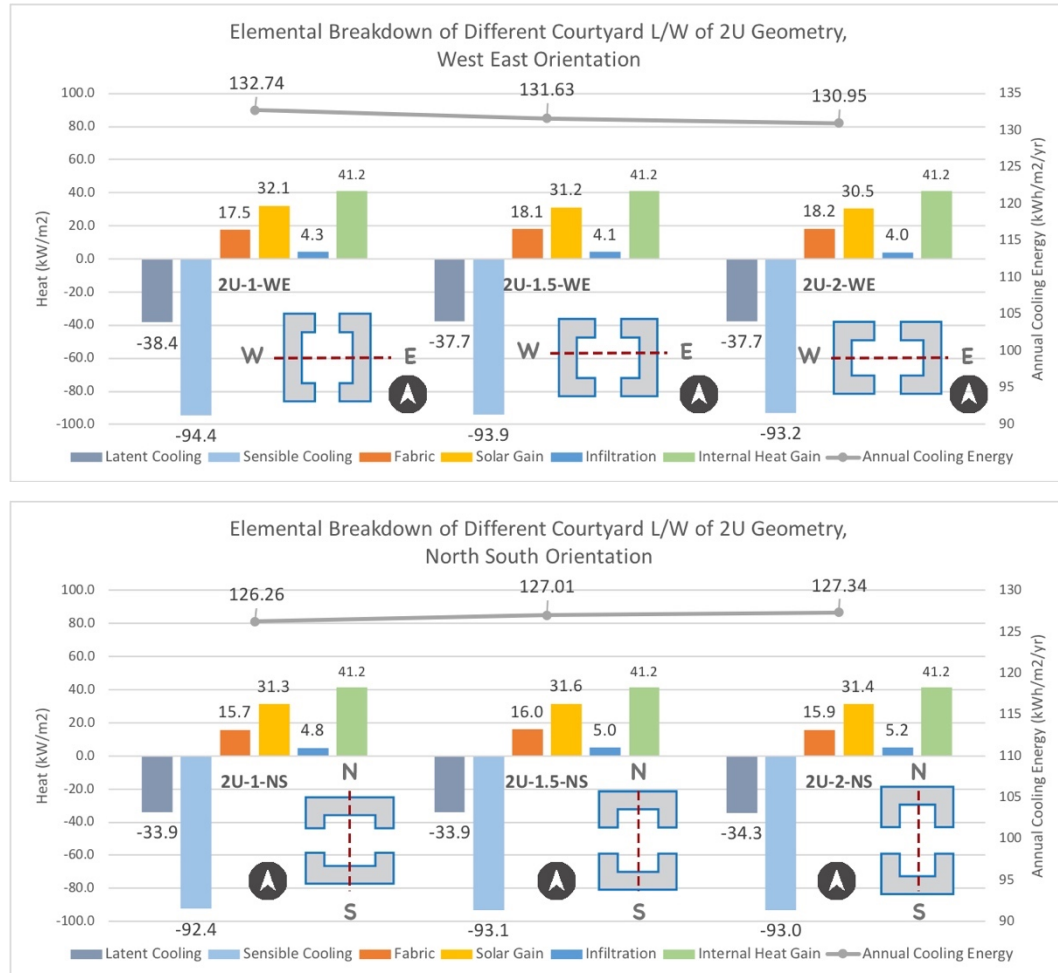


Figure 5.18 Elemental Breakdown of Double U Geometry, North South and West East Orientation

Increasing courtyard L/W from 1 to 2 of Double U geometry on north-south orientation increases annual cooling energy of 0.86%, and on west-east orientation decreases annual cooling energy of 1.35%. When the building is elongated alongside west-east axis, increasing courtyard L/W from 1 to 2 of Double U geometry will decrease the solar gain and infiltration gain about 1.6 kW/m² and 0.3 kW/m², respectively. Although the fabric gain increases (0.7 kW/m²), the sensible cooling load still decreases, because according to the regression analysis, solar gain and infiltration gain has higher relationship, than fabric gain. Latent cooling energy

also decreasing when the courtyard of Double U is elongated on west east orientation. On the other hand, increasing courtyard L/W from 1 to 2 of Double U geometry on north-south orientation will increase both solar gain and infiltration gain, thus increase the sensible cooling load. When infiltration gain increases, latent cooling load tend to increase also.

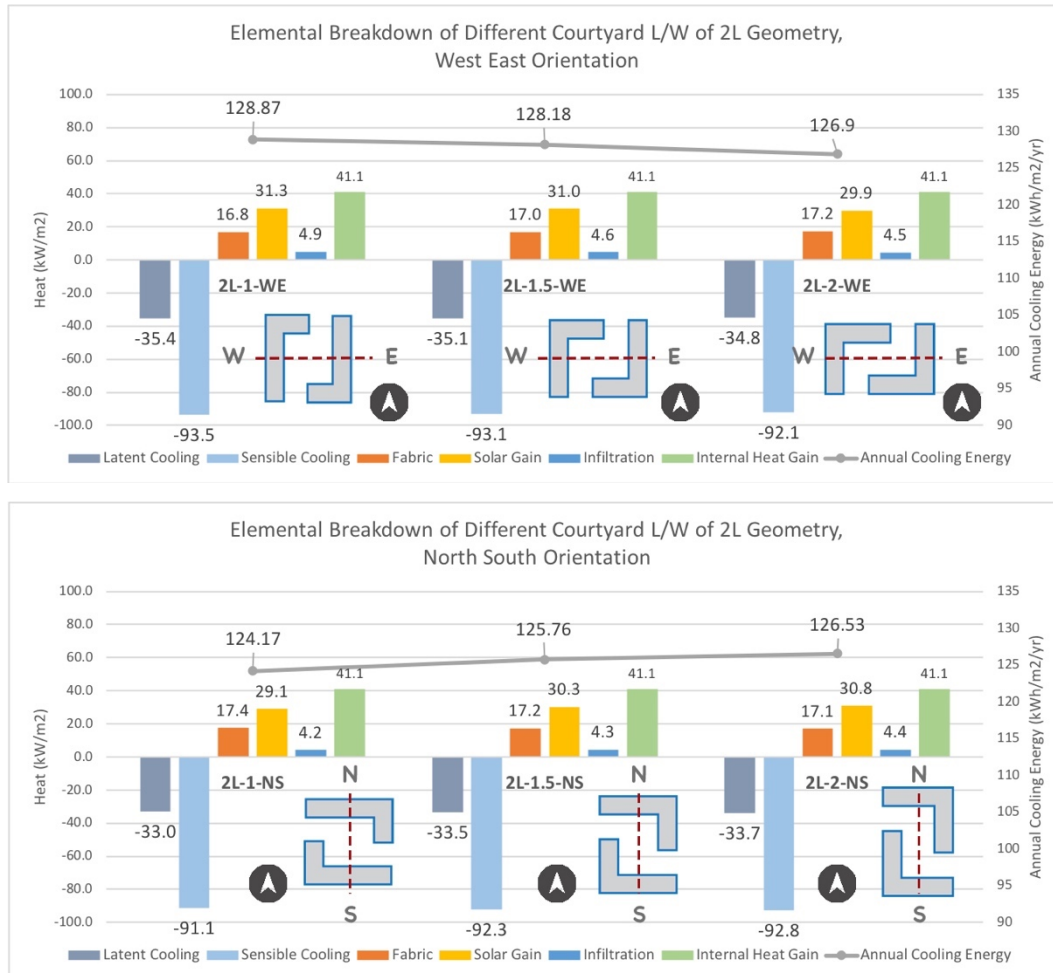


Figure 5.19 Elemental Breakdown of Double L Geometry, North South and West East Orientation

Similar with Double U geometry, increasing courtyard L/W from 1 to 2 of Double L, and Quadruple L geometries on west east orientation will increase the fabric gain, but decrease solar gain and infiltration gain. Solar gain of Double L geometry decreases 0.2 kW/m^2 and infiltration gain decreases 0.4 kW/m^2 , while solar gain of Quadruple L geometry decreases 0.9 kW/m^2 and infiltration gain decreases 0.8 kW/m^2 . Decreasing amount of solar and infiltration gain result in lower sensible cooling load. The differences of increasing courtyard L/W from 1 to

2 of Double L, and Quadruple L geometries on west east orientation is the amount of latent cooling load. For Double L geometry elongating the courtyard will result in lower latent cooling load of 0.6 kW/m^2 . On the other hand, latent cooling load of Quadruple L geometry increases 0.4 kW/m^2 and 0.2 kW/m^2 when the courtyard L/W 1.5 and 2, respectively, compared with courtyard L/W of 1. Although latent cooling load of Quadruple L geometry slightly increases, annual cooling load of Quadruple L geometry decreases because effect from decreasing sensible cooling load is higher than increasing latent cooling load.



Figure 5.20 Elemental Breakdown of Quadraple L Geometry, North South and West East Orientation

The cause of increasing annual cooling energy of Double L and Quadraple L geometries, when the courtyard L/W is increased from 1 to 2 on north south orientation is similar with Double U geometry, which is higher value of both latent and sensible cooling load. Increasing courtyard L/W from 1 to 2 of Double L, and

Quadruple L geometries on north south orientation will decrease the fabric gain, but increase solar gain and infiltration gain. Solar gain of Double L geometry increases 0.9 kW/m^2 and infiltration gain increases 0.2 kW/m^2 , while solar gain of Quadruple L geometry increases 0.1 kW/m^2 and infiltration gain increases 0.5 kW/m^2 . Latent Cooling load of both geometries also increase 0.7 .



Figure 5.21 Illustration of Solar Radiation Penetrating the Courtyard due to Courtyard Opening

In conclusion, the position of the courtyard opening within building geometry area determine the impact of elongating courtyard. Courtyard opening of Double U, Double L, and Quadruple L located in elongated side of the building. When Double U, Double L, and Quadruple L are elongated alongside north-south axis, the courtyard opening are facing west and east side, allowing solar radiation to penetrate the courtyard and diminishing shading effect of the courtyard. Compared with H and U geometry with courtyard L/W of 2, courtyard function of Double U, Double L, and Quadruple L is reduced because of solar radiation entering the courtyard.

5.3 Impact of Building Orientation on Annual Cooling Energy

As explained in 4.3.3, U, H, Double U, and Double L elongated alongside west east axis, will result in higher annual cooling energy compared with north – south axis. On the other hand, Quadruple L geometry generates lower annual cooling energy when the building is elongated alongside west east axis. In addition, buildings with courtyard L/W of 1 are more sensitive from the change of building orientation, compared with buildings with courtyard L/W of 2.

Elemental breakdown of building geometries is necessary in order to find the cause why the buildings react in different ways with the changing of orientation. Elemental breakdown related with change of building orientation will be divided in two segment. The first segment investigates H, U, and Double L geometries with courtyard L/W of 1 and 2. Changing orientation H, U, and Double L geometries

with courtyard L/W of 1 will rise annual cooling energy up to 3.79%. On the other hand changing orientation of these three geometries with courtyard L/W of 2 will increase annual cooling energy only up to 0.29%.

The second segment investigates Double U and Quadruple L geometries in which show contradictive result when the orientation is changed. Changing north south orientation to west east orientation of Double U geometry with different courtyard L/W will rise annual cooling energy up to 5.13%. On the other hand, changing north south orientation to west east orientation of Quadruple L geometry with different courtyard L/W will decrease annual cooling energy up to 1.78%.

a. Effect of Different Orientation on H, U, and Double L geometries

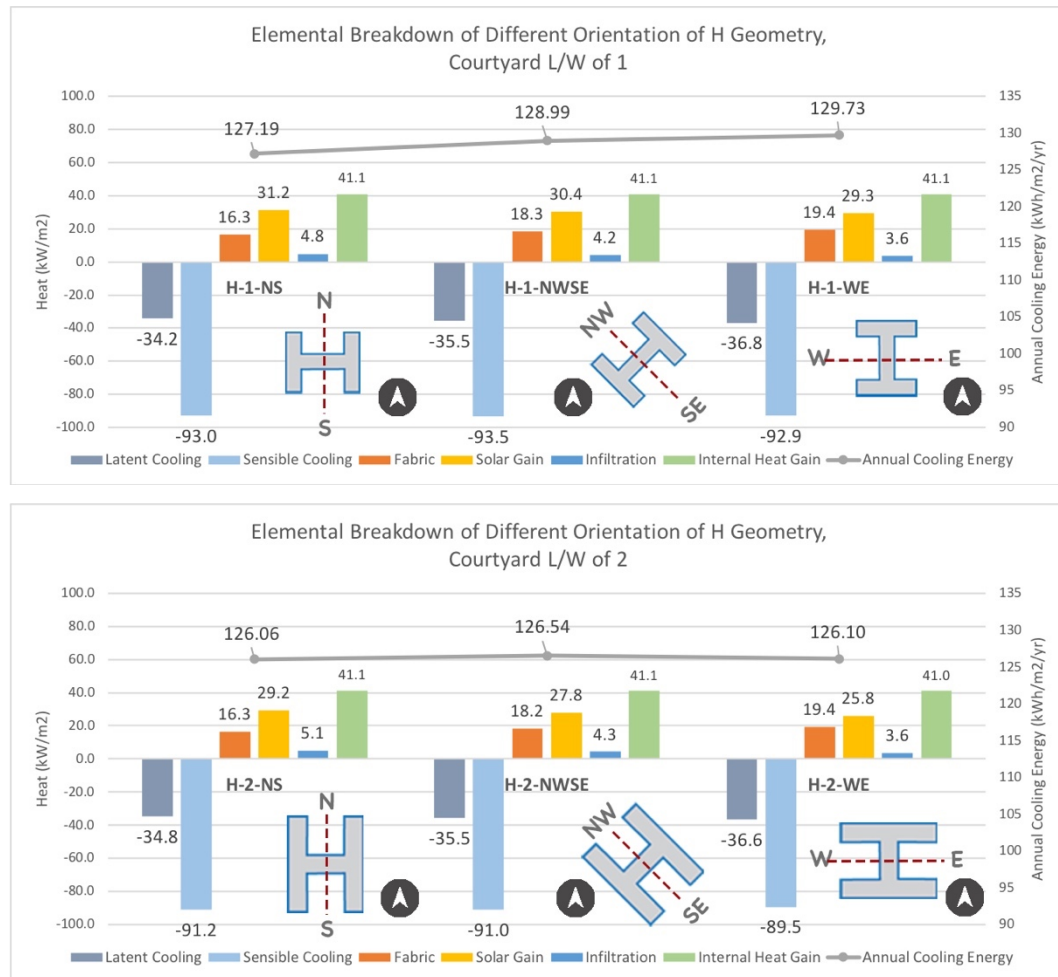
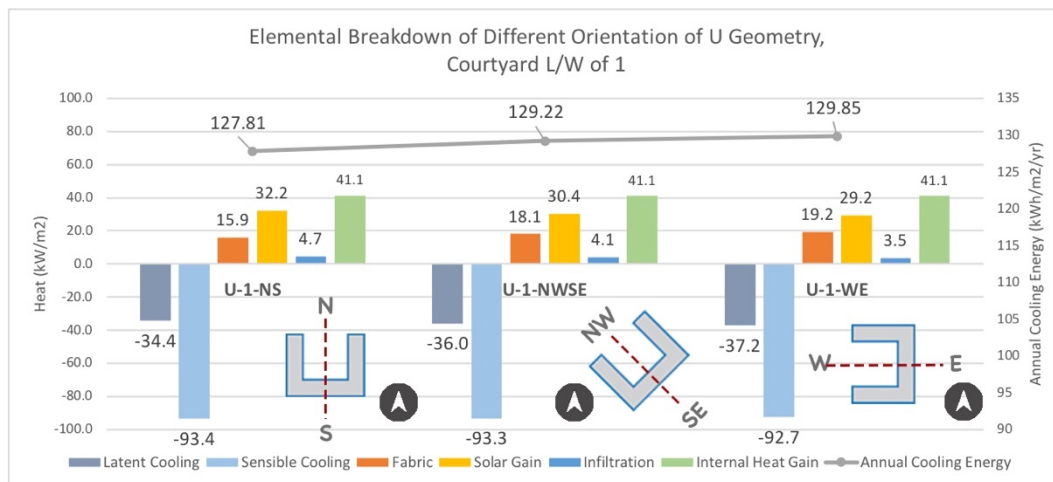


Figure 5.22 Elemental Breakdown of H Geometry, Courtyard L/W of 1 and 2.

According to the elemental breakdown, although the impact of different orientation on H, U and Double L geometries are similar, the cause is different. Increasing annual cooling energy, when the building orientation is changed, of H

and U geometries is mainly caused by latent cooling load. H and U geometries with courtyard L/W of 1 generate more annual cooling load than H and U geometries with courtyard L/W of 2, when the building orientation is changed, because building with courtyard L/W of 1 generate higher latent cooling load than building with courtyard L/W of 2. As a result, H and U geometries with courtyard L/W of 1 generate higher energy consumption when the building orientation is changed. On the other hand, for Double L geometry with courtyard L/W of 1, increased annual cooling energy is caused by both sensible and latent cooling load. In addition, Double L geometry with courtyard L/W of 2 does not experience significant change of annual cooling energy, when the building orientation is changed, because of trade-off between decreasing sensible cooling load, and increasing latent cooling load.

Solar and fabric gain of H geometry with courtyard L/W of 1 decrease 1.9 kW/m² and 1.2 kW/m², respectively. Although sensible cooling load of H geometry with courtyard L/W of 1 also decreases 0.1 kW/m², latent cooling load increases 2.6, kW/m² which result in increasing annual cooling energy of 2.54 kW/m²/yr. Similar with H geometry with courtyard L/W of 1, Solar and fabric gain of H geometry with courtyard L/W of 2 decrease 3.4 kW/m² and 1.5 kW/m², respectively. Sensible cooling load of H geometry with courtyard L/W of 2 reduces 1.7 kW/m², but latent cooling load increases 1.8 kW/m². As a result, annual cooling energy of H geometry with courtyard L/W of 2 increases slightly compared with H geometry with courtyard L/W of 1 when the building orientation is changed from north-south to west east.



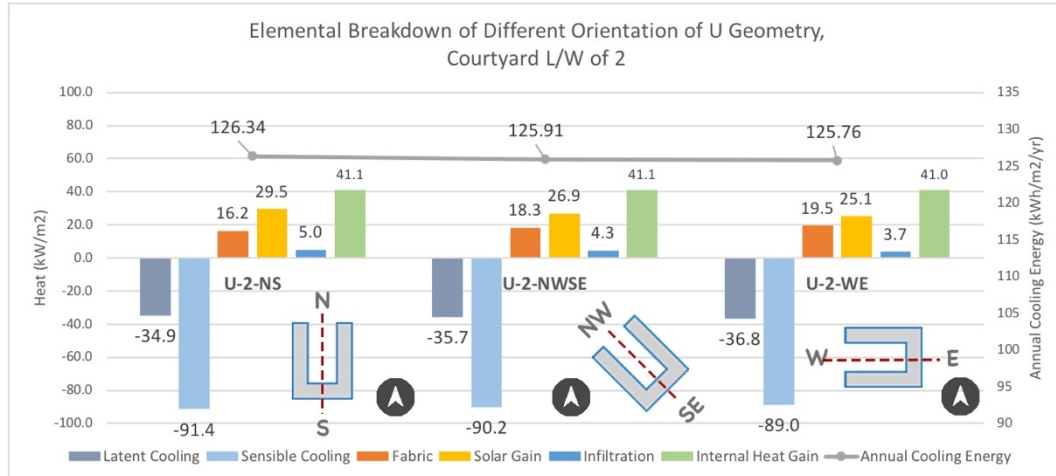


Figure 5.23 Elemental Breakdown of U Geometry, Courtyard L/W of 1 and 2.

Comparison of U geometry with courtyard L/W of 1 and 2 show similarity with H geometry with courtyard L/W of 1 and 2, when the building orientation is changed from north-south to west east. Solar and infiltration gain of U geometry with courtyard L/W of 1 and 2 decreases, 3 kW/m² and 1.2 kW/m² for courtyard L/W of 1, and 4.4 kW/m² and 1.3 kW/m² for courtyard L/W of 1, respectively. Decreasing amount of solar gain and infiltration gain reduce sensible cooling load of U geometry with courtyard L/W of 1 and 2 about 0.7 kW/m² and 2.4 kW/m², respectively. On the other hand latent cooling load of U geometry with courtyard L/W of 1 and 2 increase 2.8 kW/m² and 1.9 kW/m², respectively. As a result, annual cooling energy of U geometry with courtyard L/W of 2 reduces slightly 0.58 kW/m²/yr because the amount of decreasing sensible cooling load is 2.4 kW/m², and the amount of increasing latent cooling load is 1.9 kW/m².

Unlike H and U geometries, changing orientation for Double L geometry with courtyard L/W of 1 will increase solar and infiltration gain of 2.2 kW/m² and 0.7 kW/m², respectively, thus increasing the sensible cooling load 2.4 kW/m². The latent cooling load also increases 1.4 kW/m². Combination of both increasing sensible and latent cooling load, increase annual cooling energy 2.4 kW/m²/yr of Double L with courtyard L/W of 1, when the orientation is changed from north-south to west-east. For the case of Double L geometry with courtyard L/W of 2, sensible cooling load decreases 0.7 kW/m², because the solar gain decreases of 0.9 kW/m², when the orientation is changed from north-south to west-east. Although sensible cooling load decreases, latent cooling load increases 1.1 kW/m². As a

result, annual cooling energy of Double L with courtyard L/W of 2 increases 0.37 kW/m²/yr.

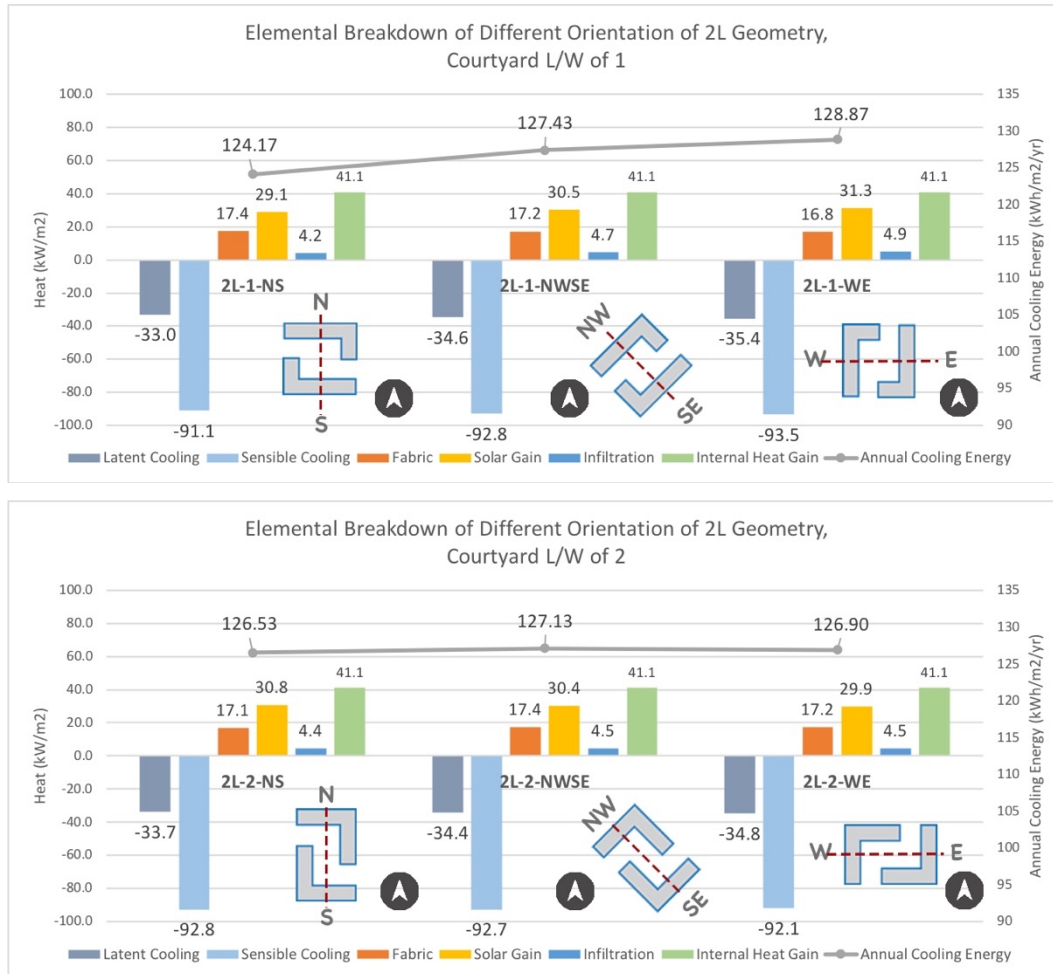


Figure 5.24 Elemental Breakdown of Double L Geometry, Courtyard L/W of 1 and 2.

b. Effect of Different Orientation on Double U and Quadruple L Geometries

Although Double U and Quadruple L geometries react differently, when the building orientation is changed from north-south to west-east, infiltration gain of these two geometries decreases 0.5 kW/m² and 1.3 kW/m², respectively. Fabric and solar gain of Double U geometry increases 1.8 kW/m² and 0.8 kW/m², respectively, thus result in increasing of sensible cooling load of 2 kW/m². Latent cooling load of Double U geometry also increases 4.5 kW/m². Combination of increasing both sensible and latent cooling load, increase annual cooling energy 6.48 kW/m²/yr of Double U with courtyard L/W of 1, when the orientation is changed from north-south to west-east.

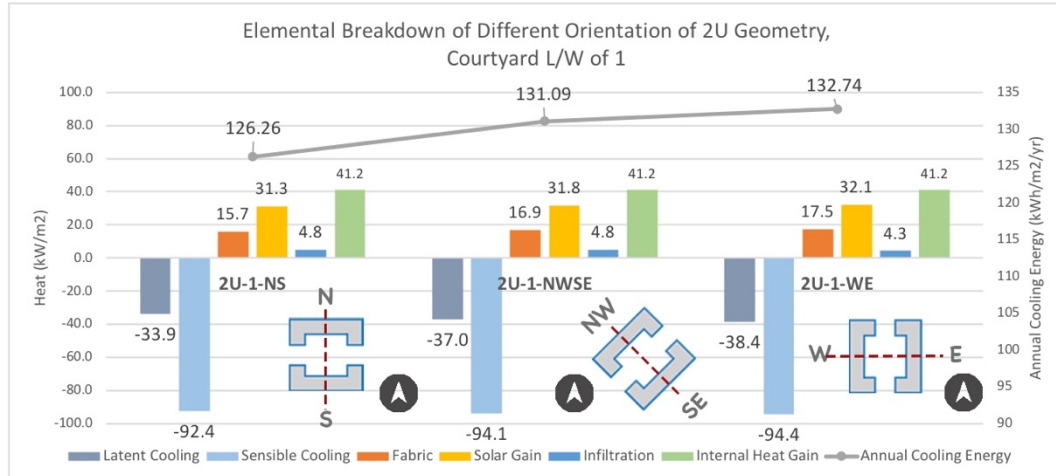


Figure 5.25 Elemental Breakdown of Double U Geometry, Courtyard L/W of 1

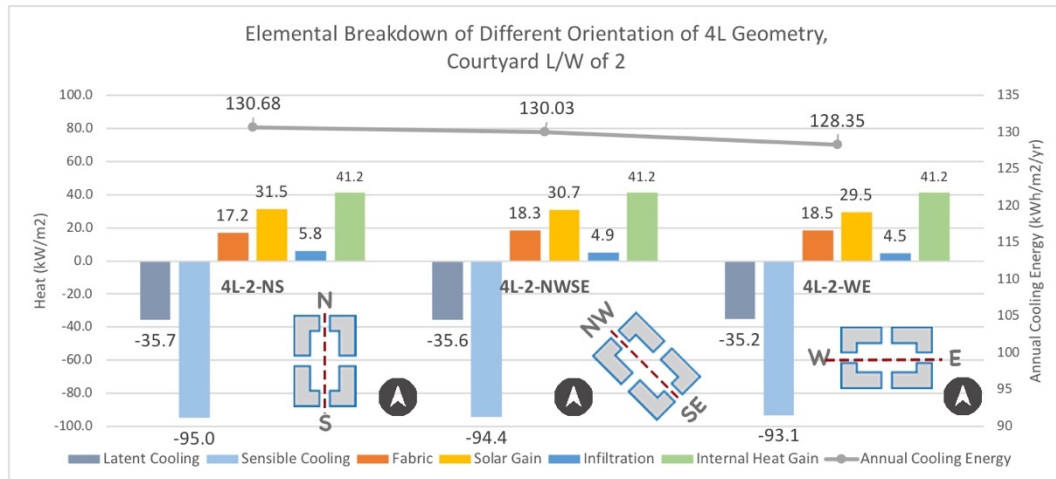


Figure 5.26 Elemental Breakdown of Quadruple L Geometry, Courtyard L/W of 2

Similar with infiltration gain, solar gain of Quadruple L geometry decreases 2 kW/m^2 , which result in decreasing sensible cooling load 1.9 kW/m^2 . In addition with decreasing sensible cooling load, latent cooling load of Quadruple L geometry decreases 0.5 kW/m^2 , when the building orientation is changed from north-south to west-east. As a result annual cooling energy of Quadruple L geometry decreases $2.33 \text{ kW/m}^2/\text{yr}$.

In conclusion, annual cooling energy of U, H, and Double L geometries are influenced by both latent cooling and sensible cooling, when the orientation is changed. On the other hand, annual cooling energy of Double U and Quadruple L geometries are influenced by sensible cooling rather than latent cooling. Double U geometry is the most sensitive geometry when the orientation is changed, because it has the highest percentage of windows located on perimeter area.

5.4 Evaluation of Each Building Geometry

Evaluation of each building geometry will investigate the best and worst performance of each building geometry. Evaluation of building geometries will be divided into three group as explained in 5.1.1 because geometries within the same group tend to have similar courtyard L/W and orientation on their best and worst performance.

5.4.1 Evaluation of H and U Geometries

Both H and U geometries generate the lowest cooling load when the courtyard L/W is 2. However, H geometry generate the lowest cooling energy of 126.06 kW/m²/yr when the building is elongated alongside north south axis (H-2-NS), and U geometry generate the lowest cooling energy of 125.76 kW/m²/yr when the building is elongated alongside west east axis (U-2-WE). Both H and U geometries generate the highest cooling load of 129.73 kW/m²/yr and 129.85 kW/m²/yr, respectively, when the courtyard L/W 1, and the building is elongated alongside west east axis.

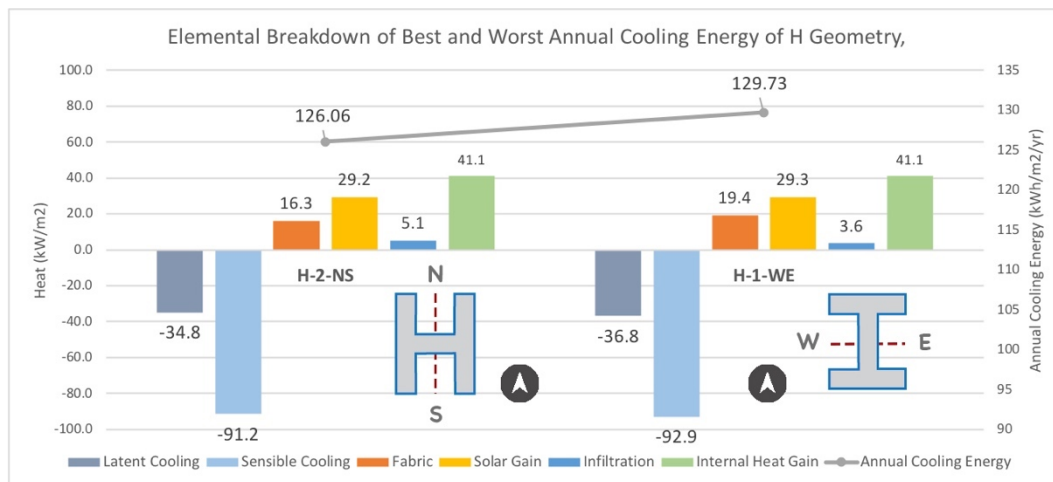


Figure 5.27 Elemental Breakdown of Best and Worst Annual Cooling Energy of H Geometry

According of elemental breakdown of best and worst case of H geometry, H-1-WE has higher latent and sensible cooling load of 2 kW/m² and 1.7 kW/m², respectively than H-2-NS. Courtyard opening of H-1-WE face west and east side, thus diminishing shading effect by courtyard, because of high solar exposure from the east and west side. In addition, H-1-WE has square courtyard (courtyard L/W of 1) which provide less shaded area than rectangular courtyard as stated by Muhaisen (2006). On the other hand, H-2-NS, which generate the lowest annual

cooling energy of H geometry, has rectangular courtyard with courtyard L/W of 2, with the courtyard opening position facing north south. The courtyard opening position of H-2-NS will block high solar exposure from the east and west side, and provide shaded area. Although H-2-NS is elongated alongside north south axis, which result in high solar exposure of elongated side of the building, H-2-NS generate lower solar gain of 0.1 kW/m^2 than H-1-WE. This is due to areas receiving self-shading by courtyard of H-2-NS is greater than the elongated side of the building facing west and east side. Other than, the solar gain factor, H-2-NS with elongated side facing west east has higher infiltration gain than H-1-WE, because the dominant wind in Surabaya come from west and east side. However, although the infiltration gain of H-2-NS is higher than H-1-WE, H-2-NS has lower sensible cooling load than H-1-WE.

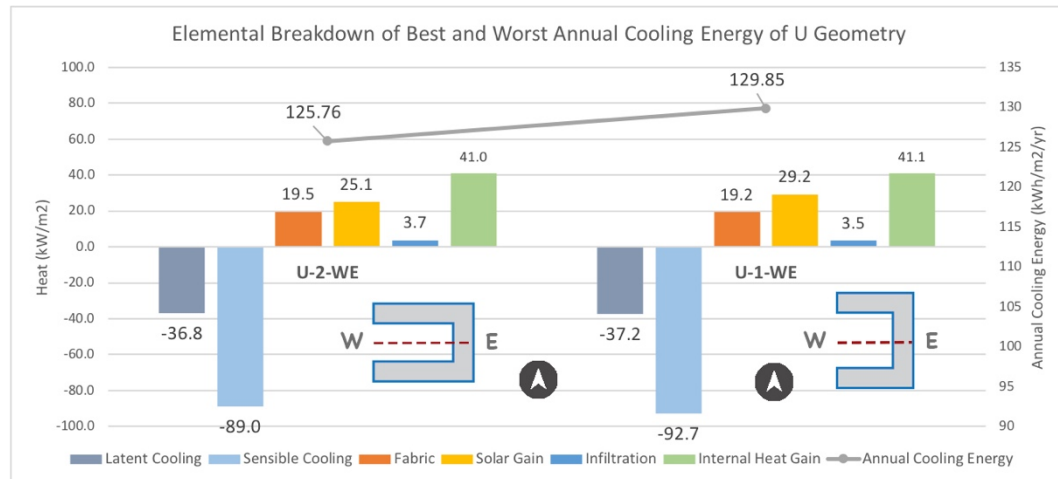


Figure 5.28 Elemental Breakdown of Best and Worst Annual Cooling Energy of U Geometry

Both best and worst case of U geometry is building elongated alongside west east axis. With similar courtyard area, U-1-WE has higher building surface area exposed to west and east side of the building, thus increasing the solar gain of 4.1 kW/m^2 . In addition, rectangular courtyard (courtyard L/W of 2) provide better shaded area than the square one (courtyard L/W of 1). Almhafdy et al. (2015) also stated that rectangular U-shape courtyard provide better thermal performance than the square one. Similar with the case of H geometry, although U-1-WE has lower infiltration gain than U-2-WE, U-1-WE generate higher latent cooling load than U2-WE.

5.4.2 Evaluation of Double U and Double L Geometries

Both Double U and Double L geometries generate the lowest annual cooling load of 126.26 kW/m²/yr and 124.17 kW/m²/yr respectively, when the courtyard L/W is 1, and the building is elongated alongside north south axis. Double U and Double L geometries also generate the highest cooling load of 132.74 kW/m²/yr and 128.87 kW/m²/yr with similar courtyard L/W of 1 and the building is elongated alongside west east axis.

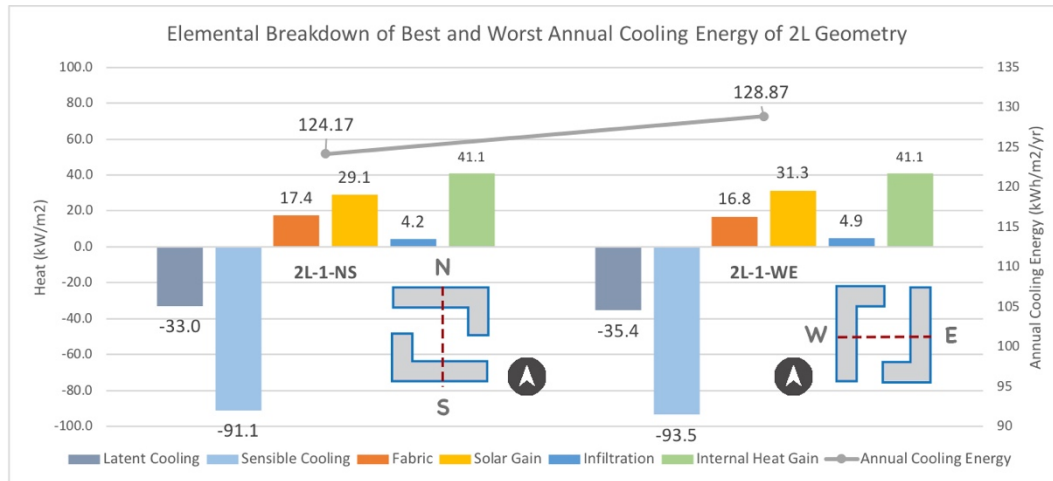


Figure 5.29 Elemental Breakdown of Best and Worst Annual Cooling Energy of Double L Geometry

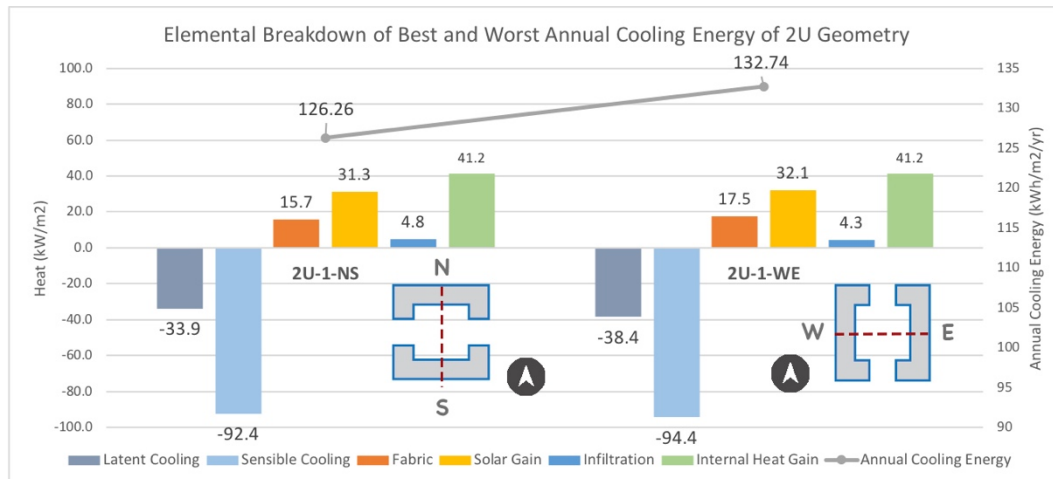


Figure 5.30 Elemental Breakdown of Best and Worst Annual Cooling Energy of Double U Geometry

It is obvious that courtyard opening position influence best and worst performance of Double U and Double L geometries. Both building geometries generate highest annual cooling energy, when the courtyard opening position are

facing north and south side, because the elongated side of apartment units are facing west and east side, receiving high solar radiation.

5.4.2 Evaluation of Quadruple L Geometry

Quadruple L geometry generates the lowest annual cooling load of 128.35 kW/m²/yr, when the courtyard L/W is 2, and the building is elongated alongside west east axis. On the other hand, Quadruple L geometry generate the highest cooling load of 131.17 kW/m²/yr when the courtyard L/W is 1, and the building is elongated alongside northwest southeast axis.

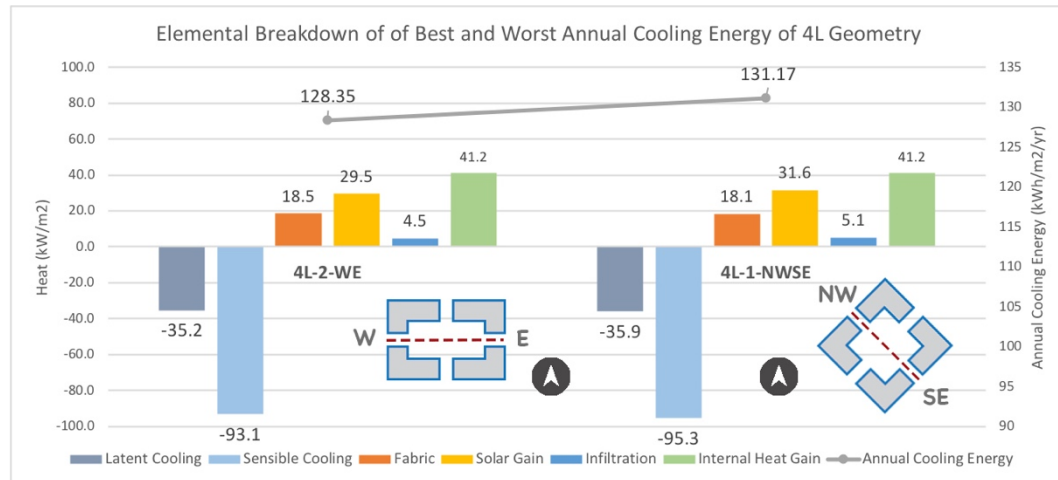


Figure 5.31 Elemental Breakdown of Best and Worst Annual Cooling Energy of Quadruple L Geometry

Quadruple L building with courtyard L/W of 2 has the lowest annual cooling energy on west-east orientation because the longest side of the building is facing north and south, minimizing solar exposure from the west and east side. When Quadruple L geometry with courtyard L/W of 1 oriented on northwest southeast orientation, the courtyard opening which located on four different side of the building lead solar radiation to penetrate the courtyard. In addition, among five different geometries studied, Quadruple L geometry has the highest volume to surface ratio, thus more susceptible towards solar radiation.

5.5 Evaluation of Building Geometries Performance

5.5.1 Experimental Results and Base Case Model

Base case model in this study is Double U geometry with courtyard L/W of 2 elongated alongside west east axis (2U-2-WE), with annual cooling energy of

base case model is 130.95 kWh/m² yr. According to the comparison with base case model performance, all performance of H, U, and Double L geometries have lower annual cooling energy. The similarity of these geometries is the location of the apartment tower width.

Table 5.1 Evaluation of Model Experiments Performance according to Base Case

Base Case Standard (130.95 kWh/m ² /yr)				
Geometry	Orientation	L/W 1	L/W 1.5	L/W 2
H	N-S	127.19	126.67	126.06
	NW-SE	128.99	127.68	126.54
	W-E	129.73	127.46	126.1
U	N-S	127.81	126.4	126.34
	NW-SE	129.22	127.21	125.91
	W-E	129.85	127.25	125.76
Double U	N-S	126.26	127.01	127.34
	NW-SE	131.09	130.55	130.12
	W-E	132.74	131.63	130.95
Double L	N-S	124.17	125.76	126.53
	NW-SE	127.43	127.15	127.13
	W-E	128.87	128.18	126.9
Quadruple L	N-S	129.82	130.55	130.68
	NW-SE	131.17	130.52	130.03
	W-E	129.82	129.34	128.35
	Indicate annual cooling energy of model experiments fall below the standard			

5.5.2 Experimental Results and Green Building Standard

Green Building Council Indonesia (GBCI) standard of apartment is used to evaluate the result of experiment result. However, the standard from GBCI accounts for all energy usage or the Energy Use Intensity (EUI), such as electricity consumption from electronic appliances, water pumping, lighting, as well as cooling energy. On the other hand, annual cooling energy is the main concern in this study, thus the other variable are regarded similar in all model experiments.

According to Boranian (2013) and survey from National Environment Agency of Singapore (2014), cooling energy consume 30 – 37% energy consumption, in a residential building. In addition, Singapore Household Consumption Survey (2012) stated that air conditioner accounts for 36% energy consumption in residential building. In order to compare the EUI standard from

GBCI and the study of annual cooling energy, this study used 30 - 37% of GBCI EUI standard of green apartment as benchmark for the result of this study.

According to this benchmark, annual cooling energy of H and U geometries on different courtyard L/W and orientation fall below the benchmark, except of H and U geometries with courtyard L/W of 1 elongated alongside west-east axis. As explained in 5.4.1, when of H and U geometries are elongated alongside west-east axis, the courtyard opening are oriented toward west (U geometry), and both east-west (H geometry). As a result, the sun radiation can penetrate the courtyard area and diminishing the self-shading of the courtyard. Annual cooling energy of H and U geometries with longer courtyard (L/W of 1.5 and 2) elongated alongside west-east axis fall below the standard, because elongated courtyard provide better shading than the square one as explained by Muhaisen (2006).

Table 5.2 Evaluation of Model Experiments Performance according to Indonesian Green Building Standards

30 - 37% of GBCI Standard (105 - 129.5 kWh/m ² /yr)				
Geometry	Orientation	L/W 1	L/W 1.5	L/W 2
H	N-S	127.19	126.67	126.06
	NW-SE	128.99	127.68	126.54
	W-E	129.73	127.46	126.1
U	N-S	127.81	126.4	126.34
	NW-SE	129.22	127.21	125.91
	W-E	129.85	127.25	125.76
Double U	N-S	126.26	127.01	127.34
	NW-SE	131.09	130.55	130.12
	W-E	132.74	131.63	130.95
Double L	N-S	124.17	125.76	126.53
	NW-SE	127.43	127.15	127.13
	W-E	128.87	128.18	126.9
Quadruple L	N-S	129.82	130.55	130.68
	NW-SE	131.17	130.52	130.03
	W-E	129.82	129.34	128.35
	Indicate annual cooling energy of model experiments fall below the standard			

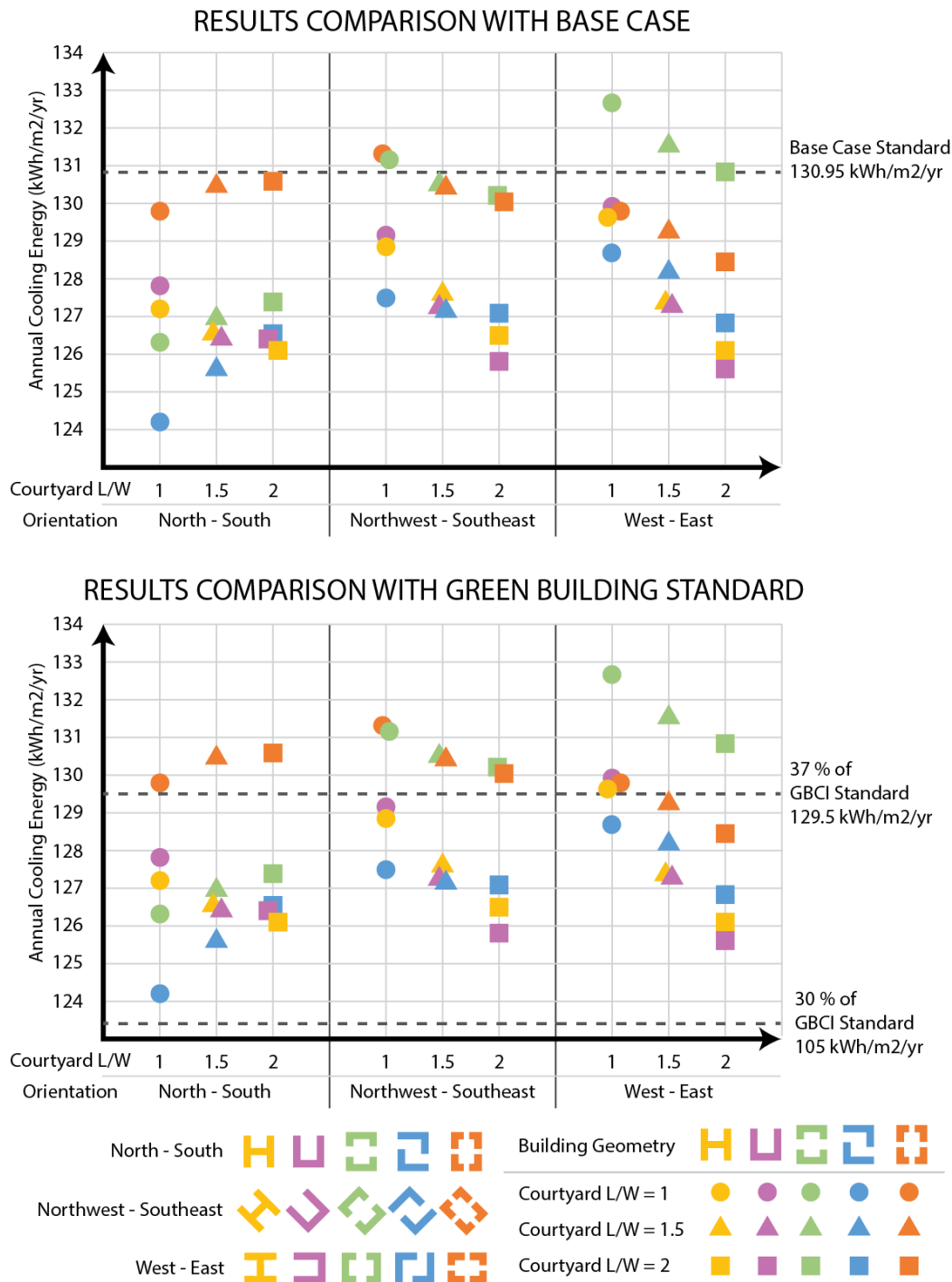


Figure 5.32 Diagram Evaluation of Experimental Research

Annual cooling energy of Double U geometry elongated alongside north south axis with three different courtyard L/W fall below the benchmark of 105 - 129.5 kWh/m²/yr. On the other hand, none of Double U geometry elongated alongside northwest southeast and west east axis generate annual cooling energy lower than 129.5 kWh/m²/yr. This phenomenon is caused by the position of

courtyard opening located on west and east side when the building is elongated alongside north south axis, thus minimizing exposure of solar radiation on west and east façade.

Although Double L geometry has similar building shape index with Double U Geometry, annual cooling energy of Double L geometry fall below the benchmark on all combination of building orientation and courtyard L/W. This is because the position of apartment tower width of Double L geometry which located on the perimeter of the building. Apartment tower width of Double U geometry face the courtyard area, and walls located in the perimeter of Double U geometry have WWR of 30%.

Almost all variation of Quadruple L Geometry generate higher annual cooling energy than the standard. This is because Quadruple L geometry has higher building perimeter area than the other three geometries. As a result, Quadruple L geometry is more susceptible towards solar radiation and wind exposure, which could increase the cooling load.

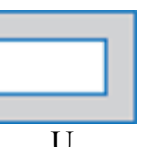
5.6 Minimum Building Geometry on Different Courtyard L/W and Orientation

In order to provide guideline for architect and developer, it is important to evaluate building geometry which consume the least cooling energy in different courtyard L/W and Orientation. According to this evaluation, Double L, H, and U geometries tend to generate lower annual cooling energy. These building geometries have higher windows percentage facing the courtyard, because of apartment tower width on the perimeter of the building, which minimize exposure of solar radiation.

According to the simulation result, Double L and U geometry tend to generate lower annual cooling energy in different orientation and courtyard aspect ratio. When the building has courtyard L/W of 1, Double L geometry consume the lowest annual cooling energy in three different orientation. For building with courtyard L/W of 1 and 1.5, Double L generate the lowest annual cooling energy when the building is elongated alongside north-south and northwest-southeast axis. On the other hand, U geometry has the lowest annual cooling energy when courtyard L/W of the building is 1.5 elongated alongside west-east axis. For

building with courtyard L/W of 2, U geometry generate the lowest annual cooling energy on northwest-southeast and west-east orientation. The high percentage of windows facing the courtyard and the courtyard opening position result in lower annual cooling energy of Double L building with courtyard L/W of 1 in three different orientation. Compared with the other geometries, U geometry only has one courtyard opening on the width side of the building, creating more shaded area when the courtyard is elongated. As a result, U geometry generate the lowest annual cooling energy when the courtyard L/W is 2. In addition, H geometry generate the lowest energy consumption than the other geometries with courtyard L/W of 2, and elongated alongside north-south axis.

Table 5.3 Best Building Geometry with courtyard in Different Orientation and Courtyard L/W

		Courtyard L/W		
		1	1.5	2
Orientation	N-S	 Double L	 Double L	 H
		124.17 kWh/m ² /yr	125.76 kWh/m ² /yr	126.06 kWh/m ² /yr
	NW-SE	 Double L	 Double L	 U
		127.43 kWh/m ² /yr	127.15 kWh/m ² /yr	125.91 kWh/m ² /yr
	W-E	 Double L	 U	 U
		128.35 kWh/m ² /yr	127.25 kWh/m ² /yr	125.76 kWh/m ² /yr

5.7 Effectiveness of Building Geometry on Annual Cooling Energy

The result of this research shows that changing the building geometry in similar orientation and courtyard aspect ratio could reduce annual cooling energy

up to 4.35%. Combination of building geometry, courtyard aspect ratio, and building orientation could reduce annual cooling energy of courtyard building up to 6.46%. The impact of three different variables studied is smaller compared to several research about various building elements conducted in warm humid tropical region.

According to previous studies, building façade component such as window area, type of glazing, and building material contribute more to the reduction of cooling energy than the result of this study. Hassan and Al-Ashwal in Mirrahimi et al. (2016) stated that adding exterior wall thermal insulation of high rise apartment in Malaysia could reduce cooling energy up to 20% and decreasing peak cooling load up to 29%. In high rise apartment of Hongkong, increasing window to floor ratio (WFR) of 10.4% lead to higher cooling energy of 12.8% (Cheung et al., 2005). Study in Malaysia of window to floor ratio (WFR) supports the previous study, as the WFR increases 10%, cooling load rises about 1.3% (Al-Tamimi and Fadzil, 2012). Not only window area of a building, substitution of glazing material from single clear glass of 6 mm to double glazed clear glass with lower emissivity could reduce cooling energy up to 19% (Al-Tamimi in Mirrahimi et al., 2016).

Although the impact of building geometry is less than the component of the building envelope, it is necessary to minimize solar exposure to the building before applying building components which could reduce annual energy consumption. While retrofitting wall insulation and substitution of glazing component could be conducted after the operation of a building, decision making of building geometry and building orientation is one of the first step in designing a building. It is recommended to consider building geometry with minimum cooling energy.

CHAPTER 6

CONCLUSION

6.1 Conclusion

The objective of this research is to analyze and evaluate the impact of various apartment geometries with courtyard towards annual cooling energy. Independent variables of this research are building geometry, courtyard L/W, and building orientation, while building annual cooling energy is dependent variable in this research. The method of this study is experimental research with simulation as tactics. Control variables of this research are the courtyard area, building window to wall ratio, building material, building height, and factors influence internal heat gain, such as number of occupant, lighting, and electronic appliances inside the building. Energy consumption other than cooling energy, such as electricity from lighting and electronic appliances, and water pump, are considered the same in all model experiments. Therefore the result of this research only represent cooling energy caused by Air Conditioner usage inside the apartment units. In real life condition, energy consumption from electronic appliances other than cooling, lighting, etc. may contribute to the higher electricity consumption than cooling energy of a building.

6.1.1 Performance of Building Geometries

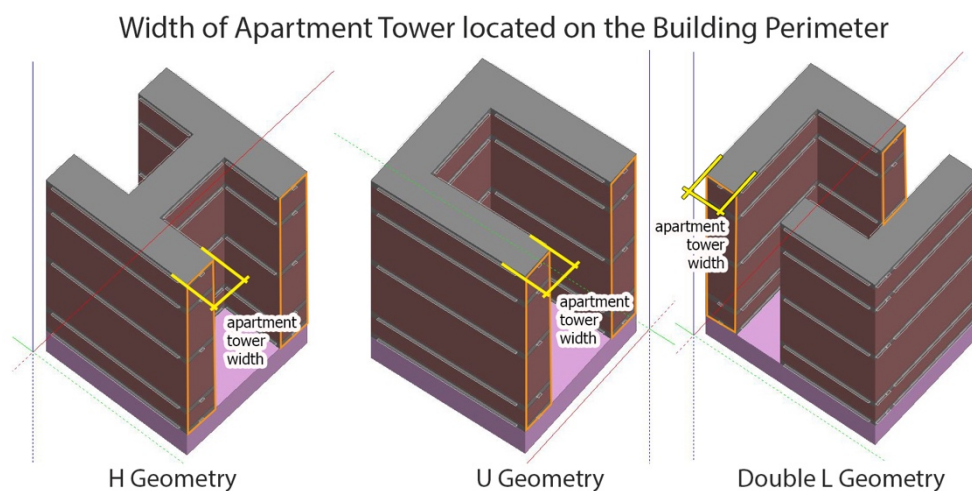


Figure 6.1 Geometries with Apartment Tower Width Located on Building Perimeter

The performance of various building geometries are evaluated according to the base case model and predicted cooling energy consumption of Green Building Council Indonesia (GBCI) standard of apartment building. The performance evaluation shows that geometries with higher percentage of windows facing the courtyard area, such as U, and Double L geometries, perform better in different orientation and courtyard aspect ratio than the other geometries. Geometries with higher percentage of windows facing the courtyard area have apartment tower width located in the perimeter area, as shown by Figure 6.1. Higher percentage of windows facing the courtyard minimize solar radiation entering the building. However, percentage of solar radiation facing the courtyard is not directly proportional to the annual cooling energy, as the position of the courtyard opening also determine cooling energy of a building.

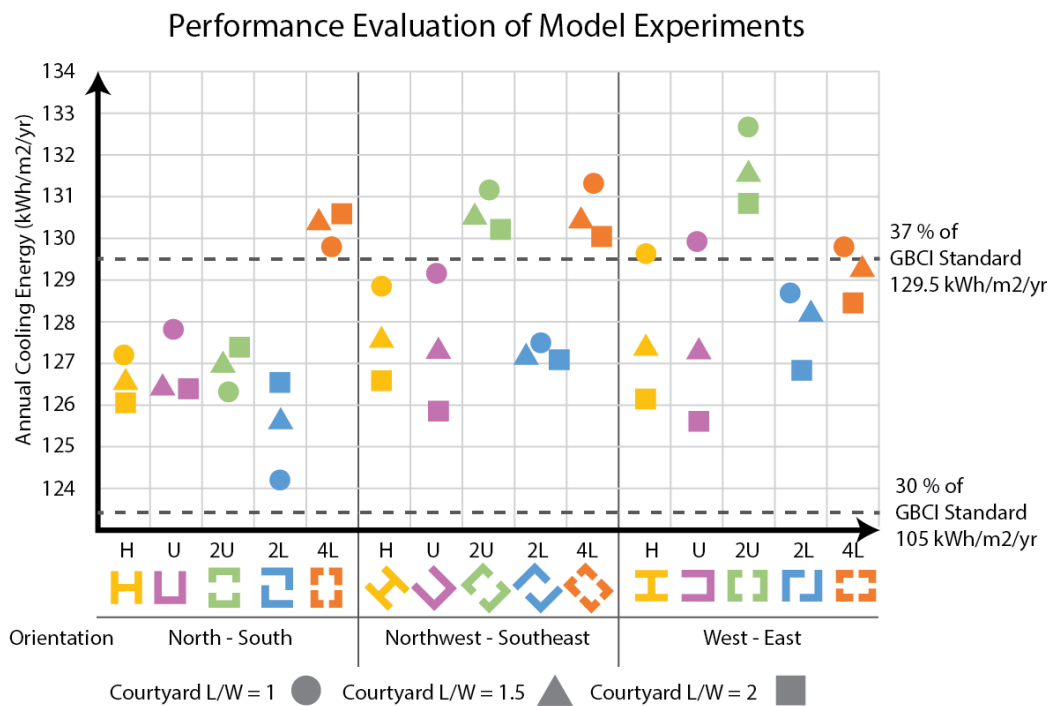


Figure 6.2 Performance Evaluation of Model Experiments

6.1.1 Impact of Building Geometry on Annual Cooling Energy

The result of this research shows that changing the building geometry in similar orientation and courtyard aspect ratio could reduce annual cooling energy up to 4.35%. Impact of three different independent variables (building geometry, courtyard aspect ratio, and building orientation) could reduce annual cooling energy

of courtyard building up to 6.46%. Findings of this research and literature review of previous studies show that the impact of building shapes are relatively small compared to the impact of window to wall ratio, building insulation, and glazing component (Al-Tamimi and Fadzil, 2012; Hassan and Al-Ashwal in Mirrahimi et al., 2016;)

a. Influence of Building Geometry on Annual Cooling Energy

Comparison of five different geometry studied is conducted within similar circumstances: similar orientation, and courtyard aspect ratio. In order to evaluate the impact of transforming building geometry, geometry which generate the highest annual cooling energy is compared with geometry with lowest cooling energy consumption. When the building is elongated alongside north-south axis, the maximum energy reduction from transforming the building geometry is 4.35% when Quadruple L geometry with courtyard L/W of 1 is transformed into Double L geometry. On northwest-southeast orientation, maximum saving of cooling energy about 3.24%, could be obtained by transforming Double U geometry with courtyard L/W of 2 into U geometry. On west-east orientation, 3.96% reduction of cooling energy can be achieved by geometry transformation of Double U geometry with courtyard L/W of 2 into U geometry.

According to Yeang (2006), building energy consumption is influenced by building form, orientation, and building volume to surface ratio. Rashdi and Embi (2016) also stated that surface to volume ratio is directly proportional to the cooling energy consumption. The result of this study shows that higher surface to volume ratio tends to have higher annual cooling energy (Quadruple L geometry), because of exposure to solar radiation. However, surface to volume ratio is not directly proportional to the cooling energy consumption, because the building shape index does not represent self-shading, window wall ratio, as well as orientation of the building as mentioned by Raji et Al. (2017).

In the case of high rise apartment with courtyard, self-shading is very important in minimizing the annual cooling energy of a building. As mentioned by Zakaria and Kubota (2014) self-shading is one of the main function of courtyard in a building. Five different geometries of high rise apartment with courtyard in Surabaya generate different annual cooling energy because the position of the

courtyard opening and percentage of window area facing the courtyard (percentage of shaded and unshaded windows area of a building). Different geometries of courtyard building will result in various layout arrangement and define the position of courtyard opening, layout arrangement, thus result in the different area of windows facing the courtyard and windows located on the perimeter area. Jang et al. (2015) also stated that layout of apartment could influence its energy demand.

b. Influence of Courtyard L/W on Annual Cooling Energy

Elongating the courtyards of H, and U geometry could reduce annual cooling energy up to 2.80%, and 3.15%, respectively. Elongating the courtyard of Double U, Double L, and Quadruple L geometries will decrease annual energy consumption up to 1.35% when the building is elongated alongside west-east, and northwest – southeast axis. On the other hand, elongating the courtyard of Double U, Double L, and Quadruple L geometries will increase annual energy consumption up to 1.90% when the building is elongated alongside north-east axis.

In general the longer the courtyard, the lower annual cooling energy of a building (Muhaisen and Gadi, 2006), Manioglu and Oral (2015). However in the case of high rise apartment with courtyard, building orientation and courtyard opening position play important role in determining effectiveness of courtyard self-shading. As stated by Almhafdy et al. (2015), courtyard opening will influence thermal condition of area surrounding the opening. As a result, U geometry which has only one courtyard opening is the most sensitive when the courtyard is elongated, because it has only one courtyard opening. When the courtyard is elongated, courtyard of U geometry will generate more shading than the other geometries with more courtyard opening. In addition, elongating the courtyard of Double U, Double L, and Quadruple L, alongside north south axis will increase annual energy consumption, because these geometries have courtyard opening located on the west and side of the building, allowing solar radiation to penetrate the courtyard.

c. Influence of Building Orientation on Annual Cooling Energy

Changing building orientation from north-south axis to west-east axis will generate higher cooling energy up to 5.30% in four geometries studied : H, U, Double U, and Double L Geometries. On the other hand, changing building

orientation from north-south axis to west-east of Quadruple L Geometry will generate lower cooling energy up to 1.78%. Similar with the impact of elongating the courtyard, position of courtyard gap and percentage of windows facing the courtyard area determine the impact of changing building orientation.

Double U geometry is the most sensitive geometry when the orientation is changed, because of lower percentage of windows facing the courtyard. Although, the impact of different building geometry, and courtyard aspect ratio are not significant on latent cooling load, the impact of changing building orientation of building contribute to the alteration of latent cooling, thus influence the building annual cooling energy, such as the cases of H, U, and Double U geometry.

Four of five different geometries studied perform better when the building is elongated longitudinally on north-south axis. Only Quadruple L which perform best on west east orientation. Muhaisen (2006) mentioned that optimum shaded area of courtyard in equatorial region is obtained when the courtyard is elongated alongside north south axis. The results of this experiments show that self-shading generated by the courtyard, when the building is elongated alongside north-south axis, is able to lower annual cooling energy of the buildings.

6.1.2 Building Geometry with Minimum Annual Cooling Energy

In this research, where building façade components are the control variables, two variables which determine annual cooling energy of courtyard building are percentage of windows facing the courtyard and position of the courtyard opening. Double L geometry generate the lowest annual cooling energy when the building courtyard L/W is 1, because it has the highest percentage of windows facing the courtyard. On the other hand, U geometry tends to perform better when building courtyard L/W is 2, because courtyard of U geometry generate more shaded area than the other geometries. In addition, windows facing the courtyard and position of courtyard opening are highly influenced building cooling energy, when the orientation and courtyard aspect ratio are changed.

6.2 Recommendation

In order to develop further investigation of various geometries of courtyard apartments, the study can be developed as follows :

1. Investigate further the impact of latent cooling on different building geometries with courtyard, and contributing factors of latent cooling.
2. Investigate the impact of various layout arrangement in different building geometries with courtyard towards annual cooling energy. Various layout arrangement could include different window, and cores position.
3. Investigate the impact of different size of courtyard openings in courtyard apartment geometries. In this research the courtyard opening area is similar in all model experiments.

According to the evaluation of impact of geometry on high rise courtyard apartment in Surabaya, there are several recommendation related to the findings of this study, as follows :

1. Double L geometry is recommended when the building has courtyard L/W of 1. U geometry is recommended when the building has courtyard L/W of 2 elongated longitudinally along northwest - southeast, and west-east axis. H geometry is suitable for building with courtyard L/W of 2 elongated longitudinally along north - south axis.
2. In high rise apartment with courtyard, the window position play important role in determining annual cooling energy of a building. Building which has higher percentage of windows facing the courtyard than windows located in the building perimeter, will generate lower annual cooling energy. It is recommended to shade windows located in the building perimeter in order to lower annual cooling energy consumption.
3. In order to lower cooling energy consumption, wall insulation, and double glazing could be installed in the perimeter façades of courtyard building which do not benefit self-shading generated by the courtyard.

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ATTACHMENT

Attachment 1 : Air Temperature of Bale Hinggil Apartment and Surabaya Area on 8th – 10th November 2017

Date	Hour	Temperature				
		Court-yard (Tc)	Roof-top (Tr)	Wonorejo, Surabaya (Ts)	ΔT (Tc - Ts)	ΔT (Tr - Ts)
8-Nov-17	1:00:00	27.86	27.12	26.89	0.97	0.23
	2:00:00	27.55	26.80	26.58	0.97	0.21
	3:00:00	27.43	26.73	26.40	1.03	0.33
	4:00:00	27.32	26.73	26.28	1.04	0.45
	5:00:00	27.16	26.47	26.34	0.82	0.13
	6:00:00	27.42	26.67	26.44	0.97	0.22
	7:00:00	28.47	29.18	27.12	1.35	2.06
	8:00:00	29.69	31.52	29.21	0.48	2.31
	9:00:00	30.45	31.46	31.56	1.11	0.11
	10:00:00	31.60	32.21	32.49	0.89	0.28
	11:00:00	33.24	32.76	33.80	0.56	1.04
	12:00:00	33.53	33.31	34.78	1.26	1.47
	13:00:00	32.79	33.17	35.32	2.53	2.15
	14:00:00	32.70	33.24	35.35	2.65	2.11
	15:00:00	31.26	31.53	34.97	3.71	3.45
	16:00:00	29.68	29.23	32.94	3.26	3.71
	17:00:00	29.92	29.50	30.01	0.09	0.51
	18:00:00	30.17	29.50	29.33	0.84	0.17
	19:00:00	29.97	29.24	29.29	0.68	0.05
	20:00:00	28.72	27.59	29.37	0.65	1.78
	21:00:00	28.65	27.85	28.18	0.47	0.34
	22:00:00	28.48	27.72	27.72	0.76	0.00
	23:00:00	28.18	27.39	27.49	0.68	0.11
	0:00:00	28.01	27.12	27.26	0.74	0.14
9-Nov-17	1:00:00	27.78	26.80	27.27	0.51	0.48
	2:00:00	27.50	26.41	26.95	0.54	0.55
	3:00:00	27.11	25.95	26.54	0.58	0.59
	4:00:00	26.93	25.95	26.04	0.89	0.09
	5:00:00	26.81	25.95	25.83	0.99	0.12
	6:00:00	27.44	27.19	25.67	1.77	1.52
	7:00:00	28.79	30.11	27.31	1.47	2.79
	8:00:00	29.82	30.98	30.26	0.43	0.73

10-Nov-17	9:00:00	30.42	31.19	31.87	1.44	0.68
	10:00:00	31.21	31.66	32.35	1.13	0.69
	11:00:00	33.16	32.55	33.57	0.41	1.02
	12:00:00	32.91	32.76	34.60	1.69	1.84
	13:00:00	32.97	33.45	34.53	1.56	1.08
	14:00:00	32.94	33.59	35.51	2.57	1.92
	15:00:00	32.98	33.52	34.99	2.01	1.47
	16:00:00	31.62	31.53	34.07	2.44	2.53
	17:00:00	30.20	29.77	32.77	2.57	3.00
	18:00:00	30.02	29.50	30.11	0.08	0.61
	19:00:00	30.15	29.50	29.16	0.99	0.34
	20:00:00	30.17	29.50	28.93	1.24	0.57
	21:00:00	29.69	28.90	28.84	0.86	0.06
	22:00:00	29.23	28.31	29.21	0.01	0.90
	23:00:00	29.11	28.31	28.52	0.59	0.21
	0:00:00	28.62	27.72	28.05	0.57	0.34
	1:00:00	28.12	27.12	27.84	0.28	0.72
	2:00:00	27.94	26.99	27.44	0.51	0.45
	3:00:00	27.59	26.47	27.19	0.40	0.72
	4:00:00	26.96	25.95	26.78	0.19	0.83
	5:00:00	27.05	26.08	26.09	0.96	0.01
	6:00:00	27.81	28.11	26.01	1.80	2.10
	7:00:00	29.40	30.51	27.82	1.59	2.69
	8:00:00	30.58	31.32	30.93	0.35	0.39
	9:00:00	31.08	31.46	32.57	1.50	1.12
	10:00:00	31.90	32.55	33.57	1.68	1.02
	11:00:00	32.62	32.34	34.30	1.69	1.96
	12:00:00	32.68	32.48	34.39	1.70	1.91
	13:00:00	32.63	32.96	34.40	1.77	1.44
	14:00:00	32.33	32.83	35.20	2.87	2.37
	15:00:00	31.64	31.53	34.56	2.91	3.02
	16:00:00	30.63	30.31	32.95	2.32	2.64
	17:00:00	30.52	29.77	30.74	0.22	0.97
	18:00:00	30.22	29.43	30.13	0.10	0.69
	19:00:00	29.52	28.57	29.75	1.18	1.18
	20:00:00	29.26	28.38	29.01	0.25	0.64
	21:00:00	29.17	28.31	28.50	0.66	0.19
	22:00:00	28.88	27.91	28.47	0.41	0.56
	23:00:00	28.74	27.85	28.00	0.74	0.15
	0:00:00	28.24	27.39	27.78	0.46	0.39

Max Air Temperature Difference of Courtyard and Wonorejo	3.71
Average Air Temperature Difference of Courtyard and Wonorejo	1.14
Max Air Temperature Difference of Rooftop and Wonorejo	3.71
Average Air Temperature Difference of Rooftop and Wonorejo	1.05
Standard Deviation of Courtyard and Wonorejo	0.83
Standard Deviation of Rooftop and Wonorejo	0.95

Attachment 2 : Relative Humidity of Bale Hinggil Apartment and Surabaya Area on 8th – 10th November 2017

Relative Humidity						
Date	Hour	Court- yard (Hc)	Roof- top (Hr)	Kebonsari, Surabaya (Hs)	ΔH (Hc - Hs)	ΔH (Hr - Hs)
8-Nov-17	1:00:00	79.98	79.25	91.83	11.85	12.58
	2:00:00	82.25	83.42	94.11	11.86	10.69
	3:00:00	82.98	82.67	98.29	15.31	15.62
	4:00:00	83.22	83.08	99.47	16.25	16.38
	5:00:00	84.82	83.75	99.90	15.08	16.15
	6:00:00	83.92	83.42	100.00	16.08	16.58
	7:00:00	79.38	71.67	97.59	18.20	25.92
	8:00:00	73.53	62.08	90.43	16.90	28.35
	9:00:00	68.68	61.33	77.33	8.65	16.00
	10:00:00	62.40	55.83	67.79	5.39	11.95
	11:00:00	49.82	45.17	65.76	15.94	20.59
	12:00:00	45.55	43.25	48.46	2.91	5.21
	13:00:00	48.33	44.33	42.27	6.07	2.07
	14:00:00	50.63	46.42	41.27	9.36	5.15
	15:00:00	59.07	57.92	44.46	14.61	13.46
	16:00:00	65.67	65.75	55.99	9.68	9.76
	17:00:00	67.68	66.50	66.43	1.25	0.07
	18:00:00	68.03	69.00	73.07	5.04	4.07
	19:00:00	69.35	69.33	72.76	3.41	3.42
	20:00:00	70.65	73.08	71.20	0.55	1.89
	21:00:00	70.67	71.25	79.45	8.78	8.20
	22:00:00	70.78	71.33	83.60	12.81	12.26
	23:00:00	72.30	72.75	83.78	11.48	11.03
	0:00:00	72.98	73.75	85.37	12.39	11.62
9-Nov-17	1:00:00	73.85	75.58	80.54	6.69	4.96
	2:00:00	75.27	77.83	81.39	6.12	3.55

10-Nov-17	3:00:00	77.93	79.92	82.23	4.30	2.31
	4:00:00	79.92	82.33	84.29	4.37	1.96
	5:00:00	81.42	83.17	86.11	4.69	2.94
	6:00:00	79.33	76.25	87.48	8.15	11.23
	7:00:00	72.38	62.83	80.01	7.62	17.17
	8:00:00	69.42	62.08	67.75	1.66	5.67
	9:00:00	67.65	62.00	60.07	7.58	1.93
	10:00:00	65.02	59.75	54.90	10.12	4.85
	11:00:00	56.98	54.75	52.28	4.70	2.47
	12:00:00	53.98	50.08	44.80	9.18	5.28
	13:00:00	46.55	41.42	28.93	17.62	12.49
	14:00:00	43.42	37.17	31.60	11.82	5.57
	15:00:00	41.65	37.33	33.54	8.11	3.79
	16:00:00	51.22	51.25	35.21	16.01	16.04
	17:00:00	63.18	63.17	44.64	18.54	18.53
	18:00:00	63.07	61.92	54.04	9.03	7.88
	19:00:00	62.50	61.42	58.16	4.34	3.26
	20:00:00	63.80	63.75	64.50	0.70	0.75
	21:00:00	67.85	68.42	66.78	1.07	1.64
	22:00:00	68.13	69.25	68.01	0.13	1.24
	23:00:00	67.97	68.92	71.58	3.61	2.66
	0:00:00	70.03	71.33	73.61	3.58	2.28
	1:00:00	72.05	73.75	74.97	2.92	1.22
	2:00:00	72.87	74.67	75.80	2.93	1.13
	3:00:00	74.83	77.42	77.74	2.91	0.32
	4:00:00	77.00	78.75	78.98	1.98	0.23
	5:00:00	76.72	77.58	81.51	4.79	3.93
	6:00:00	73.50	68.00	81.42	7.92	13.42
	7:00:00	66.45	58.00	75.64	9.19	17.64
	8:00:00	62.80	56.42	66.70	3.90	10.28
	9:00:00	60.47	55.67	54.65	5.82	1.02
	10:00:00	57.62	52.17	49.56	8.06	2.61
	11:00:00	55.42	52.67	47.44	7.98	5.23
	12:00:00	53.30	50.83	44.96	8.34	5.87
	13:00:00	51.90	48.17	42.98	8.92	5.19
	14:00:00	54.55	50.67	40.61	13.94	10.05
	15:00:00	57.20	55.83	40.93	16.27	14.90
	16:00:00	61.13	59.92	44.95	16.18	14.96
	17:00:00	62.87	63.50	56.52	6.35	6.98
	18:00:00	65.72	67.25	62.67	3.05	4.58

19:00:00	68.58	70.42	66.07	2.51	4.35
20:00:00	67.95	68.17	70.37	2.42	2.20
21:00:00	66.78	67.58	67.24	0.46	0.34
22:00:00	68.57	69.83	69.84	1.27	0.00
23:00:00	69.57	70.33	71.05	1.49	0.72
0:00:00	72.60	74.25	73.54	0.94	0.71
Max Relative Humidity Difference of Courtyard and Wonorejo					18.54
Average Relative Humidity Difference of Courtyard and Wonorejo					7.78
Max Relative Humidity Difference of Rooftop and Wonorejo					28.35
Average Relative Humidity Difference of Rooftop and Wonorejo					7.60
Standard Deviation of Courtyard and Wonorejo					5.28
Standard Deviation of Rooftop and Wonorejo					6.62

Attachment 3 : Air Temperature Measurement and Simulation Result of Room A2050 Bale Hinggil apartment on 8th – 10th November 2017

Date	Hour	TA A2050 Measurement (C)	TA Simulation (C)	Δ TA (C)
8-Nov-17	1:00:00	31.2	31.1	0.0
	2:00:00	31.1	31.1	0.0
	3:00:00	31.0	31.0	0.0
	4:00:00	31.0	30.9	0.0
	5:00:00	31.0	30.9	0.1
	6:00:00	31.1	30.8	0.3
	7:00:00	32.0	30.9	1.1
	8:00:00	32.6	31.0	1.6
	9:00:00	32.7	31.2	1.5
	10:00:00	32.6	31.2	1.3
	11:00:00	32.8	31.4	1.3
	12:00:00	32.8	32.1	0.7
	13:00:00	32.7	32.3	0.4
	14:00:00	32.7	32.4	0.3
	15:00:00	32.7	32.2	0.5
	16:00:00	32.4	32.1	0.3
	17:00:00	32.0	32.0	0.0
	18:00:00	31.9	31.8	0.2
	19:00:00	31.8	31.8	0.0
	20:00:00	31.7	31.7	0.1
	21:00:00	31.6	31.5	0.0
	22:00:00	31.5	31.4	0.0

9-Nov-17	23:00:00	31.4	31.4	0.0
	0:00:00	31.3	31.2	0.0
	1:00:00	31.2	31.2	0.0
	2:00:00	31.1	31.2	0.1
	3:00:00	31.0	31.1	0.1
	4:00:00	30.9	31.0	0.1
	5:00:00	31.0	30.9	0.0
	6:00:00	31.6	30.8	0.8
	7:00:00	32.4	30.9	1.5
	8:00:00	32.9	31.1	1.8
	9:00:00	33.1	31.3	1.7
	10:00:00	32.9	31.3	1.6
	11:00:00	32.3	31.5	0.8
	12:00:00	32.4	31.8	0.6
	13:00:00	32.8	32.0	0.8
	14:00:00	33.0	32.3	0.7
	15:00:00	33.0	32.3	0.6
	16:00:00	32.7	32.4	0.3
	17:00:00	32.3	32.2	0.1
	18:00:00	32.2	32.1	0.1
	19:00:00	32.1	32.0	0.0
	20:00:00	32.0	32.0	0.0
	21:00:00	31.9	31.8	0.1
	22:00:00	31.7	31.7	0.1
	23:00:00	31.7	31.5	0.1
	0:00:00	31.6	31.5	0.1
	1:00:00	31.4	31.5	0.0
	2:00:00	31.3	31.4	0.1
	3:00:00	31.2	31.3	0.1
	4:00:00	31.1	31.2	0.1
	5:00:00	31.2	31.2	0.0
	6:00:00	32.0	31.2	0.8
	7:00:00	32.7	31.3	1.4
	8:00:00	33.0	31.4	1.5
	9:00:00	33.1	31.6	1.5
	10:00:00	32.9	31.7	1.2
	11:00:00	33.2	31.9	1.3
	12:00:00	33.2	31.9	1.4
	13:00:00	33.3	32.3	1.0
	14:00:00	33.3	32.6	0.7
	15:00:00	33.2	32.5	0.7
	16:00:00	32.8	32.4	0.4
	17:00:00	32.5	32.3	0.2

18:00:00	32.4	32.0	0.4
19:00:00	32.3	32.0	0.3
20:00:00	32.2	31.9	0.3
21:00:00	32.1	31.8	0.3
22:00:00	32.1	31.7	0.3
23:00:00	32.0	31.6	0.4
0:00:00	31.9	31.5	0.4
Max Air Temperature Difference		1.8	
Average Air Temperature Difference		0.5	
Standard Deviation		0.55	

Attachment 4 : Relative Humidity Measurement and Simulation Result of Room A2050 Bale Hinggil apartment on 8th – 10th November 2017

Date	hour	RH A2050 Measurement (%)	RH Simulation (%)	ΔRH (%)
8-Nov-17	1:00:00	64.4	62.0	2.4
	2:00:00	65.0	62.2	2.8
	3:00:00	65.4	62.5	2.9
	4:00:00	65.5	62.8	2.7
	5:00:00	65.7	63.0	2.7
	6:00:00	65.6	63.2	2.4
	7:00:00	62.6	63.1	0.5
	8:00:00	60.5	62.6	2.1
	9:00:00	59.5	62.2	2.7
	10:00:00	57.7	62.6	4.8
	11:00:00	55.2	59.6	4.4
	12:00:00	51.4	51.4	0.1
	13:00:00	50.6	46.9	3.7
	14:00:00	51.7	46.4	5.3
	15:00:00	55.5	47.2	8.3
	16:00:00	57.6	47.4	10.1
	17:00:00	59.0	48.3	10.8
	18:00:00	59.9	50.6	9.2
	19:00:00	61.5	51.4	10.1
	20:00:00	60.8	53.0	7.8
	21:00:00	60.3	55.4	4.9
	22:00:00	60.1	56.6	3.5
	23:00:00	60.3	57.5	2.8
	0:00:00	60.6	58.3	2.2
9-Nov-17	1:00:00	60.8	58.4	2.3
	2:00:00	61.0	58.9	2.2
	3:00:00	61.6	59.5	2.1

	4:00:00	62.5	60.1	2.4
	5:00:00	62.8	60.6	2.2
	6:00:00	60.8	61.3	0.6
	7:00:00	57.5	61.1	3.5
	8:00:00	56.8	60.5	3.6
	9:00:00	56.9	59.9	2.9
	10:00:00	57.9	61.9	4.0
	11:00:00	57.3	60.8	3.6
	12:00:00	53.1	57.9	4.8
	13:00:00	45.8	54.1	8.3
	14:00:00	44.7	45.1	0.5
	15:00:00	42.6	43.5	0.9
	16:00:00	45.9	43.3	2.5
	17:00:00	51.7	44.6	7.0
	18:00:00	54.0	45.7	8.3
	19:00:00	55.0	46.3	8.7
	20:00:00	56.2	47.3	8.9
	21:00:00	57.7	49.1	8.6
	22:00:00	58.0	51.5	6.4
	23:00:00	57.9	54.8	3.1
	0:00:00	58.5	56.0	2.5
10-Nov-17	1:00:00	58.9	56.2	2.7
	2:00:00	59.2	56.5	2.7
	3:00:00	59.7	56.8	2.9
	4:00:00	60.0	57.2	2.8
	5:00:00	59.5	57.5	2.0
	6:00:00	56.7	57.6	1.0
	7:00:00	54.0	57.3	3.3
	8:00:00	53.5	56.9	3.4
	9:00:00	53.0	56.4	3.3
	10:00:00	53.3	54.3	1.1
	11:00:00	52.6	54.5	1.9
	12:00:00	51.3	51.7	0.4
	13:00:00	50.5	48.4	2.1
	14:00:00	52.2	49.3	2.8
	15:00:00	53.6	49.5	4.1
	16:00:00	55.3	49.8	5.5
	17:00:00	56.3	50.1	6.2
	18:00:00	57.0	52.0	5.0
	19:00:00	57.6	53.2	4.4
	20:00:00	57.9	54.9	3.0
	21:00:00	57.8	56.1	1.7
	22:00:00	58.0	56.6	1.3

23:00:00	58.2	56.5	1.7
0:00:00	58.4	56.5	1.9
Max Relative Humidity Difference			10.8
Average Relative Humidity Difference			3.8
Standard Deviation			2.63

Attachment 5 : Air Temperature Measurement and Simulation Result of Room A2031 Bale Hinggil apartment on 8th – 10th November 2017

Date	Hour	TA A2031 Measurement (C)	TA Simulation (C)	ΔTA (C)
8-Nov-17	1:00:00	30.5	30.0	0.4
	2:00:00	30.4	30.0	0.4
	3:00:00	30.4	30.0	0.4
	4:00:00	30.4	29.9	0.5
	5:00:00	30.3	29.9	0.4
	6:00:00	30.3	29.8	0.5
	7:00:00	30.4	29.8	0.6
	8:00:00	30.6	29.9	0.6
	9:00:00	30.6	30.0	0.6
	10:00:00	30.8	30.5	0.3
	11:00:00	30.9	30.9	0.0
	12:00:00	30.8	31.3	0.5
	13:00:00	30.9	31.3	0.4
	14:00:00	31.0	31.3	0.4
	15:00:00	30.9	30.8	0.1
	16:00:00	30.8	30.6	0.1
	17:00:00	30.7	30.4	0.3
	18:00:00	30.7	30.5	0.2
	19:00:00	30.7	30.4	0.3
	20:00:00	30.6	30.4	0.2
	21:00:00	30.6	30.3	0.3
	22:00:00	30.6	30.3	0.3
	23:00:00	30.5	30.2	0.3
	0:00:00	30.5	30.1	0.4
9-Nov-17	1:00:00	30.5	30.1	0.4
	2:00:00	30.5	30.1	0.3
	3:00:00	30.4	30.0	0.4
	4:00:00	30.4	30.0	0.4
	5:00:00	30.3	29.9	0.4
	6:00:00	30.3	30.0	0.3
	7:00:00	30.3	30.0	0.3
	8:00:00	30.5	30.1	0.5

	9:00:00	30.7	30.1	0.6	
	10:00:00	30.8	30.6	0.3	
	11:00:00	31.2	30.9	0.3	
	12:00:00	31.5	31.2	0.2	
	13:00:00	31.6	31.4	0.2	
	14:00:00	31.3	31.7	0.3	
	15:00:00	31.3	31.0	0.3	
	16:00:00	31.0	30.9	0.1	
	17:00:00	30.9	30.8	0.1	
	18:00:00	30.8	30.7	0.2	
	19:00:00	30.8	30.6	0.2	
	20:00:00	30.8	30.6	0.2	
	21:00:00	30.8	30.6	0.2	
	22:00:00	30.7	30.5	0.2	
	23:00:00	30.7	30.4	0.3	
	0:00:00	30.6	30.4	0.2	
	10-Nov-17	1:00:00	30.6	30.4	0.2
		2:00:00	30.5	30.3	0.2
		3:00:00	30.5	30.3	0.2
		4:00:00	30.4	30.2	0.2
		5:00:00	30.4	30.2	0.2
		6:00:00	30.3	30.2	0.1
		7:00:00	30.4	30.2	0.2
		8:00:00	30.6	30.3	0.3
9:00:00		30.9	30.4	0.5	
10:00:00		31.1	30.9	0.2	
11:00:00		31.2	31.1	0.0	
12:00:00		31.2	31.1	0.1	
13:00:00		31.2	31.3	0.1	
14:00:00		31.4	31.6	0.2	
15:00:00		31.3	31.1	0.1	
16:00:00		31.0	30.9	0.1	
17:00:00		30.9	30.7	0.2	
18:00:00		30.9	30.7	0.2	
19:00:00		30.8	30.6	0.2	
20:00:00		30.8	30.6	0.2	
21:00:00		30.8	30.5	0.3	
22:00:00		30.7	30.5	0.2	
23:00:00		30.7	30.5	0.2	
0:00:00		30.7	30.4	0.3	
Max Air Temperature Difference			0.6		
Average Air Temperature Difference			0.3		
Standard Deviation			0.14		

Attachment 6 : Relative Humidity Measurement and Simulation Result of Room A2031 Bale Hinggil apartment on 8th – 10th November 2017

Date	Hour	RH A2031 Measurement (%)	RH Simulation (%)	Δ RH (%)
8-Nov-17	1:00:00	67.6	66.0	1.6
	2:00:00	68.1	66.1	2.0
	3:00:00	68.4	66.2	2.1
	4:00:00	68.6	66.4	2.1
	5:00:00	68.8	66.6	2.2
	6:00:00	68.9	66.8	2.1
	7:00:00	68.5	66.9	1.6
	8:00:00	67.7	66.6	1.1
	9:00:00	66.8	66.3	0.5
	10:00:00	65.4	65.2	0.2
	11:00:00	60.7	58.5	2.2
	12:00:00	57.8	52.0	5.8
	13:00:00	58.4	50.7	7.6
	14:00:00	59.1	49.6	9.5
	15:00:00	61.8	51.7	10.1
	16:00:00	63.0	54.5	8.5
	17:00:00	63.9	57.0	6.9
	18:00:00	64.5	57.4	7.1
	19:00:00	65.5	58.5	7.0
	20:00:00	65.0	59.8	5.2
	21:00:00	64.7	61.1	3.6
	22:00:00	64.5	61.3	3.2
	23:00:00	64.4	61.7	2.7
	0:00:00	64.4	62.2	2.1
9-Nov-17	1:00:00	64.4	62.3	2.1
	2:00:00	64.5	62.7	1.8
	3:00:00	64.7	63.2	1.5
	4:00:00	65.1	63.7	1.4
	5:00:00	65.7	64.1	1.6
	6:00:00	66.1	64.3	1.8
	7:00:00	65.1	64.2	0.9
	8:00:00	64.8	64.0	0.8
	9:00:00	64.7	63.8	0.9
	10:00:00	65.1	64.7	0.4
	11:00:00	62.2	61.6	0.6
	12:00:00	57.8	59.2	1.3
	13:00:00	51.5	53.0	1.6

10-Nov-17	14:00:00	55.5	42.3	13.2
	15:00:00	53.0	42.5	10.5
	16:00:00	53.6	43.7	9.8
	17:00:00	58.1	44.5	13.6
	18:00:00	59.9	45.9	13.9
	19:00:00	60.5	47.2	13.3
	20:00:00	61.4	48.7	12.7
	21:00:00	62.8	49.7	13.1
	22:00:00	62.8	52.6	10.1
	23:00:00	62.6	56.7	6.0
	0:00:00	63.0	58.6	4.4
	1:00:00	63.0	59.0	4.0
	2:00:00	63.1	59.4	3.7
	3:00:00	63.5	59.9	3.6
	4:00:00	63.6	60.3	3.3
	5:00:00	63.4	60.7	2.7
	6:00:00	63.1	60.8	2.3
	7:00:00	62.4	60.7	1.7
	8:00:00	61.8	60.5	1.3
	9:00:00	60.9	60.3	0.6
	10:00:00	61.5	57.2	4.2
	11:00:00	64.6	56.2	8.4
	12:00:00	62.8	55.9	6.9
	13:00:00	62.5	51.0	11.5
	14:00:00	64.0	52.0	12.0
	15:00:00	64.6	53.5	11.1
	16:00:00	64.7	54.2	10.5
	17:00:00	64.8	55.9	8.9
	18:00:00	64.9	56.4	8.5
	19:00:00	64.7	58.2	6.5
	20:00:00	64.7	59.6	5.1
	21:00:00	64.4	60.6	3.7
	22:00:00	64.0	60.9	3.1
	23:00:00	64.1	60.6	3.5
	0:00:00	64.1	60.5	3.7
Max Relative Humidity Difference			13.9	
Average Relative Humidity Difference			5.1	
Standard Deviation			4.08	

Attachment 7 : Air Temperature Measurement and Simulation Result of Room
A2020 Bale Hinggil apartment on 8th – 10th November 2017

Date	Hour	TA A2020 Measurement (C)	TA Simulation (C)	ΔTA (C)
8-Nov-17	1:00:00	30.6	30.1	0.5
	2:00:00	30.6	30.1	0.5
	3:00:00	30.5	30.0	0.5
	4:00:00	30.5	30.0	0.5
	5:00:00	30.5	29.9	0.5
	6:00:00	30.5	29.9	0.6
	7:00:00	30.6	29.9	0.6
	8:00:00	30.8	30.0	0.7
	9:00:00	30.9	30.1	0.8
	10:00:00	31.2	30.6	0.6
	11:00:00	31.2	30.7	0.5
	12:00:00	31.1	31.4	0.3
	13:00:00	31.0	31.6	0.6
	14:00:00	31.0	31.7	0.7
	15:00:00	31.0	31.0	0.0
	16:00:00	30.9	30.9	0.0
	17:00:00	30.9	30.8	0.1
	18:00:00	30.9	30.6	0.3
	19:00:00	30.9	30.6	0.3
	20:00:00	30.8	30.5	0.3
	21:00:00	30.8	30.4	0.4
	22:00:00	30.7	30.4	0.4
	23:00:00	30.7	30.3	0.4
	0:00:00	30.7	30.2	0.5
9-Nov-17	1:00:00	30.6	30.2	0.4
	2:00:00	30.6	30.2	0.4
	3:00:00	30.6	30.2	0.4
	4:00:00	30.5	30.1	0.4
	5:00:00	30.5	30.1	0.4
	6:00:00	30.5	29.9	0.5
	7:00:00	30.5	30.0	0.5
	8:00:00	30.8	30.1	0.6
	9:00:00	31.1	30.2	0.9
	10:00:00	31.3	30.6	0.7
	11:00:00	31.5	30.9	0.7
	12:00:00	31.5	31.2	0.3
	13:00:00	31.3	31.3	0.0
	14:00:00	31.2	31.4	0.3
	15:00:00	31.1	31.1	0.0

10-Nov-17	16:00:00	31.1	31.1	0.1
	17:00:00	31.0	30.9	0.1
	18:00:00	30.9	30.8	0.1
	19:00:00	30.9	30.8	0.1
	20:00:00	30.9	30.8	0.1
	21:00:00	30.9	30.7	0.2
	22:00:00	30.9	30.6	0.3
	23:00:00	30.8	30.5	0.3
	0:00:00	30.8	30.4	0.4
	1:00:00	30.8	30.4	0.4
	2:00:00	30.7	30.4	0.3
	3:00:00	30.7	30.4	0.3
	4:00:00	30.6	30.3	0.3
	5:00:00	30.6	30.2	0.4
	6:00:00	30.6	30.3	0.3
	7:00:00	30.6	30.3	0.3
	8:00:00	30.9	30.4	0.5
	9:00:00	31.5	30.5	1.0
	10:00:00	31.6	31.1	0.5
	11:00:00	31.4	31.4	0.0
	12:00:00	31.3	31.2	0.1
	13:00:00	31.2	31.6	0.4
	14:00:00	31.3	31.8	0.5
	15:00:00	31.2	31.3	0.1
	16:00:00	31.1	31.2	0.0
	17:00:00	31.1	31.1	0.0
	18:00:00	31.0	30.8	0.2
	19:00:00	31.0	30.8	0.2
	20:00:00	31.0	30.7	0.3
	21:00:00	30.9	30.7	0.2
	22:00:00	30.9	30.6	0.3
	23:00:00	30.9	30.6	0.3
	0:00:00	30.8	30.5	0.3
Max Air Temperature Difference			1.0	
Average Air Temperature Difference			0.4	
Standard Deviation			0.22	

Attachment 8 : Relative Humidity Measurement and Simulation Result of Room A2020 Bale Hinggil apartment on 8th – 10th November 2017

Date	Hour	RH A2020 Measurement (%)	RH Simulation (%)	ΔRH (%)
8-Nov-17	1:00:00	67.0	65.9	1.1

	2:00:00	67.5	66.0	1.5
	3:00:00	67.8	66.1	1.7
	4:00:00	67.9	66.2	1.7
	5:00:00	68.2	66.4	1.7
	6:00:00	68.4	66.6	1.9
	7:00:00	67.9	66.6	1.3
	8:00:00	66.9	66.3	0.6
	9:00:00	65.9	66.0	0.1
	10:00:00	64.2	65.1	0.9
	11:00:00	60.1	62.7	2.6
	12:00:00	57.1	53.0	4.1
	13:00:00	56.6	48.4	8.2
	14:00:00	57.8	48.2	9.6
	15:00:00	60.6	50.4	10.2
	16:00:00	62.0	50.8	11.2
	17:00:00	62.9	51.6	11.3
	18:00:00	63.5	53.9	9.6
	19:00:00	64.6	54.8	9.8
	20:00:00	64.2	56.4	7.9
	21:00:00	63.8	58.6	5.1
	22:00:00	63.5	59.8	3.7
	23:00:00	63.5	60.8	2.7
	0:00:00	63.5	61.5	1.9
9-Nov-17	1:00:00	63.5	61.7	1.9
	2:00:00	63.5	62.0	1.5
	3:00:00	63.9	62.6	1.3
	4:00:00	64.4	63.2	1.3
	5:00:00	65.0	63.6	1.4
	6:00:00	65.2	64.4	0.8
	7:00:00	64.3	64.3	0.0
	8:00:00	63.8	63.9	0.1
	9:00:00	63.3	63.6	0.3
	10:00:00	63.2	64.8	1.6
	11:00:00	60.4	62.8	2.4
	12:00:00	58.4	59.8	1.5
	13:00:00	54.4	55.9	1.5
	14:00:00	53.0	46.9	6.1
	15:00:00	51.8	46.0	5.8
	16:00:00	53.6	46.0	7.6
	17:00:00	58.1	47.6	10.5
	18:00:00	59.6	48.6	11.0
	19:00:00	60.2	49.2	11.0
	20:00:00	60.9	50.1	10.8

10-Nov-17	21:00:00	62.4	51.8	10.6
	22:00:00	62.4	54.3	8.0
	23:00:00	62.2	57.8	4.4
	0:00:00	62.4	59.2	3.2
	1:00:00	62.4	59.4	3.0
	2:00:00	62.4	59.7	2.8
	3:00:00	62.7	60.0	2.7
	4:00:00	62.7	60.3	2.5
	5:00:00	62.7	60.5	2.2
	6:00:00	62.3	60.6	1.6
	7:00:00	61.5	60.5	1.1
	8:00:00	60.8	60.3	0.5
	9:00:00	59.3	60.0	0.7
	10:00:00	58.7	55.9	2.8
	11:00:00	59.7	56.4	3.3
	12:00:00	59.2	53.5	5.7
	13:00:00	59.0	50.5	8.5
	14:00:00	59.0	51.3	7.7
	15:00:00	60.0	52.8	7.2
	16:00:00	61.0	53.3	7.7
	17:00:00	61.6	53.7	8.0
	18:00:00	62.2	55.5	6.7
	19:00:00	62.6	56.8	5.8
	20:00:00	62.9	58.5	4.3
	21:00:00	62.6	59.8	2.8
	22:00:00	62.5	60.2	2.3
	23:00:00	62.6	60.0	2.6
	0:00:00	62.8	59.9	2.8
Max Relative Humidity Difference			11.3	
Average Relative Humidity Difference			4.3	
Standard Deviation			3.51	

Attachment 9 : Air Temperature Measurement and Simulation Result of Room A2010 Bale Hinggil apartment on 8th – 10th November 2017

Date	Hour	TA A2010 Measurement (C)	TA Simulation (C)	ΔTA (C)
8-Nov-17	1:00:00	30.6	31.0	0.4
	2:00:00	30.5	30.9	0.4
	3:00:00	30.5	30.9	0.4
	4:00:00	30.5	30.8	0.4
	5:00:00	30.4	30.7	0.3
	6:00:00	30.5	30.7	0.2

	7:00:00	30.8	30.7	0.0
	8:00:00	31.1	30.9	0.2
	9:00:00	31.4	31.0	0.4
	10:00:00	31.5	31.1	0.4
	11:00:00	31.5	31.5	0.1
	12:00:00	31.8	31.9	0.1
	13:00:00	32.0	31.9	0.1
	14:00:00	32.1	32.0	0.1
	15:00:00	31.7	31.9	0.2
	16:00:00	31.2	31.7	0.5
	17:00:00	31.2	31.5	0.3
	18:00:00	31.2	31.6	0.4
	19:00:00	31.1	31.5	0.4
	20:00:00	31.0	31.5	0.4
	21:00:00	30.9	31.3	0.4
	22:00:00	30.8	31.3	0.5
	23:00:00	30.7	31.2	0.5
	0:00:00	30.7	31.0	0.4
9-Nov-17	1:00:00	30.5	31.0	0.5
	2:00:00	30.5	31.0	0.5
	3:00:00	30.5	30.9	0.4
	4:00:00	30.4	30.8	0.4
	5:00:00	30.4	30.7	0.3
	6:00:00	30.5	30.7	0.2
	7:00:00	30.8	30.8	0.0
	8:00:00	31.1	31.0	0.1
	9:00:00	31.3	31.1	0.2
	10:00:00	31.3	31.1	0.1
	11:00:00	31.3	31.5	0.2
	12:00:00	31.4	31.9	0.4
	13:00:00	31.7	32.0	0.4
	14:00:00	31.8	32.3	0.5
	15:00:00	31.8	32.1	0.3
	16:00:00	31.6	32.0	0.5
	17:00:00	31.2	32.0	0.8
	18:00:00	31.1	31.8	0.7
	19:00:00	31.0	31.7	0.7
	20:00:00	31.0	31.7	0.7
	21:00:00	30.9	31.6	0.8
	22:00:00	30.9	31.5	0.6
	23:00:00	30.8	31.3	0.5
	0:00:00	30.7	31.3	0.5
10-Nov-17	1:00:00	30.7	31.3	0.6

2:00:00	30.7	31.2	0.5
3:00:00	30.5	31.1	0.6
4:00:00	30.5	31.0	0.5
5:00:00	30.4	31.0	0.5
6:00:00	30.6	31.0	0.4
7:00:00	30.8	31.1	0.3
8:00:00	31.0	31.2	0.2
9:00:00	31.3	31.3	0.1
10:00:00	31.4	31.5	0.1
11:00:00	31.7	31.7	0.0
12:00:00	31.9	31.7	0.2
13:00:00	32.0	31.9	0.1
14:00:00	32.1	32.2	0.1
15:00:00	31.9	32.2	0.3
16:00:00	31.6	32.0	0.5
17:00:00	31.4	31.8	0.4
18:00:00	31.3	31.8	0.5
19:00:00	31.2	31.6	0.4
20:00:00	31.2	31.6	0.4
21:00:00	31.1	31.5	0.4
22:00:00	31.1	31.5	0.4
23:00:00	31.0	31.4	0.4
0:00:00	30.9	31.3	0.4
Max Air Temperature Difference			0.8
Average Air Temperature Difference			0.4
Standard Deviation			0.19

Attachment 10 : Relative Humidity Measurement and Simulation Result of Room A2010 Bale Hinggil apartment on 8th – 10th November 2017

Date	Hour	RH A2010 Measurement (%)	RH Simulation (%)	ΔRH (%)
8-Nov-17	1:00:00	67.6	62.3	5.3
	2:00:00	68.3	62.5	5.7
	3:00:00	68.4	62.8	5.6
	4:00:00	68.5	63.1	5.4
	5:00:00	68.9	63.4	5.4
	6:00:00	68.8	63.6	5.2
	7:00:00	67.9	63.6	4.3
	8:00:00	66.8	63.0	3.8
	9:00:00	65.5	62.6	2.9
	10:00:00	65.0	63.0	2.0
	11:00:00	62.7	57.2	5.6

	12:00:00	61.1	50.7	10.4
	13:00:00	61.6	49.6	12.0
	14:00:00	60.7	48.1	12.6
	15:00:00	61.0	48.6	12.4
	16:00:00	62.2	51.3	10.9
	17:00:00	63.8	53.4	10.3
	18:00:00	64.2	53.9	10.3
	19:00:00	65.4	55.1	10.3
	20:00:00	64.7	56.4	8.3
	21:00:00	64.3	57.8	6.5
	22:00:00	64.2	58.1	6.2
	23:00:00	64.5	58.5	5.9
	0:00:00	64.5	59.2	5.3
	1:00:00	64.8	59.3	5.5
	2:00:00	65.0	59.7	5.3
	3:00:00	65.3	60.3	5.0
	4:00:00	65.8	60.8	5.0
	5:00:00	66.3	61.3	5.0
	6:00:00	66.2	61.5	4.7
	7:00:00	64.7	61.2	3.5
	8:00:00	64.3	60.8	3.5
	9:00:00	64.2	60.4	3.8
	10:00:00	64.7	62.3	2.4
	11:00:00	63.0	59.8	3.2
9-Nov-17	12:00:00	61.7	57.1	4.6
	13:00:00	56.8	52.4	4.4
	14:00:00	55.6	42.5	13.1
	15:00:00	54.6	41.5	13.1
	16:00:00	56.8	42.3	14.5
	17:00:00	60.9	42.8	18.0
	18:00:00	61.3	44.3	17.0
	19:00:00	61.2	45.6	15.6
	20:00:00	61.9	47.3	14.7
	21:00:00	63.9	48.4	15.5
	22:00:00	63.6	51.1	12.6
	23:00:00	63.5	54.6	8.9
	0:00:00	63.8	56.2	7.7
	1:00:00	63.9	56.5	7.4
10-Nov-17	2:00:00	63.9	56.9	7.0
	3:00:00	64.3	57.3	7.0
	4:00:00	64.4	57.7	6.7
	5:00:00	64.3	58.1	6.2
	6:00:00	63.7	58.2	5.4

7:00:00	62.7	57.9	4.8
8:00:00	62.2	57.5	4.6
9:00:00	61.6	57.1	4.5
10:00:00	61.2	55.9	5.3
11:00:00	61.0	54.3	6.6
12:00:00	60.0	53.4	6.5
13:00:00	59.4	49.2	10.1
14:00:00	59.8	50.2	9.6
15:00:00	60.6	50.4	10.2
16:00:00	61.1	51.0	10.1
17:00:00	62.0	52.5	9.6
18:00:00	62.7	52.9	9.8
19:00:00	63.3	54.8	8.5
20:00:00	63.6	56.2	7.4
21:00:00	63.4	57.3	6.1
22:00:00	63.3	57.5	5.7
23:00:00	63.4	57.4	6.0
0:00:00	63.6	57.3	6.3
Max Relative Humidity Difference			18.0
Average Relative Humidity Difference			7.6
Standard Deviation			3.71

Attachment 11 : Location Tab of Design Builder Simulation

Layout
Location
Region

Location Template
Template
SURABAYA/JUANDA

Site Location
Latitude (°)
-7.37
Longitude (°)
112.77
ASHRAE climate zone
1A

Site Details
Elevation above sea level (m)
3.0
Exposure to wind
3-Exposed
Site orientation (°)
0
Ground
>>
Sky
>>
Horizon
>>
Water Mains Temperature
>>
Precipitation
>>
Site Green Roof Irrigation
>>
Outdoor Air CO2 and Contaminants
>>

Time and Daylight Saving
>>
Simulation Weather Data
Hourly weather data
Surabaya Bale Inggil
Day of week for start day
8-Use weather file
Winter Design Weather Data
>>
Summer Design Weather Data
>>

Attachment 12 : Activity Tab of Design Builder Simulation

Layout Activity Construction Openings Lighting HVAC Generation Outputs CFD

Activity Template

Template Domestic Bedroom

Sector Residential spaces

Zone multiplier 1

☒ Include zone in thermal calculations

☒ Include zone in Radiance daylighting calculations

Floor Areas and Volumes

Occupancy

Density (people/m2) 0.0770

Schedule Jadwal Orang Apartemen

Metabolic

Generic Contaminant Generation

Holidays

DHW

Environmental Control

Heating Setpoint Temperatures

Heating (°C) 18.0

Heating set back (°C) 12.0

Cooling Setpoint Temperatures

Cooling (°C) 25.0

Cooling set back (°C) 28.0

Humidity Control

Ventilation Setpoint Temperatures

Minimum Fresh Air

Lighting

Computers

On

Office Equipment

On

Miscellaneous

On

Catering

Process

Attachment 13 : Construction Tab of Design Builder Simulation

Layout Activity Construction Openings Lighting HVAC Generation Outputs CFD

Construction Template

Template Project construction template

Construction

External walls Dinding Beton Eksternal PUTIH (lightweight)

Below grade walls Dinding Beton Eksternal PUTIH (lightweight)

Flat roof Atap Beton

Pitched roof (occupied) Project pitched roof

Pitched roof (unoccupied) Project unoccupied pitched roof

Internal partitions Dinding 15 cm CAT PUTIH

Semi-Exposed

Semi-exposed walls Dinding Beton Eksternal PUTIH (lightweight)

Semi-exposed ceiling 130mm concrete slab (lightweight)

Semi-exposed floor 130mm concrete slab (lightweight)

Floors

Ground floor Lantai keramik

External floor Lantai keramik

Internal floor Lantai keramik Internal

Sub-Surfaces

Internal Thermal Mass

Component Block

Geometry, Areas and Volumes

Surface Convection

Linear Thermal Bridging at Junctions

Airtightness

☒ Model infiltration

Constant rate (ac/h) 0.700

Schedule On 24/7

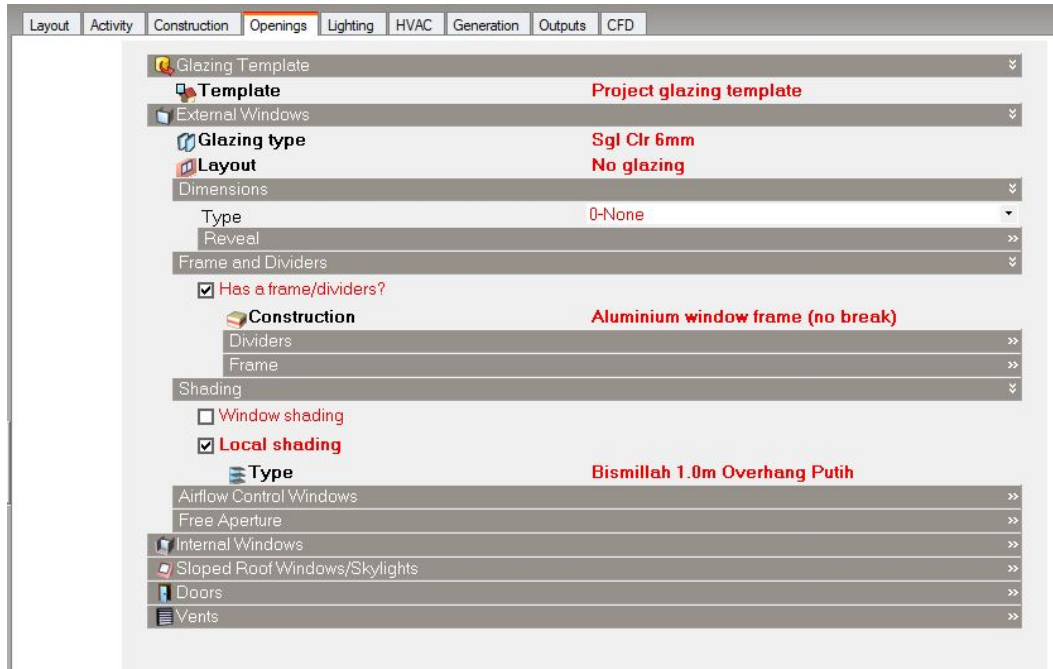
Delta T and Wind Speed Coefficients

Crack template

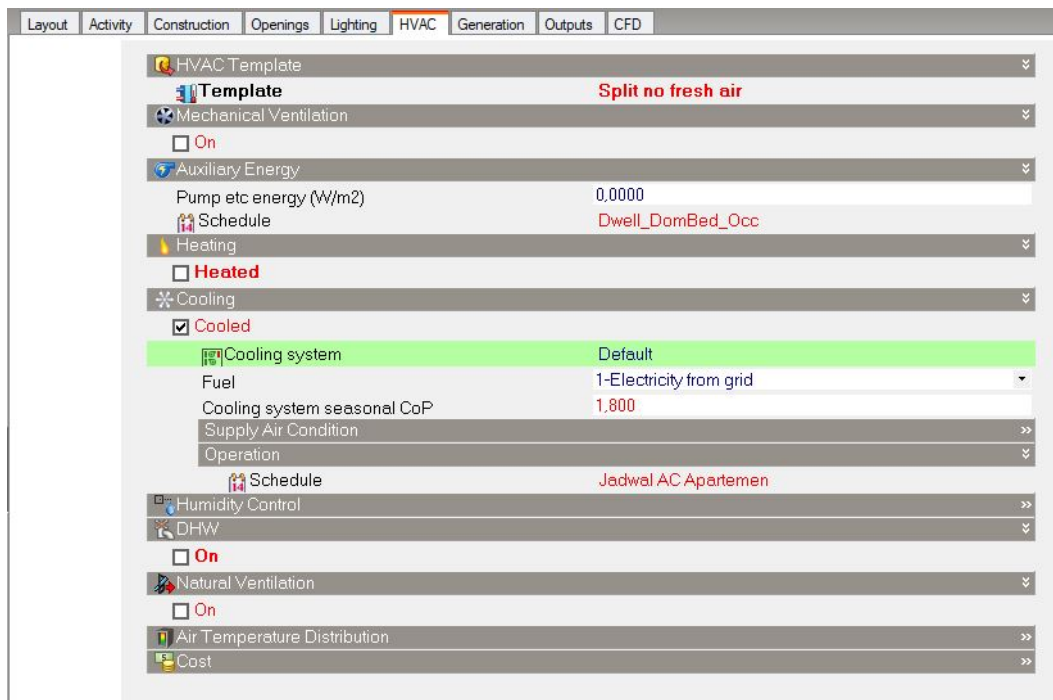
Very poor Poor Medium Good Excellent

Cost

Attachment 14 : Opening Tab of Design Builder Simulation



Attachment 15 : HVAC Tab of Design Builder Simulation



Attachment 16 : Calculation Options Tab of Design Builder Simulation

Edit Calculation Options

Calculation Options Data

General Options Output Simulation Manager

Calculation Options

Simulation method 1-EnergyPlus

Time steps per hour 6

Temperature control 1-Air temperature

Solar

☒ Include all buildings in shading calcs

☒ Model reflections and shading of ground reflected solar

Solar distribution 2-Full exterior

Shadowing interval (days) 20

Advanced >>

Help

Info Data

Calculation Options

These options can also be accessed from the Model Options dialog.

Time steps

In general, increasing the number of timesteps improves accuracy but slows the simulation (and generates more data if output is requested at the 'sub-hourly' interval).

Solar Distribution

Solar distribution should generally be set to 'Full exterior' as this provides a good compromise between accuracy and versatility.

Note that the 'Full interior and exterior' option only works for convex shaped zones (zones whose surfaces can all 'see' each other).

Include all buildings

Check the 'Include all buildings in shading calcs' if you want to use the surfaces of other buildings on the site to shade the current building in the simulation.

☐ Don't show this dialog next time

Help Cancel OK

Edit Calculation Options

Calculation Options Data

General Options Output Simulation Manager

Output Data

☒ Building and block output of zone data

☐ Include unoccupied zones in block and building totals and averages

☒ Allow custom outputs

Graphable Outputs

Energy

☒ Surface heat transfer

☒ Internal gains including solar

☒ Energy, HVAC etc

☐ Latent loads

Comfort and Environmental

Reporting period 1-All periods

☒ Environmental

☒ Fresh air supply

☐ Simple ASHRAE Standard 55

☐ Adaptive ASHRAE Standard 55

☐ Adaptive CEN Standard 15251

☐ CIBSE TM52

☐ Fanger

☐ Pierce two-node

☐ Kansas State University two-node

☐ Temperature distribution

Detailed Daylight Outputs >>

Summary Tables >>

Miscellaneous Outputs >>

Time Setpoints not Met Tolerances >>

Help

Info Data

Output Data

Control the data generated from simulations.

Zone environmental and comfort reports - allows you to restrict the simulation comfort output to just occupied periods by selecting 2-Just occupied periods. Options are:

1-All periods - comfort data is generated for all periods including times when the zone is unoccupied.

2-Just occupied periods - comfort data is only output during times when the zone is occupied so daily and monthly comfort statistics become more meaningful.

Building and block output of zone data - causes average and total zone data to be generated for building and blocks. For example average temperatures, comfort conditions, total solar radiation, internal gains, fabric transmission losses etc. It does not affect the generation of energy consumption and CO2 data at the building level.

Surface heat transfer - to generate heat flow at surface boundaries.

Environmental - generates temperatures and humidity data.

Comfort - generates Comfort output, including: FangerPMV, PiercePMVET, PiercePMVSET, PierceDISC, PierceTSENS, KsuTSV, Time Not Comfortable Summer Clothes, Time Not Comfortable Winter Clothes, Time Not Comfortable Summer or Winter Clothes

Internal gains - generate internal gains-related output.

Energy, HVAC etc - for energy consumption data.

Temperature distribution - to generate Temperature distribution data.

DXF model output - causes EnergyPlus to generate a DXF file summarising the building model. The file is called eplusout.dxf and it is stored in the EnergyPlus folder. This option can be useful for checking that the correct geometry has been generated.

Construction and surface details - causes

☐ Don't show this dialog next time

Help Cancel OK

Attachment 17 : Heat gains and losses of Model Experiments

Model Experiments	Sensible Cooling (kW)	Latent Cooling (kW)	Total Cooling (kW)	Fabric (kW)	Solar Gain (kW)	Infiltration (kW)	Internal Heat Gain (kW)
H-1-NS	-93.03	-34.16	-127.19	16.32	31.24	4.81	41.12
H-1-NWSE	-93.46	-35.53	-128.99	18.26	30.36	4.19	41.09
H-1-WE	-92.92	-36.81	-129.73	19.37	29.29	3.56	41.08
H-1.5-NS	-92.07	-34.60	-126.67	16.33	30.06	5.02	41.11
H-1.5-NWSE	-92.12	-35.57	-127.68	18.31	28.90	4.24	41.08
H-1.5-WE	-90.76	-36.70	-127.46	19.40	27.05	3.62	41.06
H-2-NS	-91.24	-34.83	-126.06	16.30	29.16	5.13	41.10
H-2-NWSE	-90.99	-35.54	-126.54	18.24	27.84	4.27	41.06
H-2-WE	-89.48	-36.62	-126.10	19.35	25.81	3.63	41.04
U-1-NS	-93.41	-34.40	-127.81	15.95	32.18	4.65	41.11
U-1-NWSE	-93.27	-35.95	-129.22	18.07	30.40	4.15	41.08
U-1-WE	-92.66	-37.20	-129.85	19.24	29.23	3.50	41.07
U-1.5-NS	-91.70	-34.70	-126.40	16.34	29.77	4.96	41.10
U-1.5-NWSE	-91.37	-35.84	-127.21	18.37	28.06	4.29	41.07
U-1.5-WE	-90.26	-36.99	-127.25	19.49	26.48	3.61	41.05
U-2-NS	-91.40	-34.94	-126.34	16.22	29.55	5.02	41.08
U-2-NWSE	-90.17	-35.75	-125.91	18.30	26.91	4.33	41.06
U-2-WE	-88.95	-36.81	-125.76	19.49	25.12	3.67	41.05
2U-1-NS	-92.37	-33.89	-126.26	15.74	31.26	4.83	41.24
2U-1-NWSE	-94.05	-37.04	-131.09	16.91	31.84	4.79	41.19
2U-1-WE	-94.35	-38.39	-110.38	17.46	32.10	4.27	41.18
2U-1.5-NS	-93.13	-33.88	-127.01	16.00	31.58	5.01	41.25

2U-1.5-NWSE	-94.17	-36.38	-130.55	17.43	31.54	4.68	41.21
2U-1.5-WE	-93.90	-37.73	-131.63	18.07	31.20	4.08	41.19
2U-2-NS	-93.01	-34.33	-127.34	15.87	31.40	5.19	41.23
2U-2-NWSE	-93.70	-36.42	-130.12	17.38	31.15	4.64	41.19
2U-2-WE	-93.25	-37.70	-130.95	18.19	30.50	4.00	41.18
2L-1-NS	-91.15	-33.02	-124.17	17.42	29.06	4.16	41.08
2L-1-NWSE	-92.85	-34.58	-127.43	17.21	30.47	4.71	41.06
2L-1-WE	-93.52	-35.35	-128.87	16.85	31.33	4.86	41.07
2L-1.5-NS	-92.29	-33.47	-125.76	17.21	30.30	4.28	41.08
2L-1.5-NWSE	-92.67	-34.48	-127.15	17.33	30.26	4.61	41.07
2L-1.5-WE	-93.09	-35.09	-128.18	17.00	31.01	4.61	41.06
2L-2-NS	-92.81	-33.72	-126.53	17.09	30.81	4.42	41.08
2L-2-NWSE	-92.72	-34.40	-127.13	17.41	30.37	4.49	41.06
2L-2-WE	-92.06	-34.83	-126.90	17.18	29.86	4.54	41.06
4L-1-NS	-94.81	-35.01	-129.82	17.50	31.41	5.35	41.24
4L-1-NWSE	-95.30	-35.87	-131.17	18.13	31.58	5.06	41.22
4L-1-WE	-94.81	-35.01	-129.82	17.50	31.41	5.35	41.24
4L-1.5-NS	-95.08	-35.48	-130.55	17.38	31.47	5.66	41.23
4L-1.5-NWSE	-94.77	-35.75	-130.52	18.28	30.95	5.00	41.22
4L-1.5-WE	-93.94	-35.40	-129.34	18.48	30.23	4.66	41.22
4L-2-NS	-95.02	-35.66	-130.68	17.17	31.46	5.85	41.22
4L-2-NWSE	-94.40	-35.63	-130.03	18.25	30.68	4.93	41.21
4L-2-WE	-93.13	-35.22	-128.35	18.51	29.51	4.55	41.20

BIOGRAPHY



The author full name is Putri Melati Dewi, who was born in Jakarta, 19th January 1995. The author went to Pacar Keling V Surabaya Elementary School, Junior High 6 Surabaya, and 5 Senior High School Surabaya. The author started studying architecture in undergraduate program of Architecture Department ITS in 2012, and finished her study in 2017, with final project, titled “Wind Tunnel Apartment”. During her undergraduate study, Author joined student exchange program in Kumamoto University Japan for one semester. The author worked at CV. Arsiyasta, an architecture design studio, before starting her master study in 2017. Discussion, recommendation and critics are welcomed. The author can be contacted by email at putri.md@gmail.com