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THE EFFECT OF BUILDING GEOMETRIC SHAPE AND ORIENTATION ON ITS ENERGY PERFORMANCE IN VARIOUS CLIMATE REGIONS

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ABSTRACT: Building thermal characteristic is one of the key factors in energy consumption. Many studies have been conducted to improve the building thermal performance for energy efficiency. In fact, building energy consumption and thermal comfort are affected by several factors, such as building geometry, structural design, building envelope materials, environment, local climate and occupancy patterns of the occupants within the occupied zone. In the building geometry aspect, two important parameters that have significant impacts on building thermal performance are building shape and orientation. The aim of this study is to evaluate the impact of these parameters on building energy consumption. In the first part, the description of building characteristics is completely explained. Extensive numerical simulations using a coupling of TRNSYS [(R)] and CONTAM [(C)] have been performed under mono-zone building thermal design. Numerical simulation results showed that a compact building shape and appropriate building orientation can reduce the energy consumption for heating and cooling systems up to 81% depending on the geographical conditions where the building is located.

Keywords: Building thermal performance, Energy consumption, Building shape, Orientation

1. INTRODUCTION

In the energy context, building sector plays a significant part in global energy consumption. The building energy is widely used for heating system for cold climate areas, air conditioning system for hot areas, ventilation, and lighting system. However, due to the global warming effect where the earth's temperature significantly rises, the energy demand for the cooling system substantially increases higher than other usages. The results of several studies showed that air cooling system took an important part of building energy consumption, especially for the hot-humid regions. For instance, in Hong Kong, 43% of national energy expenditure is used for cooling equipment. [1]. In Indonesia, the energy needs for cooling system increasingly reached up to 30% – 60% share of total building energy consumption. [2]. This consumption is predicted to continuously rise along with the increase in the number of Air Conditioning (*AC*) equipment sales. In 2018, Indonesian Air Conditioner market has grown 13% higher compared to 2013. [3]. The highest sales volume of *AC* equipment is observed in the Asia Pacific area for a 58% share of global sales. [4]. Currently, more than 46% of the buildings in *OECD* countries have been equipped with an air conditioning system. [5]. Conversely, for cold climate region, the energy in the building is more widely used for heating equipments.

Indeed, the total energy consumption depends on the climate and thermal characteristics of the building. A good building design has to consider the local climate conditions where the building is located. Inappropriate building geometry may lead to energy inefficiency. Therefore, passive building concept or bioclimatic design can be an effective solution in improving building energy efficiency. In cold climates, some passive strategies can be performed such as maximizing the heat absorption, maximizing the use of natural lighting and ventilation control system.

Building thermal performance is affected by many factors. An exhaustive improvement in various aspects including geometry design, materials characteristics, occupation pattern, and so forth could increase energy saving in the building, In fact, many studies have been conducted to improve the thermal performance of buildings in order to reduce energy consumption and improve its thermal comfort. Several aspects that have been optimized to promote indoor thermal comfort by removing unwanted heat gain. Those aspects are; geometry [6, 7], building orientation [8, 9], building materials [10–12], ventilation system [13–16], etc.

One of the important aspects affecting the thermal performance of the building is its geometry. In the present article, the effect of geometry on building energy consumption and thermal comfort will be analyzed. Two important parameters in the geometry aspect discussed in this article are building shape and building orientation. The first parameter, building shape, has affected total energy consumption and construction cost. A numerical study about building optimization conducted in the desert area indicates that a high compactness ratio of building shape provides an important impact in the reduction of energy consumption for air conditioning systems [17]. Another study on commercial buildings showed that the building shape is capable to reduce electrical load up to 6%-10% [18].

The second parameter, building orientation, also grants a considered effect on solar heat gain and natural lighting. In the northern hemisphere, the main facade of the building is generally heading to the south in order to promote solar heat gain that could be used to reduce thermal energy needs. Contrarily, during summer, this southward orientation causes a counterproductive effect on the thermal comfort of occupant due to the high intensity of solar transmission into the room. Accordingly, in optimizing building orientation, it is necessary to obtain an optimal compromise in the reduction of energy consumption for heating, cooling and lighting systems. A numerical study on a typical building located in 12 different locations (longitude 100.6°E-126.7°E and latitude 1.4°N-45.7°N) indicates that the optimal buildings orientation varies between 150° (south-east) and 192.5° (southwest) [19] depending on its geographical location.

The objective of this study is to analyze the effect of geometric shape and orientation on building thermal performance and energy demand in different climate regions. In the first part, the characteristics of the buildings are presented. In the second part, numerical modeling that represents the typical commercial building is performed by using TRNSYS and CONTAM to analyze the effect of the investigated parameters. In the last part, the results of the numerical simulation are presented along with analysis and conclusions.

2. METHODOLOGY AND CASE STUDY

2.1. Description of Studied Building

In this study, single-story commercial building with a square shape illustrated by Fig. 1 has been considered. The width (*Wb*) and length (*Lb*) of the building are 36 m with a height (*HB*) 6 m. The building main structure is made of steel. The flat roof is equipped by skylights with total surface area 31.4 m^2 that represent 2.4 % of the roof surface.

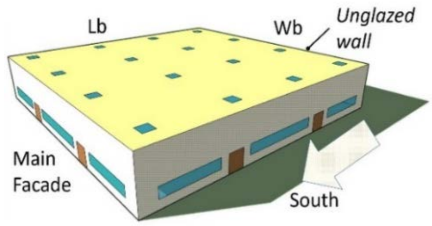


Fig. 1. The geometry of the studied building

Vertical walls (except the north side) with a thickness of 305 mm include 30 m^2 of single glass windows. Materials of the walls consist of 13 mm gypsum, 140 mm glass wool, rock wool insulation 150 mm and 2 mm steel plate. The ground floor is made of concrete with 160 mm thickness without thermal insulation and directly placed on the sand. 10 % of the building volume (787.9 m^3) is occupied by shelves to display merchandise materials consisting 40 % cardboard, 30 % oils and other liquids, 10 % metal, and 20 % plastics. The building is equipped by air conditioning system to keep the indoor temperature remains 26^0 C. To ensure the quality of indoor air, mechanical ventilation with an airflow rate of 0.75 volumes per hour is performed during the occupation period between 07:00 and 22:00 every day except on Sundays. For the case of a commercial building, the occupation rate is assumed to be 11.6 m^2/person [20]. The human heat gain is considered 1.6 Met as the normal occupant activity level.

2.2. Local Meteorological Data

Three locations that represent different climate area considered in this study are *Jakarta*, *Marseille*, and *Poitiers* (Fig. 2). The climate characteristics for all locations are summarized in Table 1. Annual temperature variations for all locations are presented in Fig. 3.

Jakarta – tropical climate

According to *Köppen climate classification*, Jakarta (6.21^{0}S, 106.85 ^{0}E) is located on the tropical-equatorial area (*Af*). The outdoor air temperature and humidity in Jakarta are quite important. Temperature varies between 22.8^{0}C and 37.6^{0}C with an average of 27.3 ^{0}C. The solar radiation intensity is almost constant throughout the year with an annual average and the maximum value is 417 W.m^{-2} and 1053 W.m^{-2}, respectively. The high solar absorption and transmission by the building envelope (wall, windows...) cause the thermal discomfort in the occupied zone. Moreover, Jakarta is located in a coastal area with the high thermal inertia of the sea. With these environment characteristics, the crucial problem often encountered in Jakarta is summer thermal discomfort. Meanwhile, the energy requirements for the heating system are neglected (see Table 1).

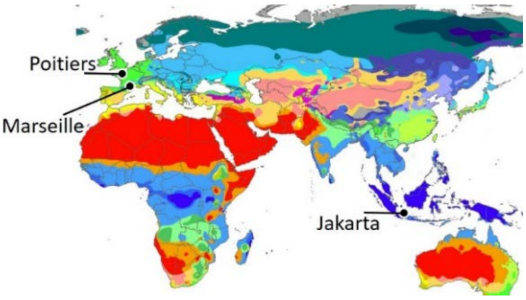


Fig. 2. Three selected locations in the study [21]

Marseille – Mediterranean climate

Marseille (43.29N, 5.38E) is located in a Mediterranean climate area. There are significant temperature variation between winter (min 2.1 ^{0}C) and summer (max 34.2 ^{0}C). The average annual temperature in this location is 14.8 ^{0}C. In Marseille, the energy demand for heating and cooling system is almost equivalent. Consequently, building envelope must be thoroughly designed based on both seasons.

Poitiers – Oceanic climate

Poitiers (46.58N, 0.33E) is situated in the oceanic climate area with outdoor temperature is relatively cooler than two previous locations. The outside temperature varies between -1.2 ^{0}C and 33.6 ^{0}C with an annual average of 11.6 ^{0}C. In this condition, the energy needs for heating is needed more significantly compared to the cooling one.

Table 1. Climate characteristics for the three different locations

Parameters	Jakarta	Marseille	Poitiers
Annual outdoors mean temperature (^{0}C)	27.3	14.8	11.6
Annual mean relative air humidity (%)	79.8	68.6	78.5
Maximal / annual solar irradiation (w.m^{-2})	1053 / 417	986 / 353	930 / 289
Wind speed (m.s^{-1})	2.15	4.87	3.89
Degree-hour of heating (outdoor temperature < 18^{0}C) in ^{0}Ch	0	48500	70374
Degree-hour of cooling (outdoor temperature > 26^{0}C) in ^{0}Ch	17102	1217	382

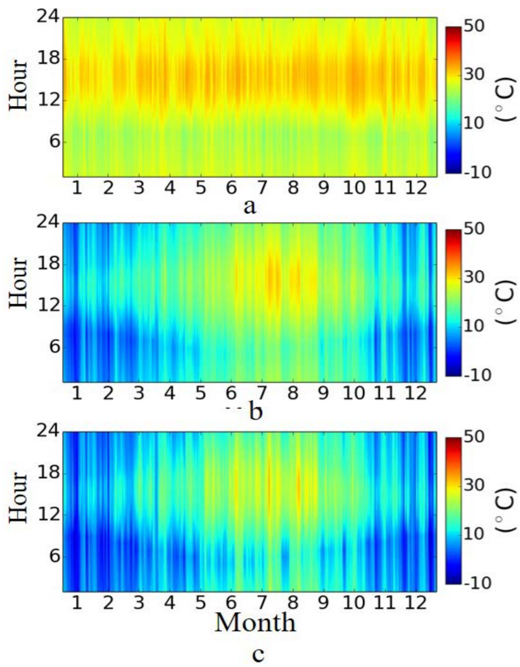
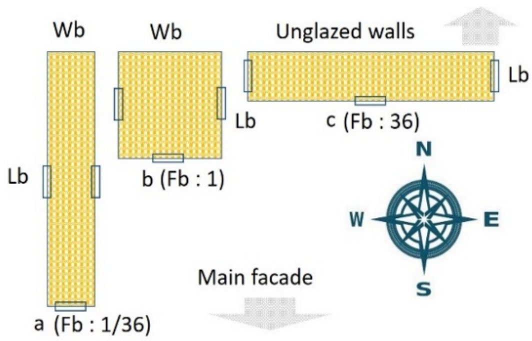


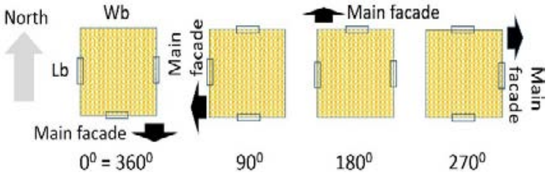
Fig. 3. Outdoor temperature variations within one year period for (a) Jakarta, (b) Marseille and (c) Poitiers

2.3. Design of Building Geometry

In order to analyze the effect of building shape on thermal performance, two coefficients are introduced in this study; *Cb* and *Fb*. These coefficients can be expressed in Eq.1 dan Eq.2. The first coefficient (in *m*) is the ratio of building volume *Vb* (m^3) to the total envelope surface that associated directly to outdoor *Sd* (m^2) including floor, walls, and roof. The second one (dimensionless) is the ratio of the width (*Wb*) to the length (*Lb*) of the building. In this case, the building height *(HB)* is constant at 6m. The surface of the windows is kept constant 30 m^2 on each side. For the parametric study, the building shape will be modified based on the width-length ratio (*Fb*) which varies from 1/36 to 36 (Fig. 4.a).



a.



b.

Fig. 4. a. Building shape for different value of *Fb*, b. Building orientation (0^0 indicates the south direction for the main facade).

$$C_b = \frac{V_b}{S_d} = \frac{L_b\ W_b\ h_b}{2\,(L_b\ W_b + L_b\ h_b + W_b\ h_b)} \quad (1)$$

$$F_b = \frac{W_b}{L_b} \quad (2)$$

2.4. Numerical Modeling

In this study, numerical simulations are performed under TRNSYS-CONTAM simulation tools to analyze the building thermal performance (Fig. 5). The studied commercial building is modeled as a single zone (*mono-zone model*) which consists of several elements in thermal-aerodynamic aspects: (a) thermal model under type 56 to presents the thermal characteristics of building envelope, thermal inertia, occupation, etc and (b) the aerodynamic model under type 97 to determine the air flow-rate, ventilation, infiltration, etc.

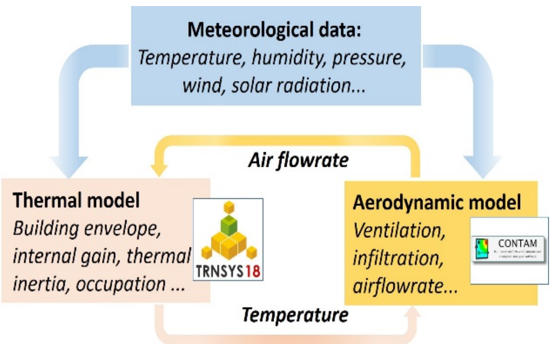


Fig. 5. Numerical modeling under TRNSYS-Contam environment tools

In the aerodynamic model, air flowrate across the flow path on building envelop (ventilation and infiltration) is calculated by pressure difference based on the Bernoulli equation comparing inside and outside of the building. The coefficient of discharge for the windows is assumed to be 0.6. The average air density is assumed 1,204 kg.m^{-3}. Based on the experimental study conducted by Persily (1998) [22], the air permeability for a commercial building with metallic structure is 2cm^2.m^{-2}. In the modeling of wind dynamic effects, the coefficient of pressure proposed by Swami and Chandra (1988) for similar buildings are considered [23]. On the ground level, the heat transfer is modeled by a three-dimensional approach.

3. RESULTS AND DISCUSSION

3.1. Effects of Building Shape

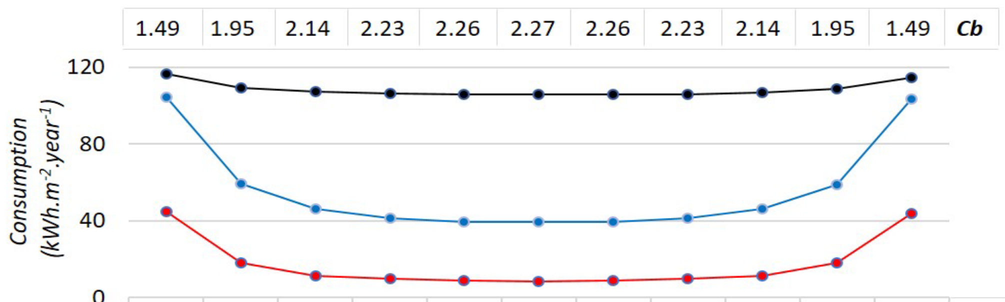
The effect of building shape on energy demand for three selected locations are presented in Fig. 6. By comparing the energy consumption of cases based on coefficient *Fb* as described in the previous section (see paragraph 2.3), the results show that the building shape has a significant effect on heating-cooling energy need for all locations. The lowest energy demand is obtained for a square building (*Fb*: 1). The square building shape is more suitable for all climate locations to reduce building energy consumption. However, the energy efficiency level remains different for each location.

In Jakarta where the cooling needs are more significant, the effect of building shape on energy demand is less significant compared to the cold region. The energy consumption in this regions varies between 105.7 kWh.m^{-2}.year^{-1} for a compact building (square shape) and 116.4 kWh.m^{-2}.year^{-1} for non-compact one. The cooling energy saving due to the building shape is 10.7 kWh.m^2.year^{-2}, equivalent to 9.2% (Table 2). This energy saving is caused by the smaller area of envelope surface that absorbs solar heat gain in a square building shape (Fig. 6).

In the equatorial region, building envelope (roof, walls) will absorb heat flux from the environment (outside air, solar radiation, thermal radiation of surrounding objects, etc.) in the daytime. Consequently, the indoor temperature during the occupied time (daytime) was significantly increased in uncompacted building shape. Therefore, the energy demand for the cooling system in this building becomes important. On the contrary, at night the unwanted heat in the room will be released outdoor through the building envelope. However, because of small fluctuation of outside temperature between day and night the heat releasing becomes less optimal. Therefore, the extension of the envelope surface (in uncompacted building case) show a negative impact on thermal comfort while free cooling effect in nighttime was not too significant.

In the cold region, the effect of building shape on building energy demand is more important than the hot region. In Marseille (Mediterranean climate), heating-cooling energy demand varies between 8.5 and 44.7 kWh.m^2.year^{-2} (Fig. 6).

Meanwhile, in Poitiers, it varies from 39.5 to 104.4 kWh.m^2.year^{-2}. In any case, the square building shape is still the most applicable design for energy saving. Otherwise, uncompacted shape frequently could double energy consumption compared to the compact ones.



	0,028	0,111	0,25	0,444	0,694	1	1,44	2,25	4	9	36	Fb
Jakarta	116,4	109,2	107,1	106,2	105,8	105,7	105,7	106	106,7	108,5	114,8	
Marseille	44,7	18	11,4	9,9	9	8,5	8,7	9,8	11,1	17,8	43,5	
Poitiers	104,4	59,3	46,3	41,5	39,6	39,5	39,6	41,4	46,1	58,9	103,6	

Fig. 6. Building energy consumption depends on the coefficient of Fb

In addition, the results show that the longitudinal or latitudinal extending wall surface indicate almost identical energy consumption. The variation of the width-length ratio (*Fb*) did not have a significant impact on energy consumption (Fig. 6). For example, the latitudinal extending wall surface (*Fb* 0.028, *Cb* 1.49), as illustrated in Fig. 6 indicate almost the same results to the longitudinal one (*Fb* 36, *Cb* 1.49).

3.2. Effect of Building Orientation

The impact of the building orientation on energy consumption highly depends on the geographical location where the building was constructed. For regions in the northern hemisphere with a latitude greater than 22.45^0, the sun position is always in the southern side of the building, and vice versa. For cold areas, to maximize the penetration of solar radiation into the occupied zone, the glazed wall should be directed to sun position. As for the equatorial region, the sun's trajectory alternate between northside and south side of building depending on the season.

The simulation results show that the optimal direction of building in Poitiers (46.58N) is 0^0 where the unglazed wall is heading to the north side. Positioning the glazed walls to the east, west and south direction would maximize the solar transmission. While the north side wall does not need to be fitted by glass windows since it will increase thermal loss especially at nighttime. The energy requirement for space heating in this place is more important than air cooling. Therefore, the free heating by solar radiation can raise the indoor temperature and reduce the overall energy consumption. Energy efficiency obtained by comparing the optimal orientation (0^0) to the opposite (180^0) is 11.8 kWh.m^2.year^{-2} (22.2%) (Table 2).

In Marseille where heating and cooling needs are balanced, the building orientation must be carefully designed. During winter, solar heat gain is useful to reduce the heating need so the windowless wall should be directed to the north. Contrarily in summer, solar heat gain must be reduced by directing the unglazed wall to the south. In this case, the optimal building orientation is 270^0 where the unglazed wall leads to the west (Fig. 7). It is the best compromise to obtain the lowest energy consumption by considering the two different seasons. The energy savings obtained due to optimal orientation is 9 kWh.m^2.year^{-2} or equal to 27.4% (Table 2).

For Jakarta, the optimal building orientation (the unglazed wall is leading to east or west side) can reduce solar heat gain through the windows during the day. The minimization of wall surface that directly exposed to the sun could reduce the building space overheating. By positioning the unglazed walls into the optimal direction (east or west) in this location can reduce the cooling need about 6.3 kWh.m^2.year^{-2} (5.9%) compared to the nonoptimal ones (Table 2).

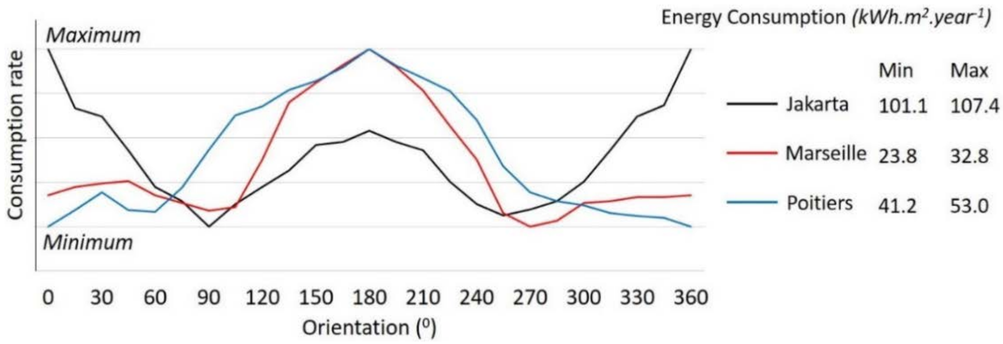


Fig. 7. The effect of building orientation on energy consumption

In addition, the effect of building orientation on energy consumption in Jakarta is less important. This is due to the almost constant of sun azimuth angle at midday throughout the year. The high sun's azimuth angle in Jakarta ($\geq 70^0$) makes the solar absorption and transmission through the vertical windows becomes less significant compared to the skylights. The solar radiation in the hottest time in the day (11.00-14.00) is not optimally distributed to the vertical windows

Table 2. Optimal parameters for different locations

Parameters	Jakarta-Tropical	Marseille-Mediteranean	Poitiers-Oceanic
Appropriate building shape	Square (FB 1)	Square (FB 1)	Square (FB 1)
Energy saving by building shape factor (kWh.m^2.y^{-2})	10.7 (9.2%)	36.2 (81%)	64.9 (62.2%)
Optimal and non-optimal orientation (^{0})	90^0 / 0^0	270^0 / 180^0	0^0 / 180^0
Energy saving by orientation factor (kWh.m^2.y^{-2})	6.3 (5.9%)	9 (27.4%)	11.8 (22.2%)

4. CONCLUSIONS AND PERSPECTIVES

The building shape and building orientation provide a significant impact on building's energy performance and thermal comfort. The compact buildings with a square shape which has a small surface of the envelope in contact to outdoor air will absorb less solar heat gain in the hot area (by radiation and convection) than the uncompact ones. Therefore indoor air temperature will be lower and capable of further improving the thermal comfort of occupants during the day. Contrariwise, in the cold area, the compact building surface is able to reduce the heat loss through building envelopes, consequently, the heating energy needs can be reduced.

Related to building orientation, for the tropical-equatorial regions, the glazed walls should be positioned into opposite direction of the sun to reduce the solar transmission through the windows. Whereas in the oceanic climate areas, the windows' direction has to face the sun position to promote solar heat gain. In addition, the size and position of windows must be considered carefully as it might have a considerable influence on the thermal discomfort level on one side and gain of natural lighting on the other side. As the perspective of this work, we will perform the optimization study of windows surface area on the benefit of natural lighting and the control of solar heat gain for the same type of building.

5. ACKNOWLEDGMENTS

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