

The effect of building shape and orientation on energy use at sloped sites in tropical climates using sefaira

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ARTICLE INFO	ABSTRACT
<p><i>Article history:</i> Received August 24, 2021 Received in revised form Sept. 30, 2021 Accepted October 19, 2021 Available online April 01, 2022</p> <p><i>Keywords:</i> Energy saving Orientation Sefaira Shape Site topography</p> <p>*Corresponding author: Piyanka G. A. S. K. N. Notodipuro Department of Architecture, Faculty of Engineering, Universitas Katolik Parahyangan, Indonesia Email: pazzahra@gmail.com</p>	<p>One of the biggest contributors to energy usage are built infrastructures (up to 40%). Minimizing energy usage efficiently could reduce cost and give a better impact on the environment in terms of sustainability. As a tropical country that experiences sun exposure throughout the year, designing a building in Indonesia needs to respond to the impact of solar radiation inside the room for comfort and energy-saving effort. In addition, the topography of the site is considered throughout the process of designing a building, in which the site is located on sloped terrain (with a slant of 15 degrees celsius) and may influence the orientation and shape as it affects access to sunlight and view. This paper aims to identify which building orientation and shape of a project have the least energy usage during its preliminary phase on sloped terrains in tropical climate areas. 3 different building orientations (west-east, combination, North-east – South-west) and shapes are analyzed through experimental method by utilizing Sefaira as a plugin to Sketchup software using ASHRAE 90.1 - 2019 (ZONE 2) as material standard for the analysis. This research focuses on how a sloped site, as well as climate, affects building efficiency and how the orientation and shape of the building affect the building's energy consumption. Difference in characteristics of the land, preferably regarding flat or sloped terrain lands, does not guarantee whether the energy usage will change, but it shows that sloped terrain sites could benefit on reducing the cooling load of a building as well as daylighting.</p>

Introduction

Energy consumption is one of the global issues that affects the world economically, and environmentally since greenhouse gas emissions have been increasing rapidly from time to time. One of the biggest contributors to this problem are built infrastructures, or buildings which lead up to 40% of total energy used. This matter does not stop at producing greenhouse gas emission, but also contributes to increasing local pollution and health side effects (Boechler et al. 2021).

Indonesia is one amongst countries in the world with tropical climate that experiences sun

exposure throughout the year, where it heavily relies on cooling in buildings to maintain thermal comfort. It is by far (as of 2016) one of the 23 countries that consumes high energy in the world (Kallakuri, Vaidyanathan, and Cluett 2016). Due to the heat, it could be the reason why energy usage on building cooling in tropical climate countries could consume over 50% of the building's energy demands (Boukhanouf et al. 2014). According to Jakarta Provincial Government, Indonesia has a high intensity when it comes to the amount of building growth. Due to that, the government has the ambition to reduce energy use by 26% from Business as Usual

(BAU) and reduce energy use up to 41% if the building is accommodating the international community (The Government of the Province of Jakarta Capital Special Territory 2016). With these records about energy consumption in Indonesia, it would seem natural for upcoming buildings to be designed in a way that it could benefit the environment and reduce its energy usage.

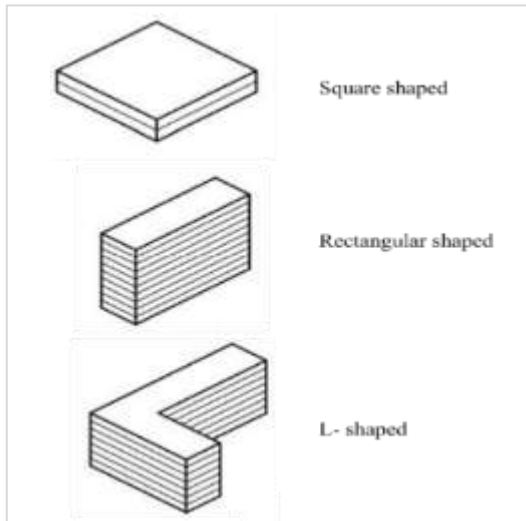


Figure 1. Form building implications
Source: (Lechner 2015)

Benefactors of energy consumption in a building would include the size, orientation, and form of a building, where they hold a great impact on resources needed for construction and operation. Thus, designing a sustainable building will achieve reduction of energy usage, where orientation and shape of the building itself could influence energy demand by 30% to 40% (Brophy and Lewis 2011). By comparing form building implications between squared, rectangular, and L-shaped designs, rectangular shaped buildings have higher potential for passive solar heating. The form of rectangular buildings is designed in a way that it would allow another solution on attaining thermal comfort, such as most windows could face the ideal direction or orientation of north and south and have high potential for cross ventilation while maintaining its optimal daylighting without worrying about energy consumption on heating. Compared to rectangular building forms, both square shaped and L-shaped building windows could not face ideal orientation and would deal with other problematic orientation matters (Lechner 2015). Due to positioning of

orientation, windows or façades that are exposed by the sun are also affected by it which is why daylighting could also be the benefactor of energy consumption (Yu and Su 2015).

Moreover, the topography of a designated site could also be a problem in designing an energy-saving building. The energy consumption of a sloped terrain is lower than flat terrain, where flat lands have higher air temperature amplitudes, thus creating a higher demand of heating and cooling (Golany 1996). A study shows that having sloped terrains as a building site is better than flat terrains as it could provide 25% cooling saving and demand savings of 42%, although flat lands are 8% cheaper to construct which could reduce if maintenance as well as operational costs are considered (de Castro and Gadi 2017). In general, the difference in the topography of a site utilizes different methods. For example, on sloped sites, the ancient Greeks solved solar heating efficiency by building their towns on southern slopes area, while the streets were stretched along the east-west side if it's possible. On the other hand, on flat sites in an area that are very hot in summer, shadings are necessary. For instance, in Santa Fe, New Mexico, they use a colonnade to protect pedestrians from rain as well as sun, where it shades the walls and windows. Another example is that multistory buildings are often built on narrow streets in order to create shade for both streets and buildings (Lechner 2015).

One of the methods on minimizing the usage of energy is by using energy simulation software during the preliminary design phase of building (U.S. Green Building Council 2015). Plenty of software could be utilized to achieve this, but for this study, the authors use Sefaira System software using ASHRAE 90.1 - 2019 (ZONE 2) as material standard for the analysis. Sefaira is a software that was established in 2009. It allows users to measure and analyze the level of energy efficiency in a building, including thermal comfort, daylighting, and HVAC (Trimble Inc 2009).

Aside from the cooling load needed in a tropical climate building, daylighting could also be one of the factors of high amounts in energy consumption. Daylighting is one of the passive strategy methods used to improve energy performance whilst enhancing users' visual comfort in an inexpensive way (Lim et al. 2012). Even though daylight is a cheap and practical way of improving energy performance without butchering environmental aspects, in some

conditions, daylight could cause glaring problems, particularly in places where a visual environment is needed (Balocco and Calzolari 2008; Loutzenhiser, Maxwell, and Manz 2007).

The amount of energy consumption of lighting in an office building could reach up to 40% (Lechner 2015), which shows how significant lighting is to human daily activities. The cost of a daylighting system depends on how it is done, where it could cost up to zero if the building could design a better orientation, window placement, and window size. Shading could also be helpful, where it could reduce air conditioning in a space. For climate areas, priorities are given for envelope – dominated buildings, such as small offices or residences, whereas in terms of large office buildings are less affected by climate and have smaller heating and greater cooling needs. Due to that, it requires an efficient amount of daylighting (Lechner 2015).

There has been plenty of research that discusses the reduction of energy consumption based on its building shape (Camporeale and Mercader-Moyano 2019; Choi, Cho, and Kim 2012; Ciardiello et al. 2020; Geraldi et al. 2021; Quan et al. 2014) and orientation (Abanda and Byers 2016; Alghoul, Rijabo, and Mashena 2017; Karimimoshaver and Shahrak 2022; Kim et al. 2016; Valladares-Rendón, Schmid, and Lo 2017), but those who study in the context of sloping land are still limited. With both combined, it might consolidate to save energy consumption in the world, especially in tropical climate countries. With this lack of research about the effect of sloped terrains on energy consumption especially in tropical climates, it begs to question: How do slope terrains affect building energy efficiency in tropical climates? And how does the shape and orientation of the building affect the its energy consumption?

Method

This research aims to identify which building orientation and shape of a project have the least energy usage and its impact on lighting and cooling load during its preliminary phase on sloped terrains in tropical climate areas using Sefaira as the software of simulation. Firstly, simulations are applied on flat surfaced site, then onto sloped site to compare which terrains could contribute on minimizing energy used in the

building. Afterwards, the usage of energy that is affecting lighting and cooling load are shown from Dynamic Overshadowing by Andrew Marsh, to justify the coverage of shadow in the slope terrain building and the impact it gives (Marsh 2016). Some of his works are accessible in his website, where Dynamic Overshadowing could be utilized and under the category of Web Applications section.

While using experimental method, this study can figure out the best energy-saving orientation of the project by comparing its form and location.

The simulation variables are listed below:

1. Sefaira material standard: ASHRAE 90.1 - 2019 (ZONE 2);
2. Controlled variables:
 - o Site topography (sloped terrain)
 - o Tropical climate
 - o Function of the building
3. Independent variables:
 - o Changes in building orientation
 - o Changes in building roof shape
4. Dependent variables:
 - o Energy Usage Intensity (EUI)
 - o Cooling load
 - o Lighting: Annual Sunlight Exposure (aSE) and sDA (spatial Daylight Autonomy).

Energy Usage Intensity (EUI) presents a building's energy use by dividing annual building energy consumption in one year by total gross of floor area as kBtu/sf. Generally, factors that affect the amount of Energy Usage Intensity (EUI) are its building function, size, and other characteristics such as facades or materials (Yang and Choi 2015). Cooling load is a calculation that is carried out to estimate the space needed to gain heat in a building (Bhatia 2006). For estimating the number of cooling loads needed in one building, one must consider the unsteady state of the process, because peak cooling load occurs during the daytime, and a variety of external factors might affect it significantly throughout the day due to solar radiation. The calculations of cooling load are also to estimate the cool needed in all internal sources to obtain the required cooling capacity.

sDA (spatial Daylight Autonomy), is a tool to calculate the level of natural light that enters a space during normal operating hours (8 am to 6 pm), while Annual Sunlight Exposure (aSE), represents the number of hours per year where the direct sun is incident on the surface that could potentially cause discomfort, glare, or increase in cooling loads (IESNA 2012). According to LEED

v4, the recommended aSE value in a space should be less than 10%, while sDA values range from 55% to 74% indicates a space in which daylighting is considered as nominally accepted by occupants and 75% is considered as a space in which daylighting is more preferred (U.S. Green Building Council 2021). Many studies have used the aSE and SDA climate-based metrics to measure the daylighting performance of buildings (Lee, Boubekri, and Liang 2019; Mangkuto et al. 2019; Mohsenin and Hu 2015; Nezamdoost et al. 2017).

Site review

The location of the project is in Jl. Penyandan, Cimenyan District, Kabupaten Bandung, Indonesia with the coordinate of 6°52'32"S, 107°40'26"E. The building is a mixed-use building, where it accommodates as a travel education center as well as a production house, and research center facilities.



Figure 2. Site location (satellite view)

The site has a total area of 11 660 m², around 800 to 1200 above sea level. Due to that, the topography of the site is considered as having a sloped terrain, which could be one of the constraints of the project.

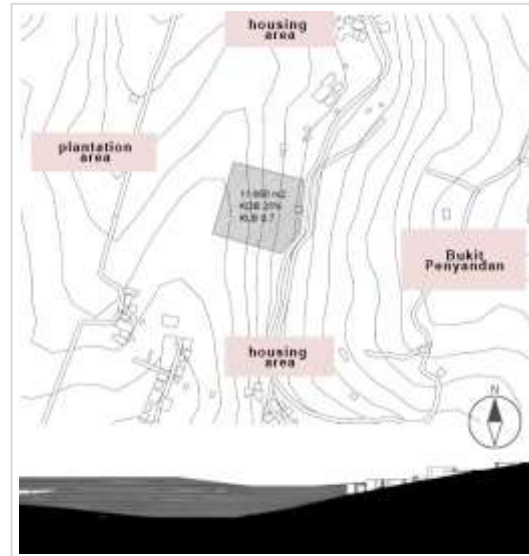


Figure 3. Site and existing (above) top view, (below) section view

The existing soil conditions in the Cimenyan district generally consist of 80% land with topography that varies from undulating land and hills. The slope at the site is less than 30% (around 25 meters from the highest to lowest). However, one of the issues that could be found on the site is the fact that its slope terrain is facing towards the East and West side, where the chances of being exposed to solar radiation are far greater than facing towards South and North.

Modelling and simulation settings

By using ASHRAE 90.1 - 2019 (ZONE 2), the materials used for glazing and type are based on the standard. The building element properties used in the simulation are clarified as the following:

- 1) Façade Glazing: Assembly U-Value amount is 3.41 W/m².K with Solar Heat Gain Coefficient (SHGC) 0.23;
- 2) Walls material used is brick with Assembly U-Value 0.48 W/m².K;
- 3) Floors finishing are tiles with Ground Floor U-Value 0.49 W/m².K;
- 4) Infiltration type is Façade Area at 75Pa with Design Infiltration Rate of 7.2 m³/ m².h;
- 5) Roof Glazing Assembly U-Value amount 2.40 W/m².K with Solar Heat Gain Coefficient (SHGC) 0.6;
- 6) Roofs type is Slope Frame (flat and slanted roof with the average angle of 30°) with Roof U-Value 0.22 W/m².K;

7) HVAC system type: VAV – Return Air Package.

Buildings have the same layout, but different orientations with the same number of storeys, openings, materials, and roof types. 3 different building orientations are mentioned below:

Table 1. List of building orientations

Building orientation	2D Plan	3D
West – east (Orientation A)		
Combination, Dominant on South–North (Orientation B)		
North-west and South-west (Orientation C)		

Result and discussion

Firstly, analysis using Sefaira is applied to flat surfaced sites. Each building has the same total surface area, which is 7 357 m², with an average number of storeys that ranges from 2 up to 4 floors. The building typology used for the analysis is office since it is a non – residential mixed-use building.

Table 2. Sefaira results for EUI, energy distribution and daylighting result of orientation A

Orientation A		
Energy Use Intensity (kWh/m ² /yr)	Energy Segments (kWh/yr)	Daylighting (% of floor area annually)
131	Heating = 547 Cooling = 530 704 Lighting = 262 384	Underlit = 24 Well lit = 13 Overlit = 63

Equipment=	655 960
Fans =	210 042
Pumps =	0

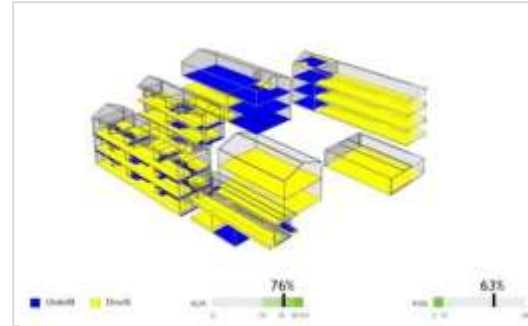


Figure 4. Sefaira for daylighting visualization of orientation A

Based on Sefaira simulation software, Orientation A (west–east) results shows that the total Energy Usage Intensity (EUI) of the building annually is 131 kWh/m²/yr, which is more than the amount of 2030 Challenge EUI that aims to get less than 79 kWh/m²/yr. The high amount of EUI is mostly spent on building equipment (up to 655 960 kWh/yr) and cooling necessities (up to 530 704 kWh/yr), while the least energy used is for heating which is only 547 kWh/yr. This could be due to the location of the site, where it is situated in a tropical climate country. Although it qualifies the criteria for average sDA which is 76%, 63% of the total floor area of the building are overlit, 13% well-lit, while 24% of the total floor area are underlit.

Table 3. Sefaira results for EUI, energy distribution, and daylight result of orientation B

Orientation B		
Energy Use Intensity (kWh/m ² /yr)	Energy Segments (kWh/yr)	Daylighting (% of floor area annually)
129	Heating = 465 Cooling = 512 074 Lighting = 262 384 Equipment= 655 960 Fans = 200 778 Pumps = 0	Underlit = 24 Well lit = 34 Overlit = 41

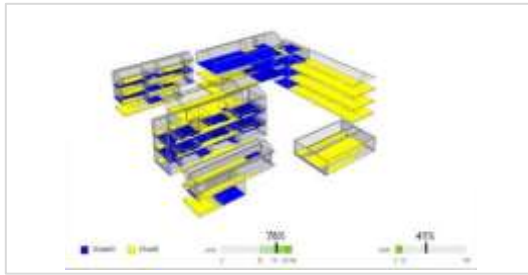


Figure 5. Sefaira for daylighting visualization of orientation B

As for Orientation B, most of the buildings are tilted towards the North and South direction which affect significantly on the amount of EUI, cooling load, and daylight. The amount of EUI decreased up to 129 kWh/m²/yr while the cooling load decreased to 512 074 kWh/yr. The amount of energy used on cooling per year is 3% below Orientation A while daylighting percentage show that this orientation has better well-lit areas per annual than Orientation A, which is 34% of total building floor area and a total of 76% for sDA, while aSE is 41% which is above average.

Table 4. Sefaira results for EUI, energy distribution, and daylight result of orientation C

Orientation C		
Energy Use Intensity (kWh/m ² /yr)	Energy Segments (kWh/yr)	Daylighting (% of floor area annually)
130	Heating = 729 Cooling = 496 719 Lighting = 250 425 Equipment = 626 063 Fans = 196 105 Pumps = 0	Underlit = 25 Well lit = 27 Overlit = 48

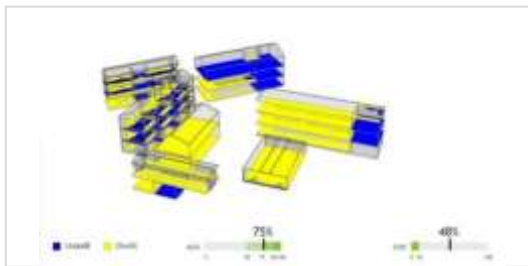


Figure 6. Sefaira for daylighting visualization of orientation C

Orientation C doesn't seem to show a prominent difference, for yearly EUI takes up to 129 kWh/m²/yr. The total energy use annually for Orientation C is dominated by equipment (up to 626 063 kWh/yr), but it also takes less energy on cooling load than Orientation A and B, which is 496 719 kWh/yr. This amount of cooling load is 3 - 6% less than the rest of the orientation models. The amount of sDA on Orientation C is 75%, while aSE is 48%.

Applying sloped terrain onto simulation

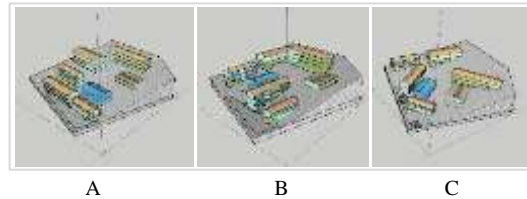


Figure 7. Building modellings after applying sloped terrain

After testing out on flat-surfaced terrain for simulation on Sefaira, sloped surface terrain is applied to each model. Keep in mind that in this study, thermal energy transferred by ground is excluded, since this study only aims at the positioning of the building.

Table 5. Sefaira results for EUI, energy distribution, and daylight result of Orientation A after applying sloped terrain

Orientation A in sloped terrain		
Energy Use Intensity (kWh/m ² /yr)	Energy Segments (kWh/yr)	Daylighting (% of floor area annually)
131	Heating = 1 012 Cooling = 536 151 Lighting = 266 027 Equipment = 665 068 Fans = 212 367 Pumps = 0	Underlit = 24 Well lit = 12 Overlit = 63

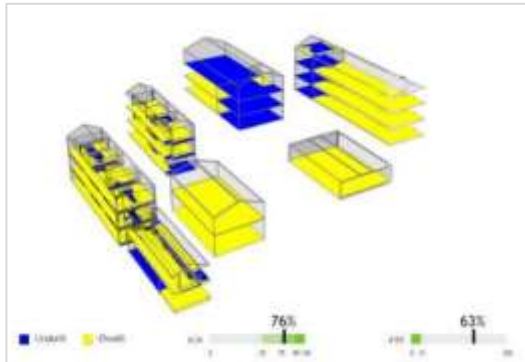


Figure 8. Sefaira for daylighting visualization of orientation A after applying sloped terrain

Energy Usage Intensity results in Orientation A at sloped terrain is 131 kWh/m²/yr. aSE has the same amount as Orientation A at flat terrain, which is 63%. Although the location of the site is in a tropical climate country, heating equipment is still needed where it could spend up to 1 012 kW due to the night humid temperature whereas for cooling load could take 536 151 kWh/yr especially during the day (compared to Orientation A on flat terrains, the cooling load decreased for 1%). It clearly shows that having sloped terrain affects the cold temperature at night due to more exposure of wind direction on buildings, which is cooler than on flat terrain sites (as shown from the increasing amount of heating load). Both sDA for Orientation A on flat and sloped terrains have the same amount (76%).

Table 6. Sefaira for EUI, energy distribution, and daylight result of orientation B after applying sloped terrain

Orientation B in sloped terrain		
Energy Use Intensity (kWh/m ² /yr)	Energy Segments (kWh/yr)	Daylighting (% of floor area annually)
129	Heating = 1 712 Cooling = 518 121 Lighting = 265 374 Equipment = 663 435 Fans = 203 447 Pumps = 0	Underlit = 22 Well lit = 33 Overlit = 46

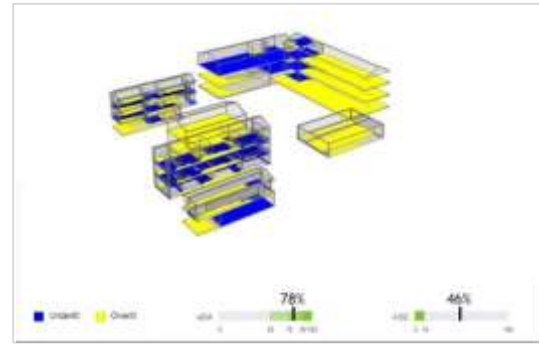


Figure 9. Sefaira for daylighting visualization of orientation B after applying sloped terrain

Unlike Orientation B at flat terrain, Orientation B in sloped terrain has decreased its cooling load by 1%, with Orientation B on sloped terrain having the amount of cooling load of 518 121 kWh/yr. However, the amount of EUI still remains the same, which is 129 kWh/m²/yr. Compared to Orientation A and C in sloped terrain, Orientation B (facing towards North and South) has the least amount of Energy Usage Intensity, although the difference is not that much. Spatial Daylight Autonomy of Orientation B in sloped terrain increased from 76% of the total area on flat terrain to 78% of the total building area. Meanwhile, the amount of Annual Sunlight Exposure per total building area reaches 46%.

Table 7. Sefaira for EUI, energy distribution and daylight result of orientation C after applying sloped terrain

Orientation C in sloped terrain		
Energy Use Intensity (kWh/m ² /yr)	Energy Segments (kWh/yr)	Daylighting (% of floor area annually)
130	Heating = 2 008 Cooling = 439 400 Lighting = 222 710 Equipment = 556 776 Fans = 173 942 Pumps = 0	Underlit = 25 Well lit = 30 Overlit = 45

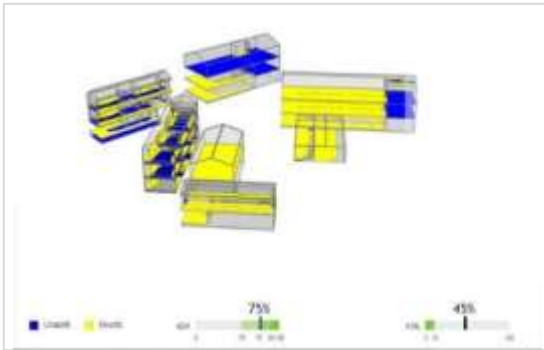


Figure 10. Sefaira for daylighting visualization of Orientation C after applying sloped terrain

Orientation C (facing towards North-west and South-east) has the amount of Energy Usage Intensity of 130 kWh/m²/yr. Unlike the rest of the building orientation models, Orientation C has the smallest amount of cooling load (439 400 kWh/yr). ASE decreased from 48% to 45% than Orientation C on flat terrain, while sDA for this model reached 75%, which is the same as Orientation C on flat terrain. Based on the analysis and data above, the following patterns were found:

Table 8. Accumulation of simulation result from Sefaira

Flat terrain				
Building orientation	EUI (kWh/m ² /yr)	Cooling load (kWh/yr)	aSE (%)	sDA (%)
A (West-east)	131	530 704	63	76
B (combination)	129	512 074	41	76
C (NW-SE)	130	496 719	48	75
Sloped terrain				
Building orientation	EUI (kWh/m ² /yr)	Cooling Load (kWh/yr)	aSE (%)	sDA (%)
A (West-east)	131	536 151	63	76
B (combination)	129	518 121	46	78
C (NW-SE)	130	439 400	45	75

Source: (Sefaira Web App 2021) and plugin

It is shown in table 8 above that sloped terrain does not affect the Energy Usage Intensity annually. Although EUI does not change, the distribution of energy usage of a building is affected, especially on cooling load. For example, Orientation A (facing towards west-east) requires

a cooling load with the total amount of 530 704 kWh/yr on flat surface lands, but on slope lands it, requires more, which is around 536 151 kWh/yr due to more exposure of solar radiation.

Each orientation shows a great amount of energy usage on cooling load as well as equipment necessities, which might be affected due to the immense amount of aSE that reaches up to 75 – 78%, s while its average aSE allowed in a building could only extend up to 10% of total floor area. Due to that, it shows the building accomplished the average target of sDA of a building, which is from 55% up to 100% because of the building attributes (with thin proportion and having two openings on each side of the building), but it came to a risk: most of the percentage acquired from getting sDA is probably due to the high amount of aSE. By having a large aSE percentage of the total floor area in the building, more glare and heat are received into the interior of the building. This could be affected due to solar heat transferring onto buildings that are more exposed on sloped terrain sites than on flat terrain sites.

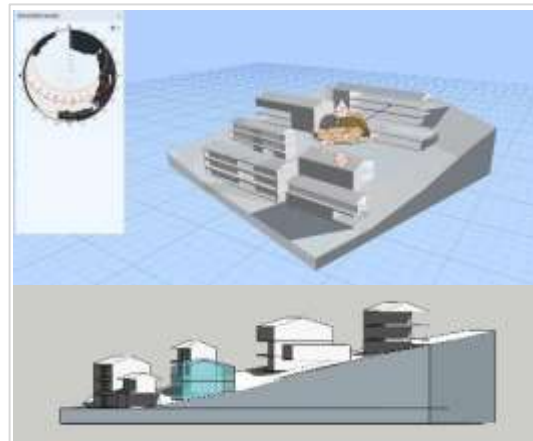


Figure 11. Overshadowing on Orientation A in sloped terrain





Figure 12. Overshadowing on Orientation B in sloped terrain

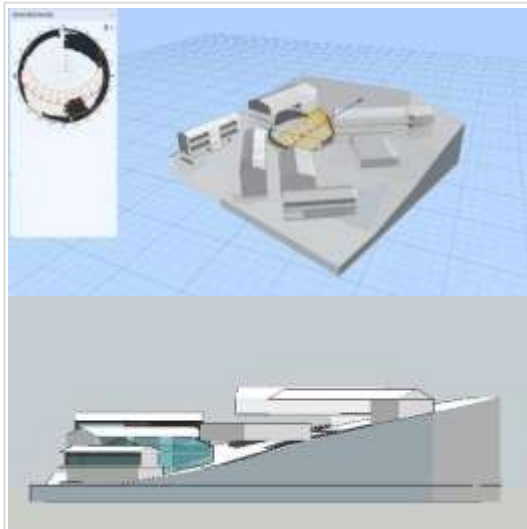


Figure 13. Overshadowing on Orientation C in sloped terrain

Based on Dynamic Overshadowing simulation, it is proven that the amount of shade on Orientation C covers around the area of the central outdoor area. The shadow covering by each mass of Orientation C contributes to the lower percentage of aSE, which is 45% of the total floor area of the building, compared to the other models that reach up to 63% of the total floor area. Adding vegetations or a double skin façade could lessen the amount of aSE on Orientation C, decreasing glare and heat from entering. Aside from that, those that cover most from shadows from building masses could also be used as a public open space where humans can interact with each other and nature.

Conclusion

The results show that the amount of energy usage on this building takes more than 2030 Challenge on office building type (maximum of 79 kWh/m²/yr), but the least building that consumes energy is Orientation B (dominantly facing towards North and South) at sloped terrain sites,

which consumes EUI up to 129 kWh/m²/yr (1,63:1 of 2030 Challenge) with 2 512 074 kWh/yr cooling load. Although buildings that are facing towards the North and South side could lessen the amount of EUI, it does not mean that the cooling load will also decrease or is any better. It reveals that instead of Orientation B that faces towards the South and North side, Orientation C has the least amount of cooling load on either flat or sloped terrain where it is 3% less than the amount of cooling load needed on Orientation B per year. The result could potentially be due to the reason of increased amount in the total heating load because of its orientation characteristics that dominantly face towards Northwest and Southeast, making it cooler than Orientation A which faces more towards West and East. The total heating load surges probably during the night.

Interestingly, EUI on sloped terrains does not change significantly compared to flat terrains, but it shows that sloped terrain sites could benefit from reducing the cooling load of a building. By considering building orientation during the preliminary phase could lessen the contribution of energy consumption, as well as it is affected by its topography (climate and terrain). It indicates that change in building orientation could decrease energy usage from 4 up to 19% while cooling load on slope terrain lands could reduce cooling load (estimated 1% up to 13%) from a building compared to flat terrain lands. However, differences in characteristics of the land, preferably regarding flat or sloped terrain, do not guarantee whether the energy usage will change. Because the ground slope orientation decreases to the west, the façade of the building tends to be more exposed towards sunlight during the day and evening (for buildings that are not shaded between masses). As result, the cooling load and glare are higher for orientations A and B, thus the orientation that is tilted (Orientation C) is better.

Orientation also affects building daylighting, meanwhile, characteristics of a terrain slightly change (aSE: 1 to 3% of total floor area, while sDA: 2% of total floor area). These changes could be for the better or the opposite. Both terms (Annual Sunlight Exposure and Spatial Daylight Autonomy) are related to each other, where result concludes that most of the building orientation fulfills the average percentage of total floor area needed for sDA, but it could be due to the high amount of glare and heat coming inside the building, which is measured with aSE.

Determining building orientation could be one of the solutions to reduce energy consumption and different characteristics in site terrains (whether it is sloped or flatlands) could slightly affect it, but other factors such as designing of building openings, façades, and choices of materials would reduce energy consumption or glare and heat coming through the interiors of a building.

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Author(s) contribution

Priyanka G. A. S. K. W. Notodipuro contributed to the research concepts preparation, methodologies, investigations, data analysis, visualization, articles drafting and revisions.

Ariani Mandala contribute to methodology, supervision, and validation.