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OPTIMIZATION OF URBAN THERMAL ENVIRONMENT FOR INDONESIA COASTAL-CLIMATE URBAN AREA: A MICROCLIMATIC MODELING

OPTIMALISASI LINGKUNGAN TERMAL UNTUK KAWASAN PERKOTAAN DENGAN IKLIM PESISIR DI INDONESIA: PEMODELAN IKLIM MIKRO

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ABSTRAK

Kawasan perkotaan dengan iklim pesisir yang salah satunya adalah PIK 2, Kabupaten Tangerang, Indonesia memiliki karakteristik iklim yang khas: perubahan angin darat dan laut selama musim yang berbeda, serta tingkat kelembaban dan kecepatan angin yang tinggi, yang mempengaruhi kenyamanan termal. Perlu adanya studi mengenai massa bangunan optimal untuk mencapai kondisi kenyamanan termal yang ideal dan dapat secara efektif merespons karakteristik iklim yang berbeda dari daerah perkotaan lainnya. Penelitian ini mengidentifikasi lingkungan termal perkotaan dan menyimulasikan dampak orientasi bangunan, bentuk, dan rasio H/W dengan bantuan perangkat lunak ENVI-met. Penempatan bangunan secara diagonal menghadap laut dengan sudut 45 derajat secara efektif mengurangi kecepatan angin yang berlebihan, sehingga menghasilkan skor PMV yang tergolong nyaman. Selain itu, menyertakan skybridge dalam desain bentuk bangunan memberikan peneduh yang memadai dan berkontribusi pada pencapaian kenyamanan termal yang optimal di daerah perkotaan beriklim pantai. Rasio H/W optimal adalah 0,5 yang dapat mengurangi kecepatan angin tanpa menurunkan suhu secara signifikan, sehingga menjaga kenyamanan termal di kawasan perkotaan dengan iklim pesisir.

Keywords: *Simulasi Bangunan; Kawasan Perkotaan Pesisir; ENVI-met;Iklim Mikro; Kenyamanan Termal.*

ABSTRACT

Coastal urban areas, one of which is the PIK 2, Tangerang Regency, Indonesia, as the study case, have distinctive climate characteristics: changes in land and sea breezes during different seasons and high humidity and wind speed levels, which affect thermal comfort. The optimal building mass needs to be studied to achieve ideal thermal

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comfort conditions, which can effectively respond to climate characteristics different from those of other urban areas. This paper investigates the existing urban thermal environment and models the impact of building orientation, form, and H/W ratio simulated in ENVI-met. Based on the study findings, it has been determined that positioning a building diagonally towards the sea at a 45-degree angle effectively reduces excessive wind speeds, resulting in a favorable PMV score. Additionally, incorporating a sky bridge into the building form design provides adequate shading and contributes to achieving optimal thermal comfort in coastal-climate urban areas. Moreover, the optimal H/W ratio is 0.5, which can reduce wind speed without significantly lowering the temperature, thereby maintaining thermal comfort.

Keywords: *Building Model; Coastal-Climate Urban Area; ENVI-met; Microclimate; Thermal Comfort.*

INTRODUCTION

The coastal-climate urban areas are regions that are built and developed adjacent to the coastline, vulnerable to climate change and changes in land and sea breezes during different seasons, sea level rise, and extreme weather temperatures due to high humidity and wind speed, commonly threatened by seawater flooding (Kantamaneni et al., 2023). The thermal conditions or environment in the coastal-climate urban areas are also affected by exposure to sea breezes and proximity to water bodies, which can increase relative humidity. One of the factors that influences the urban thermal environment, including coastal-climate urban areas, is population, which has become a recurring problem in developed countries; several other studies in China urban areas as case studies found that population density due to urbanization and expansion of built areas for residential use is positively correlated with an increase in the intensity of the Urban Heat Island (UHI) on the surface of the area, resulting in more heat generation (Liu et al., 2020; Kang & Pan, 2019).

CBD at Pantai Indah Kapuk 2 (PIK 2), which has the concept of a 'modern waterfront lifestyle city,' utilizes the potential of areas near the coast for land use, which is based on the findings of previous studies of coastal-climate urban areas principally have a unique coastal-climate urban condition such as high humidity and wind speed than any other urban topography. Pedestrians who engage in outdoor activities in CBD in PIK 2 are at risk of being exposed to the effects of the influence of the coastal climate, which can reduce outdoor thermal comfort. According to a study by Wang et al. (2018) and Hakim et al. (2018), coastal climate conditions are affected by the building designs and spatial planning or land use that did not consider the climate context, such as increases in temperature and humidity in waterfront areas, can cause UHI.

Thus, it is necessary to design the building masses in coastal-climate urban areas in the CBD PIK 2 area in Tangerang Regency, Indonesia, based on the existing land use, which is responsive and optimal to the urban thermal environment. This study contributes to the novelty of microclimate modeling to improve thermal comfort in coastal-climate urban areas, specifically in the study area in Indonesia, which still lacks a case study. Microclimate modeling is also used to assess the effectiveness of coastal-climate urban planning and design.

Literature review

Microclimate modeling for optimizing the outdoor thermal environment in the coastal-climate urban areas in this study applies selected dependent thermal variables, including outdoor temperature, wind speed, wind direction or flows, and outdoor humidity (Dyvia & Arif, 2021; Mamani et al., 2022). Building mass factors that influence outdoor temperature include the ratio between building height and road surface width (H/L or H/W ratio) and sky view factor (SVF) (Aicha et al., 2022), building height, density or distance between buildings, layout, ratio between permeable green coverage (softscape) and pavement (hardscape) (Yang et al., 2017), building facade materials and colors, road pavement materials, and placement of vegetation (shade trees) in urban areas (Leetongin et al., 2022).

Meanwhile, wind speed is influenced by building mass factors such as building height, ratio (aspect ratio) of building width and height, building mass density (Zaki et al., 2022; Hu et al., 2018), building shape and orientation (Bakirci & Mohammed, 2023), the formation of land contours and topography, the shape of building facades, and the skyline rhythm index. Meanwhile, wind direction is influenced by building mass factors such as the orientation tilt angle of the building rotation (Huifen et al., 2014), building shape, neighborhood road width (Miao & Chiou, 2013), and floor area ratio (FAR) (Li et al., 2018). The humidity in outdoor spaces is influenced by factors such as humidity from building construction materials, exposure to rainfall on facades or building wall surfaces, and is strongly influenced by environmental temperature, rainfall, and humidity due to proximity to water bodies (Kaczmarek, 2017), while mainly occurs in coastal-climate urban areas.

This study only focuses on analyzing the influence of selected independent building mass variables from several factors that influence thermal and Microclimate variables and were previously examined from similar microclimate modeling by Ali-Toudert and Mayer (2006), Priyadarsini et al. (2008), i.e., building orientation, building shape, and the ratio between building height and road surface width between opposing buildings (H/W ratio) (Alnimer et al., 2023). Building designs that are responsive to solar radiation and wind gusts by modifying the upper and lower structures of the building, openings in the body of the building, and architectural components of building masses affect the thermal comfort of outdoor spaces and wind flow to provide comfort for pedestrians (Klemm, 2022), particularly in high rise buildings with aerodynamic shapes.

The H/W ratio, as mentioned in the previous section, significantly affects the thermal comfort of urban outdoor spaces by regulating air temperature, road shade, and wind flow speed and patterns. However, the H/W ratio increased according to several studies. The former causes thermal discomfort and increases UHI due to large shadows from building canyons and reduced openness of the road surface to the sky (Yi et al., 2023; Khraiwesh dan Genovese, 2023). In addition, a study by Grifoni et al. (2013) found that the H/W ratio of a building influences outdoor thermal comfort through the Predicted Mean Vote (PMV) parameter, which is further explained in the research method.

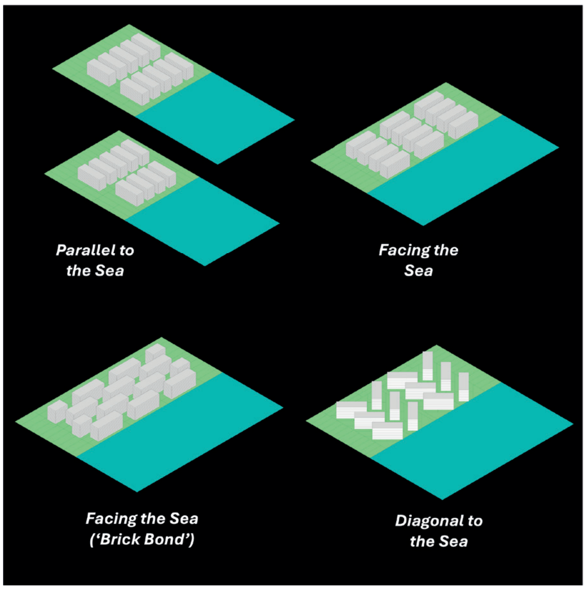


Figure 1.
Examples of variation in the building orientation
Source: Data Analysis (2024)

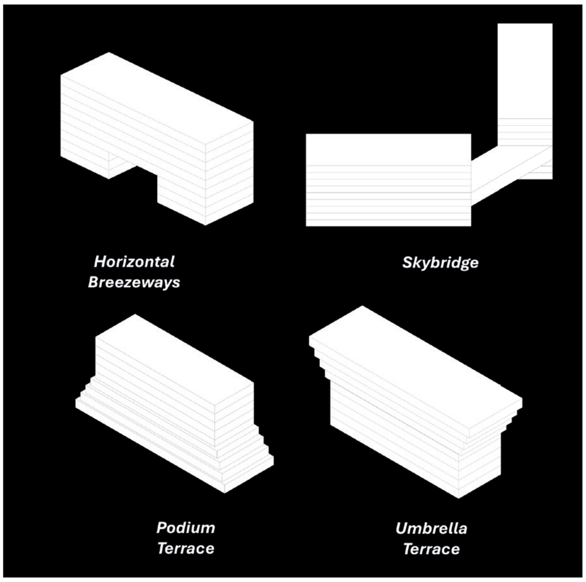


Figure 2.
Example of modification to the building forms
Source: Data Analysis (2024)

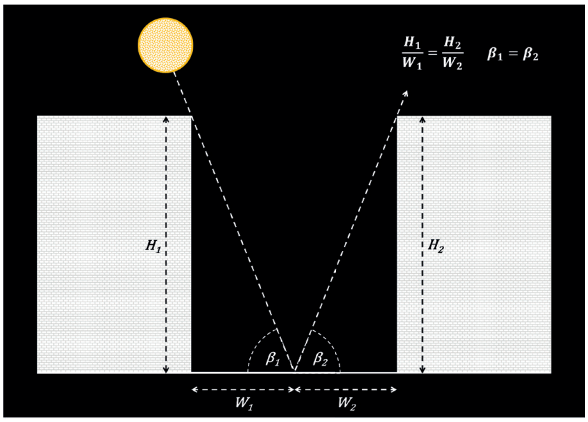


Figure 3.
Height-to-width (H/W) ratio of the street canyon between two identical buildings
Source: Data Analysis (2024)

METHOD

The coastal-climate urban area that was selected as the study area is CBD at Pantai Indah Kapuk 2 (PIK 2), Tangerang Regency, Indonesia. The microclimate data is inputted into ENVI-met software and then simulated with various alternative building design strategies, including orientation, shape, and height proportions of two or more buildings that form a 'canyon' in the street areas and open space. Quantitative microclimate simulations aim to analyze the design of high rise buildings that can respond well to coastal climate conditions and provide thermal comfort for pedestrians around them. Frequently, as found in the study by Tsoka (2023), microclimate simulations are conducted in the field of urban design to estimate the effect of urban temperature on building or space energy requirements using computer software such as ENVI-met.

However, the opposite is true in other studies by Srivastava (2023), which use the same tool to analyze building design factors that influence air temperature, solar radiation temperature, and thermal comfort in residential open spaces. Detommaso et al. (2021) conclude that modeling or simulation in predicting the thermal sensation of pedestrians in outdoor environments is needed to reduce heat stress, in line with a large amount of research on strategies for mitigating the impact of UHI and extreme climates in urban open spaces.

In the previous section, Predicted Mean Vote (PMV) was mentioned as one of the microclimate indices for energy balance in the human body by considering the relationship between metabolism, body covering or clothing, the surrounding environment, and human thermal sensation and perception. The ISO 7730:2005 standard PMV model formulated in 1982 by Povl Ole Fanger - a professor at the University of Denmark - identified the cold sensation at a value of 03 to the hot sensation at a value of 3 perceived by humans, with a range of -1 to 1 according to ASHRAE 55:2010 is categorized as the most comfortable thermal condition. The PMV value scale is obtained from analysis of the climate variables that will be observed in this study, such as temperature, wind, and relative humidity in the study area (Binarti et al., 2020).

The effectiveness of strategies to reduce climate impacts in coastal-climate urban areas can be observed through quantitative models that combine selected microclimate parameters to estimate thermal sensations for pedestrians, one of which is through simulation tools in the form of massively updated software such as ENVI-met, which will be utilized in this study. ENVI-met was previously reviewed by Sugiono (2016) as a digital tool for computational fluid dynamics (CVD) numerical simulations that analyze the relationship between buildings and open spaces or green areas in urban areas. The software is used in scientific research to assess pedestrian thermal comfort in urban environments or specific open spaces (Barnstorf, 2023).

ENVI-met simulates microclimate conditions, including temperature, relative humidity, and wind speed, based on the city's spatial structure in measuring thermal comfort indices such as PMV. After ENVI-met generates various environmental variables, including ambient temperature, wind speed, airflow, outdoor humidity, and PMV. However, the variables used to compare one alternative to another in this study are wind speed and PMV. Alternatives featuring better-distributed wind speeds, particularly those ranging from 0-1 m/s, and PMVs approaching the value of +1 are selected. The comparison between one alternative and another uses descriptive analysis, which includes the creation of box plots and comparison of averages. The range above is based on standards that can be viewed in the following table.

Table 1.
Assessment Indicator of Alternatives

Variables	Indicator	Source
Windspeed	1.0-2.0 m/s	Koch-Nielsen, 2002
PMV	-1, 0, +1	ASHRAE 55, 2010

Source: Literature Review (2024)

The research methodology involves collecting existing condition data through direct surveys and field observations to gather microclimate variables such as wind direction, wind speed, humidity, and cloud cover. Subsequently, ENVI-met software models alternative building orientations, building forms, and building H/W ratios. The results of these models are then compared against each other, considering wind speed and PMV parameters obtained from ENVI-met. The research concludes with selecting the optimal alternative thermally based on the analysis conducted.

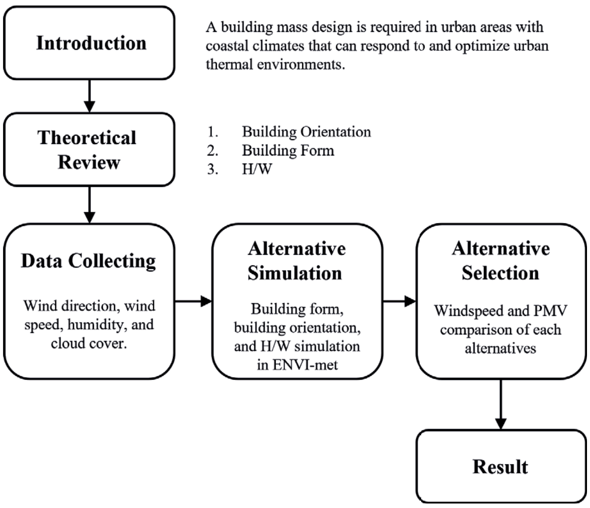
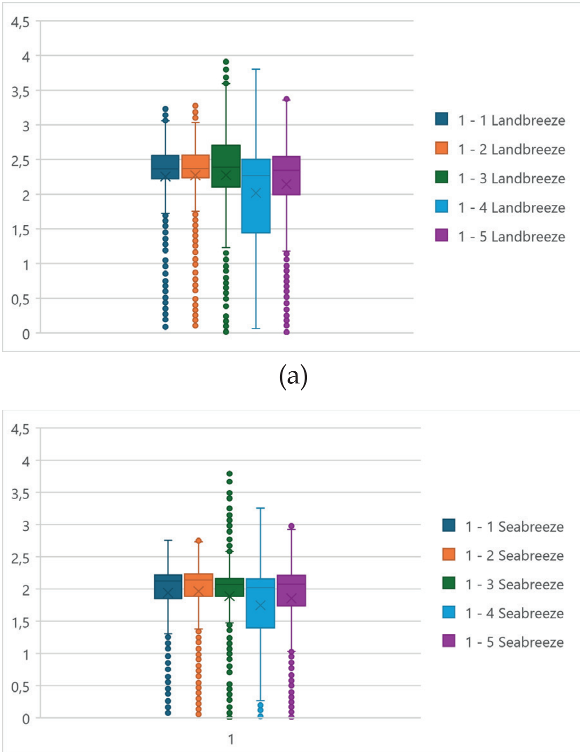


Figure 4.
Methodology flow
Source: Data Analysis (2024)

RESULTS AND DISCUSSION

Microclimate Modeling Based on Building Orientation

The analysis for Microclimate Modeling Based on Building Orientation is conducted by qualitatively reviewing wind movement from contour maps and wind vector diagrams and quantitatively examining the Predicted Mean Vote (PMV) results for each alternative. A comparison of wind movement patterns is depicted in Appendix 1 and Figure 5.



(b)

Figure 5.
Box plot of wind speed comparison result on building orientation
Source: Data Analysis and Modeling (2024)

Looking at the results of wind pattern mapping and the comparison of the box plots above, it can be observed that the alternative diagonal to the sea is the most favorable option. This is evidenced by its lowest score of wind speed and its ability to distribute wind more evenly, thus minimizing stagnant or solid wind spots. This is likely due to the diagonal shape of the building, which disrupts the wind flow. Besides the wind movement pattern, alternatives are also selected based on comparing PMV for each strategy.

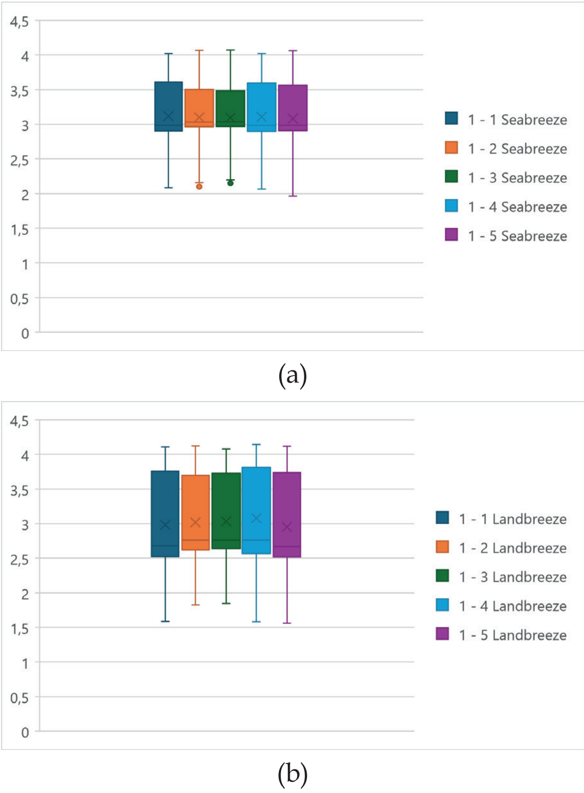


Figure 6.
Box plot of PMV comparison result on building orientation
Source: Data Analysis and Modeling (2024)

From the table and box plot above, it is evident that the diagonal to the sea alternative is selected based on the comparison of PMV because it has the value closest to 1. The next alternative is parallel to the sea because it has the lowest PMV value after diagonal to the sea. Then, facing the sea is the least desirable alternative due to its relatively high PMV.

Impact of Building Form on Microclimate

Similar to the previous subsection, the analysis of the Impact of Building Form on Microclimate is conducted by qualitatively reviewing wind movement from contour maps and wind vector diagrams and quantitatively examining the Predicted Mean Vote (PMV) results for each alternative. Appendix 2 and Figure 7 compare wind movement patterns.

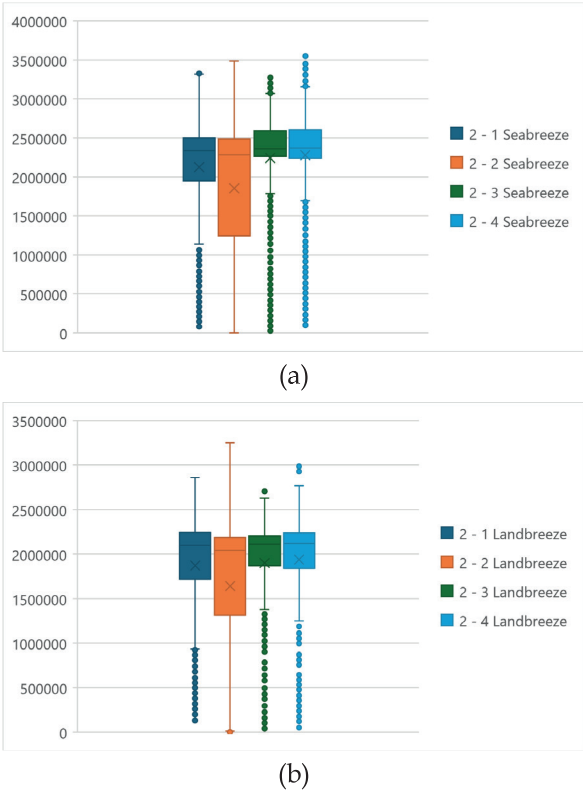
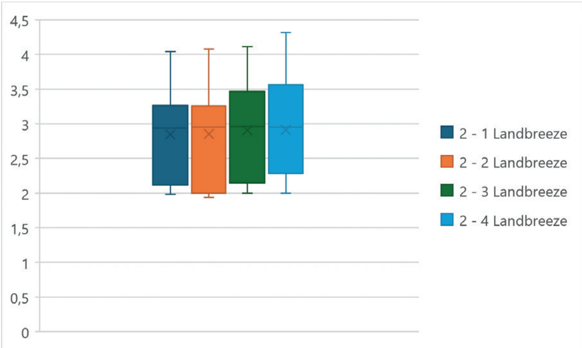


Figure 7.
Box plot of wind speed comparison results on building form
Source: Data Analysis and Modeling (2024)

Adding a sky bridge for building form will result in the lowest wind speed score and relatively comfortable conditions compared to other building form alternatives. However, it is undeniable that integrating various elements in building form can achieve more optimal results for wind speed and wind direction distribution. Besides the wind movement pattern, alternatives are also selected based on comparing PMV for each strategy.



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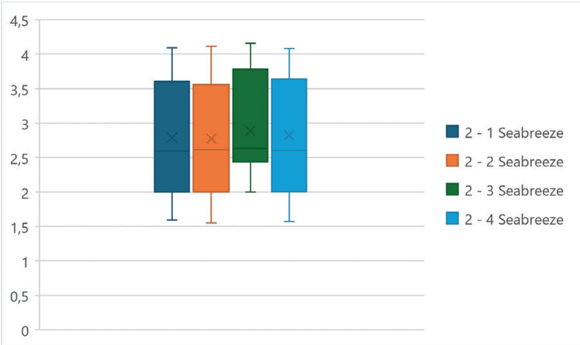

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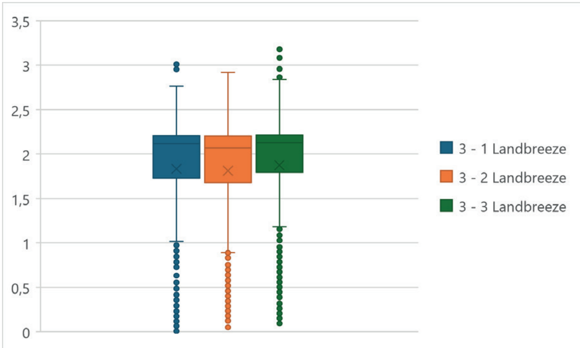
Figure 8.
Box plot of PMV comparison result on building form
Source: Data Analysis and Modeling (2024)

Based on the comparison of PMV, the results also indicate that a building form with a sky bridge can achieve a more comfortable PMV. However, it is indisputable that integrating various elements in building form can lead to more optimal PMV results.

Height-to-Width (H/W) Ratio Effects on Microclimate

The analysis for Ratio Effects on Microclimate is conducted by qualitatively reviewing wind movement from contour maps and wind vector diagrams and quantitatively examining the Predicted Mean Vote (PMV) results for each alternative. A comparison of wind movement patterns is depicted in Appendix 3 and Figure 9.



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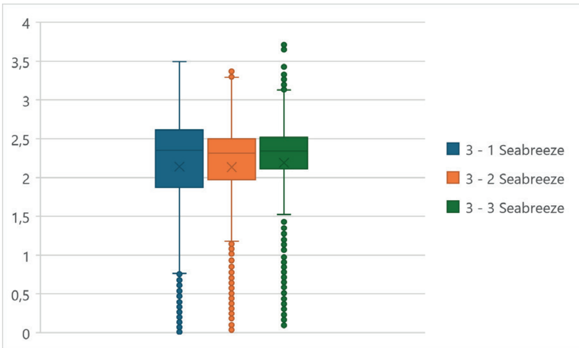


(b)

Figure 9.
Box plot of wind speed comparison result on building ratio
Source: Data Analysis and Modeling (2024)

Table 2.
PMV Comparison Result on Building Orientation

Alternatives		PMV Score	Average PMV Score
Parallel to the sea (0), grid 1	Landbreeze	2,9829	3,05036
	Seabreeze	3,11782	
Parallel to the sea (0), grid 2	Landbreeze	3,01734	3,05765
	Seabreeze	3,09473	
Facing the sea (90), grid 1	Landbreeze	3,0319	3,06331
	Seabreeze	3,09473	

Alternatives		PMV Score	Average PMV Score
Facing the sea (90), grid 2	Landbreeze	3,0785	3,07932
	Seabreeze	3,08016	
Diagonal to the sea (45)	Landbreeze	2,9173	3,01594
	Seabreeze	3,08016	

Source: Data Analysis and Modeling (2024)

Table 3.
PMV Comparison Result on Building Form

Alternatives		PMV Score	Average PMV Score
Horizontal Breezeways	Landbreeze	2,788076	2,81654
	Seabreeze	2,845005	
Skybridge	Landbreeze	2,774654	2,81304
	Seabreeze	2,851446	
Podium Terrace	Landbreeze	2,885729	2,89591
	Seabreeze	2,906095	
Facing the sea (90), grid 2	Landbreeze	2,8216	2,866801
	Seabreeze	2,912003	

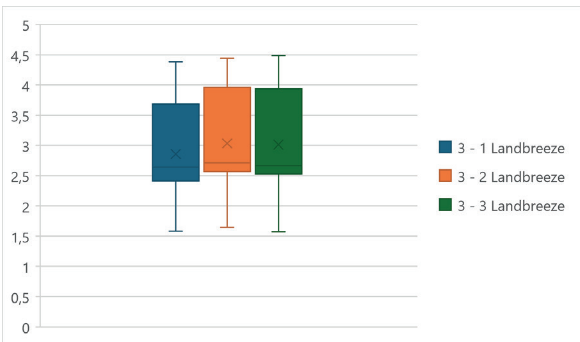
Source: Data Analysis and Modeling (2024)

Table 4.
PMV Comparison Result on Building H/W Ratio

Alternatives		PMV Score	Average PMV Score
H/W 0,5	Landbreeze	2,85752	2,8885
	Seabreeze	2,91953	
H/W 1	Landbreeze	3,03275	3,0234
	Seabreeze	3,01794	
H/W 1,5	Landbreeze	3,01175	3,0192
	Seabreeze	3,02674	

Source: Data Analysis and Modeling (2024)

A building with a H/W ratio 0.5 will have a reasonably good and comfortable airflow distribution because, based on the average boxplot and mapping results, a H/W ratio 0.5 yields sufficiently good and comfortable thermal conditions. In addition to the wind movement pattern, alternatives are also selected based on the comparison of PMV for each strategy.



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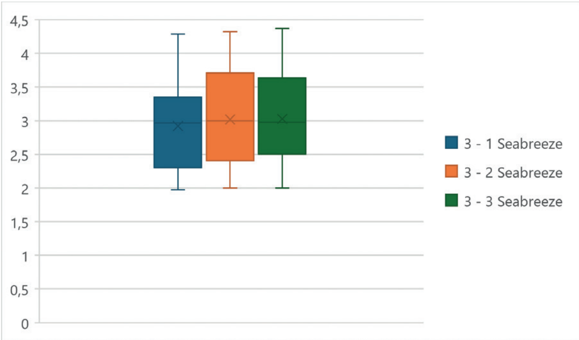

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Figure 10.
Box plot of PMV comparison result on building ratio
Source: Data Analysis and Modeling (2024)

From the comparison of PMV, a H/W ratio 0.5 also yields PMV results that approach the best PMV, with an average PMV of 2.8885, which is lower than other alternatives.

CONCLUSION

A study on the simulation results of three case studies indicates that proper building orientation, building form, and selection of H/W ratio can make coastal urban ventilation more comfortable. From the Microclimate Modeling Based on Building Orientation, the most favorable alternative is the diagonal to the sea. Meanwhile, from the Impact of Building Form on Microclimate, the best alternative is the one with an added skybridge. However, it is undeniable that integrating various elements in building form can achieve more optimal results for thermal comfort. Based on the comparison of H/W ratios, a building with an H/W ratio of 0.5 is the most thermally comfortable. All three comparisons above were previously conducted by examining wind and PMV comparisons spatially and quantitatively on average, which were also depicted through box plots.

This study has not accounted for the cooling elements in coastal cities represented by buildings, such as vegetation surrounding them. For instance, vegetation can lower ambient temperatures and promote increased airflow. If vegetation can contribute to reducing surrounding temperatures and enhancing airflow, a similar calculation considering the effects of vegetation would likely demonstrate even better cooling effects for urban ventilation. Additionally, this study has not attempted to combine case studies due to time constraints. Therefore, further research incorporating a combination of case studies could serve as a continuation of this study.

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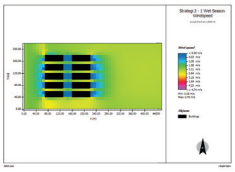
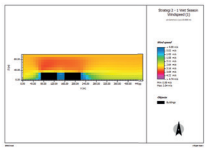
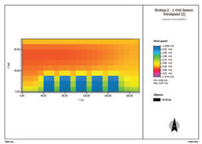
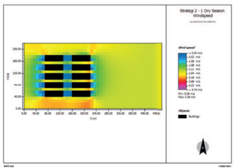
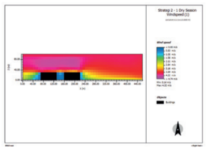
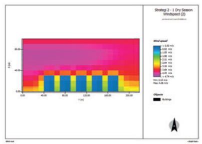
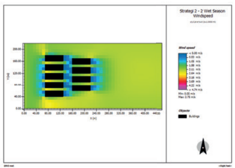
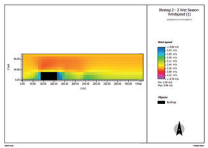
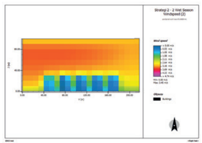
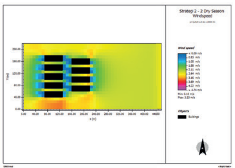
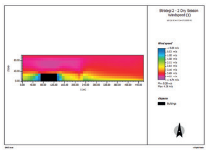
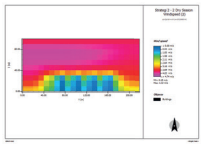
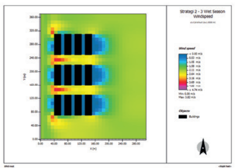
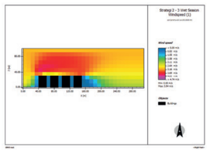
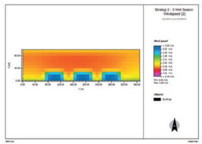
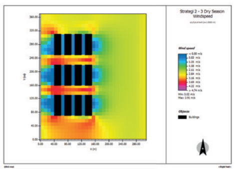
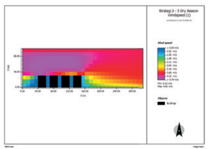
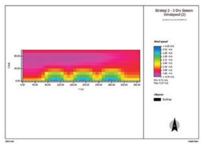
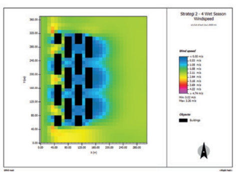
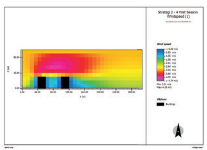
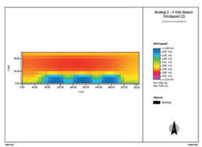
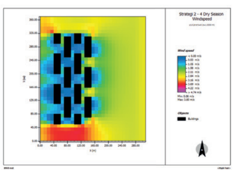
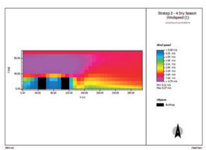
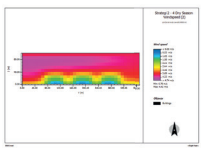
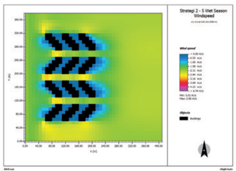
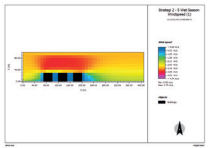
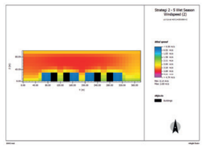
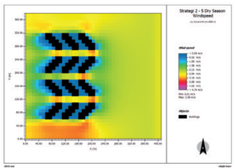
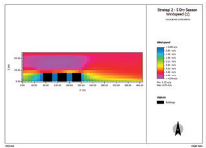
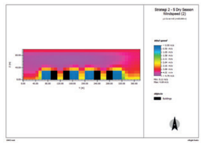
Appendix 1

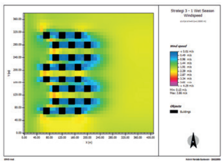
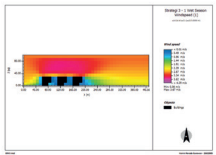
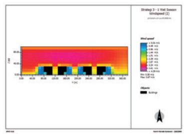
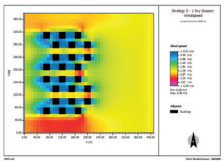
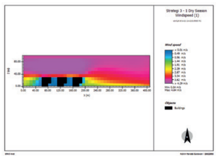
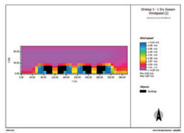
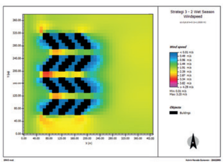
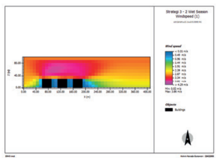
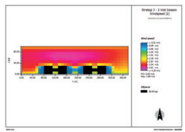
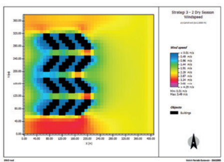
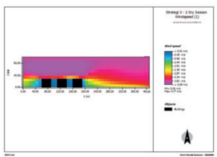
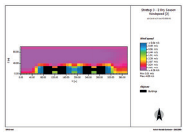
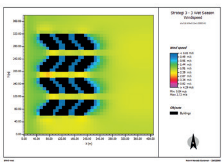
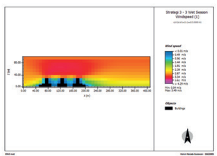
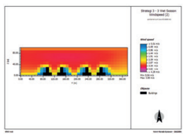
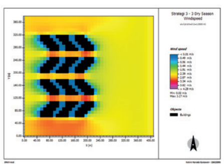
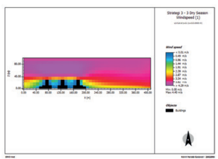
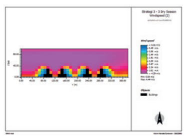
Comparison Result of Wind Movement Modeling Based on Building Orientation

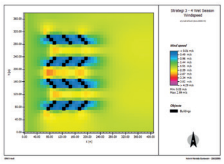
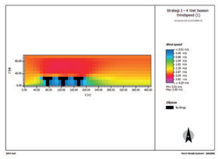
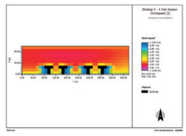
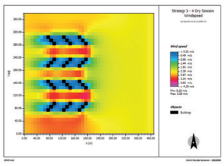
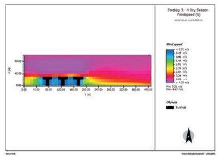
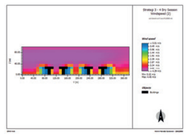
Alternatives		Top View	Section 1	Section 2
Parallel to the sea (0), grid 1	Landbreeze			
	Seabreeze			
Parallel to the sea (0), grid 2	Landbreeze			
	Seabreeze			
Facing the sea (90), grid 1	Landbreeze			
	Seabreeze			
Facing the sea (90), grid 2	Landbreeze			
	Seabreeze			

Alternatives		Top View	Section 1	Section 2
Diagonal to the sea (45)	Landbreeze			
	Seabreeze			

Appendix 2

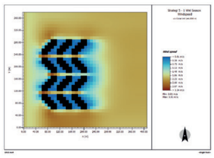
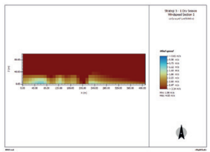
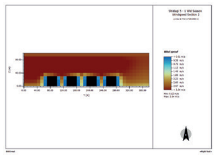
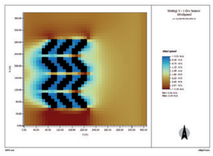
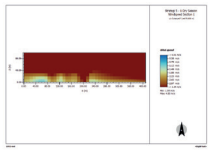
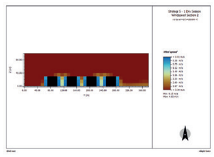
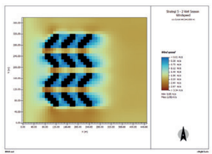
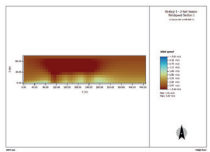
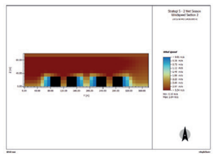
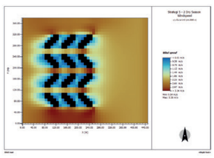
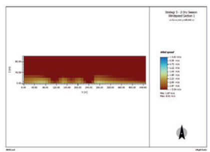
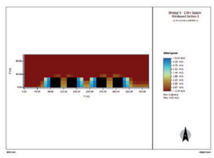
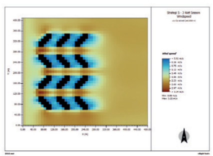
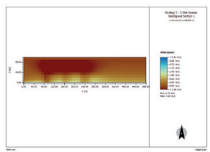
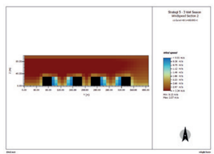
Comparison Result of Microclimate Modeling Based on Building Form

Alternatives		Top View	Section 1	Section 2
Horizontal breezeways	Landbreeze			
	Seabreeze			
Skybridge	Landbreeze			
	Seabreeze			
Podium terrace	Landbreeze			
	Seabreeze			

Alternatives		Top View	Section 1	Section 2
Umbrella Rooftop	Landbreeze			
	Seabreeze			

Appendix 3

Comparison Result of Microclimate Modeling Based on H/W Ratio

Alternatives		Top View	Section 1	Section 2
H/W 0.5	Landbreeze			
	Seabreeze			
H/W 1	Landbreeze			
	Seabreeze			
H/W 1.5	Landbreeze			
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