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The impact of building spatial layouts on microclimate in residential districts: a case study in Kumamoto

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Abstract: The configuration of building spatial layouts within residential districts plays a critical role in shaping microclimate conditions, directly impacting resident comfort and well-being. This study delves into the urban design challenges of Kumamoto, Japan, focusing on how these layouts influence microclimate phenomena, including the urban heat island effect. By addressing the current lack of knowledge, this research establishes a correlation between specific spatial configurations and microclimate outcomes, highlighting the potential of urban design to improve thermal comfort and air quality. Employing computational simulations alongside empirical field measurements, this study assesses the impact of various building layouts on wind patterns and temperature distribution. The findings indicate that certain designs significantly enhance natural ventilation and reduce temperatures, offering improvements over traditional urban layouts. These results not only highlight the significance of strategic building placement but also contribute valuable empirical evidence to the field of climate-responsive urban planning. The research achievements extend beyond theoretical implications by offering practical insights for urban planners and architects, and presenting a methodological framework for designing sustainable urban habitats. The practical applications of this study are manifold, with the potential to inform future urban development strategies in Kumamoto and other regions facing similar climatic challenges, thereby advocating for a global discourse on sustainable architectural practices.

1. Introduction

The study of microclimates in residential districts has garnered much attention in recent years, given its major role in shaping urban sustainability and liveability. Residential districts, particularly in cities like Kumamoto, are complex ecosystems where building spatial layouts significantly influence local weather conditions [1]. Despite the growing body of research, there remains a gap in understanding how specific spatial layouts interact with microclimate factors to either exacerbate or mitigate environmental challenges. For instance, the implementation of green-roof installations in low-rise residential neighborhoods has been shown to improve human thermal comfort by reducing pedestrian-level air temperature and mitigating heat stress (Peng et al. 2013) [2]. A pioneering study by Rui et al. (2018) demonstrated that the layout a in residential districts could significantly influence microclimate and, consequently, the thermal comfort of occupants [3]. However, despite these advancements, there is a noticeable lack of studies focusing on the microclimate adaptability of residential districts, particularly in Kumamoto. The present study aims to fill this gap by investigating the impact of building spatial layouts on microclimates in residential districts, using Kumamoto as a case study. Utilizing a combination of field measurements and computational simulations, this study offers a comprehensive analysis of microclimate conditions in various residential layouts. Our findings reveal that specific spatial layouts can significantly improve occupants' comfort by optimizing microclimat conditions, thereby contributing to the growing body of knowledge aimed at enhancing urban sustainability and residents' well-being through informed architectural design.

We also use CiteSpace software further substantiates the importance of this research area. It is a tool commonly used for scientific literature analysis, revealed that the topic of building spatial layouts and their impact on microclimates is an emerging focus in the field, highlighting the timeliness and relevance of the current study. This paper uses the web of science core database as the data source, and uses “urban microclimate,” “residential blocks’ microclimate” as the search term. The period was 2012-2022, and the search was conducted on December 30, 2022. Four thousand one hundred sixty relevant documents were retrieved. After repeated screening and de-duplication, we finally obtained 2911 valid literature samples (Figure 1). The literature data in Refworks format were exported from the web of science database, and then imported into Citespace as the data source for this study. Through the analysis model of citespace, we can clearly know the research hotspots in the field of urban microclimate. This can help to identify areas where climate conditions may be particularly extreme or challenging, and can inform the development of strategies to mitigate these effects.

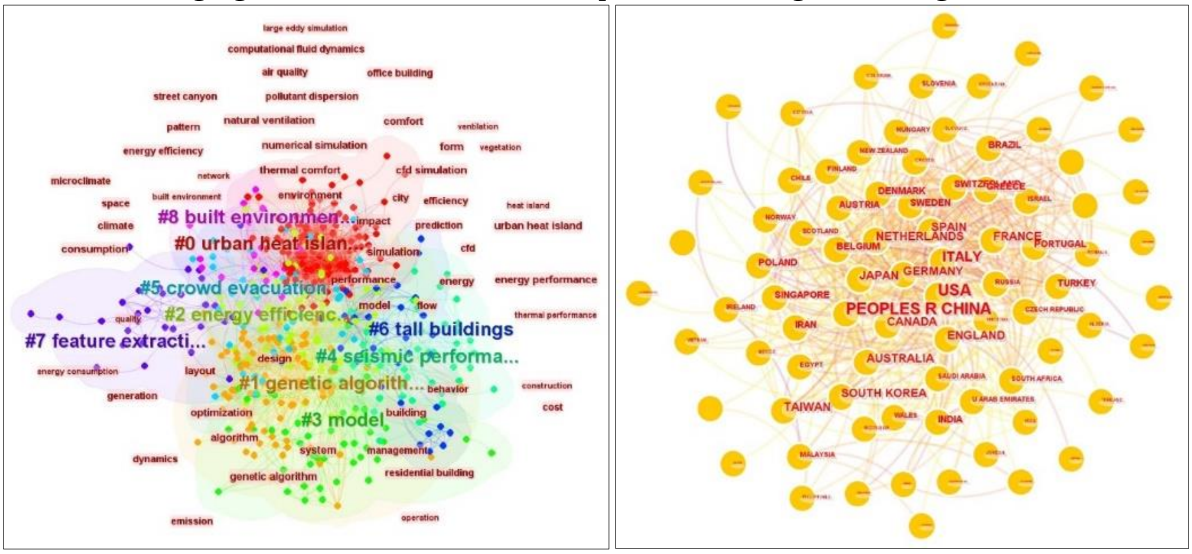

Figure 1: Cluster view map of national research quantity

2. Methodology

This study aims to explore the influence of building spatial layouts on microclimates in residential areas, using field measurements taken with Pocket Weather Meters and simulations conducted with ENVI-met software. The residential areas for this study were selected based on their distinct architectural layouts, which are representative of the broader urban design in Kumamoto. The residential areas under study exhibit three types of architectural layouts: open irregular layouts (Spot A), enclosed layouts (Spot B), and open parallel layouts (Spot C). Spot A is characterized by its open irregular layouts, a distinctive urban design found in the Chuo Ward of Kumamoto City, specifically in Kurokami 5-chome. This area is predominantly inhabited by international students, with the majority aged between 20 to 30 years. The architectural uniqueness of Spot A lies in its non-linear and asymmetrical building arrangements, which create a diverse and dynamic urban fabric. This open and irregular layout facilitates varied spatial interactions and potentially influences the microclimate conditions, offering unique environmental and social dynamics within the urban landscape. Located in Kurokami 2-chome of Kumamoto City's Chuo Ward, Spot B presents an enclosed layout, a stark contrast to the open designs of Spot A. This area is primarily occupied by employees from nearby companies and students from local schools, with an age range predominantly between 20 to 40 years. The enclosed layout of Spot B is characterized by buildings arranged in a manner that forms a defined and cohesive perimeter, creating a sense of enclosure and community. This design not only impacts the social interactions but also has significant implications for the microclimate within the area, potentially offering a controlled and moderated urban environment. Spot C, situated in Watoka 1-chome of the Chuo Ward in Kumamoto City, is defined by its open parallel layouts. The resident population mainly comprises company employees, with ages ranging from 30 to 50 years. The architectural feature of Spot C is its linear and parallel building configurations, which promote uniformity and order in the urban design (Figure 2). This layout is conducive to efficient wind flow and solar access, potentially enhancing the microclimate conditions of the area. The open parallel layouts in Spot C represent a modern approach to urban planning, focusing on functionality and environmental adaptability. This approach aligns with existing research that emphasizes the significant impact of architectural planning and layout on microclimate characteristics in residential areas (Wang et al., 2019) [4]

Figure 2: Site research of three spots

A comprehensive suite of in-situ meteorological observations were systematically executed to ascertain key microclimate parameters, such as ambient temperature and wind velocity, within the delineated residential zones. We were using three Pocket Weather Meters, measurements were taken in three different residential areas in Kumamoto. These areas were selected based on their unique architectural layouts: one with an enclosed layout, another with an open parallel layout, and the third with an open irregular layout. Measurements were conducted on August 1, 2023, capturing a 24-hour window of microclimate conditions (Figure 3). During this time, data were collected at hourly intervals to ensure a comprehensive set of readings.

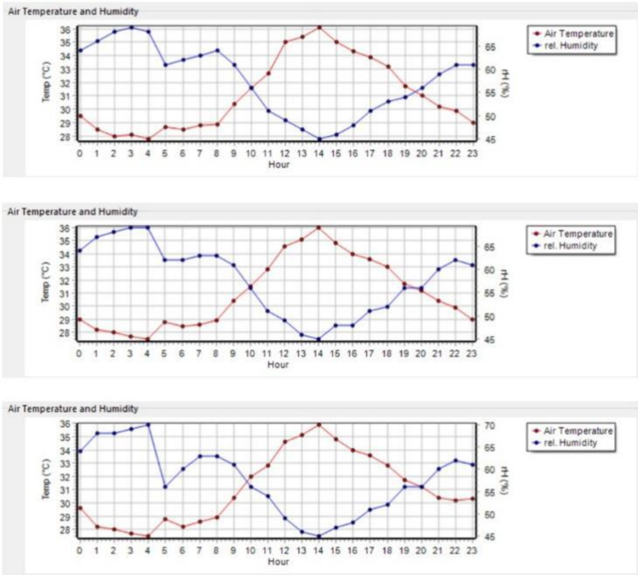

Figure 3: 24 hours microclimate conditions

After recording and organizing the measured data, we conducted modeling and simulation of the study area (Figure 4). The measurements were meticulously planned and executed with a focus on minimizing external variables that could influence the data. To ensure the integrity and reliability of the collected data, established meteorological protocols were strictly adhered to, including the calibration of the Pocket Weather Meters prior to the commencement of the study. The field measurements were complemented by simulations conducted using ENVI-met software. The reliability of this software in capturing diurnal cycles under various meteorological conditions has been affirmed by Acero & Arrizabalaga (2016) [5]. Further validation of its applicability for residential areas comes from Chatzinikolaou et al. (2018), who demonstrated its effectiveness in mitigating Urban Heat Island effects [6].

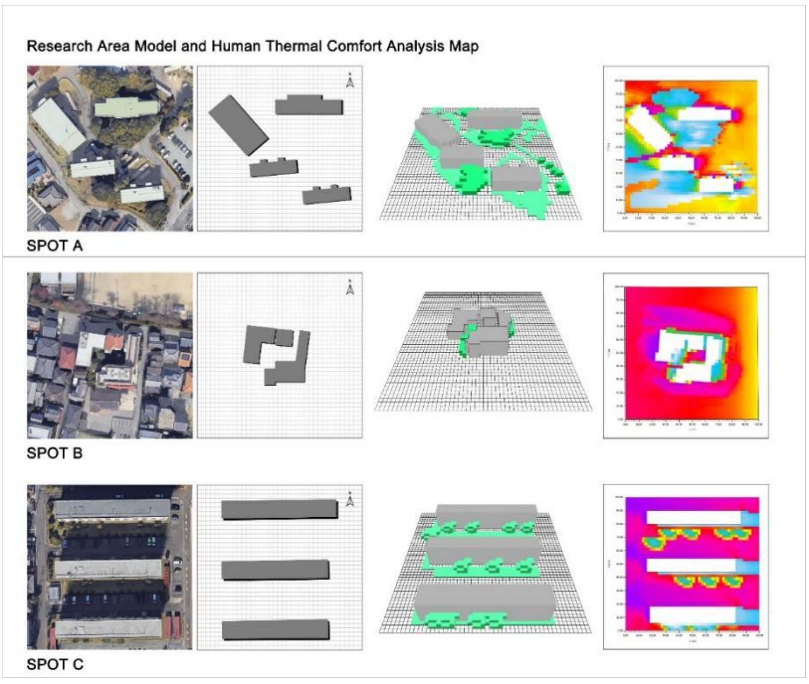

Figure 4: Models and simulation of three spots

We also conducted a questionnaire survey among residents of the selected areas to get more information on their thermal comfort experiences. The questionnaire was designed to capture various aspects of thermal comfort, including perceived temperature, wind conditions, and overall satisfaction with the local microclimate. It was distributed both electronically and in paper form to ensure a wide reach among residents. The survey results will be analyzed and cross-referenced with the ENVI-met simulation data to provide a comprehensive understanding of the microclimate conditions in the selected residential areas. This multi-method approach enhances the robustness and validity of the study's findings.

Although the methodology aims for rigor and comprehensiveness, it is not without potential limitations. For instance, the research focuses solely on residential areas in Kumamoto, and the findings may not be generalizable to other geographical or climatic conditions. And sudden meteorological changes such as unexpected rain or wind gusts could affect the accuracy of the Pocket Weather Meters. Additionally, equipment malfunctions, if not promptly addressed, could introduce a degree of variability or error into the collected data.

3. Results

Data obtained in previous studies indicate a significant correlation between urban spatial layout and microclimate comfort. According to Xiaoyu Chen's study, different building arrangements can substantially influence local wind patterns and temperature distribution [7]. In my study, field measurements were conducted to gather precise microclimate data, which were then input into the ENVI-met simulation software for detailed analysis. This integrated approach of real-world data collection and advanced simulation provided a nuanced understanding of the microclimate impacts of urban spatial layouts. The PMV (Predicted Mean Vote Model) in the context of ENVI-met is a key indicator for assessing thermal comfort, reflecting the average thermal sensation of people based on environmental factors such as temperature, humidity, and wind speed. Figure ## presents a comparative analysis of the Predicted Mean Vote (PMV) values across three measurement locations, offering insights into the perceived thermal comfort in different urban layouts. Comparing these PMV outcomes with existing studies, it is evident that urban layouts with more open and irregular designs tend to enhance thermal comfort, aligning with findings from Priscila Weruska Stark da Silva, D. Duarte, and S. Pauleit's study (2023). Stark da Silva, P.W.; Duarte, D.; Pauleit, S. The Role of the Design of Public Squares and Vegetation Composition on Human Thermal Comfort in Different Seasons a Quantitative Assessment. Land 2023, 12, 427. https://doi.org/10.3390/land12020427. This contrast is particularly pronounced when comparing the microclimate comfort of densely built areas, which, as indicated by Hamed and M. Santamouris's research (2022), Heshmat Mohajer, H.R.; Ding, L.; Kolokotsa, D.; Santamouris, M. On the Thermal Environmental Quality of Typical Urban Settlement Configurations. Buildings 2023, 13, 76. https://doi.org/10.3390/buildings13010076, normally, the PMV scale is defined between -4 (very cold) and +4 (very hot) where 0 is the thermal neutral (comfort) value. The basic PMV equation for all cases, indoor and outdoor, is given by

$$PMV=[0.028+0.303 \cdot \exp(-0.036 \cdot M/A_{Du})] \cdot (H/A_{Du}-E_d-E_{sw}-E_{re}-L-R-C)$$

We assume that all assumed to be defined at the biometeorolgical reference height of 1.6 m or the next closest level in case of model data. The PMV reference person is always 35 years old, male, with a height of 1.75 m and a weight of 75 kg. These assumptions cannot be modified in the PMV calculations [8].

And here are some scaling terms:

0.028+0.303(...) Empirical based fitting coefficients to transfer the energy balance of the body to the PMV scale range;

Body energy production:

M/A_{Du}: Mechanical energy production of the body. Gross energy production of the body related related to 1 m ^{2}of skin. Mechanical energy production depends on the persons activity.

H/A_{Du}: Internal remaining energy.

Skin water/ vapour exchange:

E_d: Vapour diffusion through the skin. Amount of vapour diffusing directly through the skin Ed=0.305 · (57.3−0,07 · H/ A_{Du}-e) with eVapor pressure of the air in [hPa].

E_{sw}: Evaporation of sweat on the skin. Cooling effect of liquid sweat evaporating from skin E_{sw} =0.42 · (H/ADu-58).

L: Sensible heat exchange through breathing. Energy lost/gained directly through heat exchange with the breathed air withing the body L=0.0014 · M/ADU · (34-ta) with ta Air temperature deg C.

Energy exchange at body (cloths) surface:

R: Radiative energy balance of the body (cloths).

C: Energy exchange through convection.

The data distinctly highlights that Spot A exhibited a marginally higher microclimat comfort level compared to Spots B and C, a result possibly attributed to its open and irregular layout, which facilitates better air circulation and reduces heat accumulation. A notable observation in the study is the PMV value at 1 PM, where Spot A significantly outperformed Spots B and C in terms of thermal comfort. This pronounced difference highlights the effectiveness of Spot A's layout in providing a more comfortable microclimate during peak sunlight hours. We made a lit of analysis of the PMV value changes over a 12-hour period, from 8 AM to 8 PM (Table 1 & Figure 5). The data reveals a distinct pattern of thermal comfort across Spots A, B, and C. Notably, during peak sunlight hours in the afternoon, Spot A consistently demonstrated higher PMV values compared to Spots B and C. This indicates a significantly enhanced thermal comfort level at Spot A, attributable to its open and irregular layout, which optimizes both sunlight exposure and air circulation.

Table 1: PMV values per hour in one day

TIME/SPOTS	SPOT A	SPOT B	SPOT C
8:00-9:00	-1.54-1.88	-1.61-2.92	-0.92-1.76
9:00-10:00	-1.85-1.93	-2.01-2.95	-1.82-1.98
10:00-11:00	-2.10-2.49	-2.34-2.81	-2.62-2.37
11:00-12:00	-2.09-2.56	-3.15-3.01	-2.91-2.92
12:00-13:00	-2.42-2.12	-3.91-2.92	-3.58-3.21
13:00-14:00	-3.36-2.67	-4.11-3.47	-3.68-3.08
14:00-15:00	-3.31-3.01	-3.90-3.65	-3.54-3.02
15:00-16:00	-2.85-2.73	-3.62-2.91	-2.90-2.86
16:00-17:00	-2.74-2.31	-3.31-2.32	-2.69-2.40
17:00-18:00	-1.96-2.30	-1.90-2.31	-2.11-1.98
18:00-19:00	-1.90-1.91	-1.95-2.09	-1.89-1.63
19:00-20:00	-1.69-1.89	-1.87-2.02	-1.64-1.77

The comparative analysis of hourly PMV values not only underscores the dynamic nature of microclimate conditions throughout the day but also highlights the effectiveness of Spot A's design in maintaining a comfortable urban microclimate, especially during periods of intense sunlight. Spot A's elevated PMV values are largely due to its open, irregular layout, which not only enhances sunlight penetration but also facilitates superior ventilation, thereby significantly improving thermal comfort by ensuring a balanced distribution of natural light and effective air circulation.

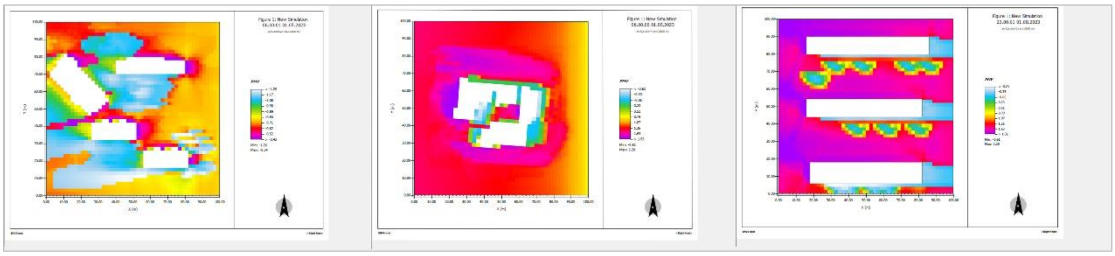

Figure 5: Visualization of PMV values

While these findings offer valuable insights, it is important to acknowledge the limitations of this study, including its focus on specific urban settings, potentially limiting the generalizability of the results, and the reliance on simulation data from ENVI-met, which may not capture the full complexity of real-world microclimate interactions. Despite these limitations, the study's implications for urban design are significant, suggesting that innovative spatial configurations can play a pivotal role in enhancing microclimate comfort in residential areas, thereby contributing to the broader goals of sustainable urban development.

4. Discussion

This study significantly contributes to the existing literature by providing empirical evidence on how different urban layouts influence microclimate comfort, particularly in residential areas. We first demonstrated that open and irregular urban layouts significantly improve microclimate comfort, consistent with the literature of Priscila and S. Pauleit's study (2023) [9]. In particular, the Spot A area was shown to exhibit higher PMV values, indicative of better thermal comfort. Regarding this concern, E. Gatto, Fabio Ippolito, and colleagues' (2021) research reported similar findings in their urban layout studies [10]. Using this methodology, our research demonstrated that strategic layout planning could significantly influence resident comfort levels. As a result, the importance of urban design in microclimate regulation was emphasized, as determined by the comparative analysis of Spots A, B, and C. Our results clearly illustrated that the microclimate comfort in Spot A was superior, particularly at peak sunlight hours, a finding that echoes the importance of layout design in urban thermal regulation. Moreover, the contrast observed between Spots B and C highlights the complex interplay between building density, layout orientation, and their cumulative effect on local microclimates, warranting further exploration in future studies. The insights gained from this study have practical applications in urban planning, particularly in designing residential districts, where strategically planned layouts can significantly improve residents' thermal comfort and overall quality of life. Despite the valuable findings, this study has limitations, such as its focus on specific urban settings and reliance on ENVI-met simulations, which may not fully capture the complexity of real-world urban microclimates. Future research should consider a broader range of urban environments and incorporate more diverse data sources, including long-term climatic data, to validate and expand upon these findings. The observed correlation between urban layout and microclimate comfort aligns with the findings of J. Hou, Yupeng Wang, Dian Zhou, and Zhe Gao (2022), who noted the significant impact of architectural design on urban heat distribution [11]. Furthermore, the work of D. Dursun and M. Yavaş (2019) in urban sustainability studies reinforces our conclusion, highlighting the critical role of green spaces and open layouts in enhancing environmental quality in urban areas [12]. In conclusion, our study not only adds valuable insights to the body of knowledge on urban microclimates but also serves as a catalyst for future urban design strategies, emphasizing the need for holistic planning that integrates microclimate comfort with sustainable urban development.

5. Conclusions

We have synthesized and characterized the impact of urban spatial layouts on microclimate comfort, focusing on three different spots in a residential district. The background of this research is rooted in the growing need to enhance urban liveability in the face of rapid urbanization and climate change. It addresses a significant gap in existing literature regarding the quantifiable impact of urban layouts on microclimate, particularly in residential areas. The methodology employed involved a detailed analysis of PMV values across different times of the day, reflecting the dynamic nature of urban microclimates. A key finding of this study is the superior thermal comfort provided by open and irregular layouts, particularly in Spot A, as compared to more densely built areas. This result signifies the potential of thoughtful urban design in improving residents' comfort and overall environmental quality. However, the study acknowledges its limitations, including a focus on specific settings and the inherent constraints of simulation data. Future research directions could include exploring a wider variety of urban settings and incorporating more diverse climatic data to further validate and extend these findings. In conclusion, our study not only adds valuable insights to the body of knowledge on urban microclimates but also serves as a catalyst for future urban design strategies, emphasizing the need for holistic planning that integrates microclimate comfort with sustainable urban development.

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