Residential cluster design and potential improvement for maximum energy performance and outdoor thermal comfort on a hot summer in Thailand

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Abstract

Thailand committed to achieving the Sustainable Development Goals to increase urban livability and reduce energy use in the building sector. However, the design information to achieve those challenge goals has been undefined. This study aimed to investigate and examine potential improvements for outdoor thermal comfort and energy efficiency in 136 designs of the two-type residential cluster in Pathum Thani, Thailand, via designs of building orientation, geometry and window-to-wall ratio (WWR). The daily cooling energy consumption in residential clusters was performed using eQuest under the modified weather data from the prior microclimate analysis. The energy-saving scenarios were calculated and compared to the acceptable outdoor thermal comfort hours. It is found that the row house cluster had the potential to be more sustainable than a single house. The row house clusters on orthogonal street orientation offered the highest percentage of hours in outdoor thermal comfort of 46% and energy efficiency below the new standard of Thailand. The cooling energy savings through increasing H/W with lowering WWR was up to 32%. This study’s results could provide urban planners and architects with the new design guidelines and improvement potentials to make cities more energy efficient and environmentally friendly for outdoor living in Thailand.

Keywords: urban typology; energy simulation; cooling energy consumption; WWR; urban microclimate

1. INTRODUCTION

Bangkok is ranked as a megacity, being the fifth largest urban area in East Asia in 2010 [1]. The expansion of urban construction land use and impervious surfaces in Bangkok neighborhoods has led to an increase in air temperature and mean radiant temperature of outdoor urban spaces [2, 3]. With an extreme outdoor air temperature, people tend to use air conditioners for indoor cooling. The increase in housing demand and cooling energy use results in a significant increase in the magnitude of energy consumption in the city [4]. Such high energy consumption critically raises the future global temperature, which is not suitable for outdoor living.

Thailand is committed to achieving the 2030 Agenda and Sustainable Development Goals (SDGs), including mitigation of the global temperature issue. The SDG 7 and 11 were important discussion topics on how the city could improve the quality of life for people, access to affordable sustainable and modern energy, as well as the well-being of the planet [5]. In partnership with United Nations Thailand, Bangkok Metropolitan Administration (BMA) has played a significant role in developing goals and identifying potential livability indicators. In the 20-year development plan for Bangkok Metropolis [6], one of the six-dimension visions was to increase urban livability by increasing accessibility to public areas and green areas and providing pleasant streetscape and better outdoor environmental quality.

At the same time, the Energy Policy and Planning Office (EPPO), Ministry of Energy, has sought the energy-savings potential as well as providing renewable energy use to meet the demand. In Thailand’s 20-year development plan [7], EPPO established the outcome of electricity-saving potential in large...
commercial buildings in 2030, aiming at 44% lower than the demand in BAU (business-as-usual) case. The new building energy code (BEC) has been enforced since 2018 to control energy consumption in new buildings, where the area is greater than 10,000 m², through building envelope design and using high-performance systems. However, the energy performance standard for residential buildings has not been determined. The Department of Alternative Energy Development and Efficiency (DEDE) [8] investigated the cooling energy consumption in single houses and row houses. A new energy efficiency standard was established that aimed to decrease the cooling energy consumption below 25 kWh/m² a year for a single house and 44 kWh/m² a year for a row house. However, the guidelines on building designs achieving the new standard have not been proposed in that strategic plan.

Urban planning and architectural design can have a significant effect on outdoor thermal comfort in street canyons. At the same time, such designs and their effects reflect energy consumption within the buildings. Several outdoor thermal comfort works have presented that shading effects from nearby buildings and building orientation can considerably improve thermal comfort conditions in outdoor spaces. In Thailand, Srivanit and Jareemit [9] investigated that higher aspect ratio or H/W (as referred to building height (H) to street width (W)) could allow thermal comfort hours to be expanded by 4 hours on a hot day (26 April 2016). Regarding the street canyon orientation, N–S oriented canyons could provide the maximum outdoor thermal comfort hours for hot conditions [10, 11, 12]. In a prior study [9], a maximum comfort hour occurred in the N–S orientation was 46%.

On the side of building energy analysis, architects have tried to maximize a building’s energy savings by decreasing heat transfer through the building envelope. Several techniques have been addressed, for example, improving thermal properties of the wall, roof materials and using high-performance glazed windows [13, 14], adding shading devices [13, 15, 16] and reducing glazing window areas [17]. However, few studies have explored the cooling effect of the outdoor environment on building energy consumption by use of such elements as trees and green spaces [18], cool pavement materials [19] and street canyon geometries [20, 21, 22]. Huang and Li [20] presented that an arrangement of building clusters and its geometries could minimize energy consumption in each building by up to 37.7%.

Several works have mentioned that the N–S delivers the maximum outdoor thermal comfort conditions; however, the rectangular-shaped building on this elongated orientation consumes the highest cooling energy demand [20, 23]. The maximum envelope area of the rectangular building on the N–S elongated orientation could expose the solar heat 33% more than that of the square shape [12]. As comprehensive reviews, the design solutions for improving energy efficiency and outdoor thermal comfort in Thailand’s context have been addressed separately. The cross-disciplinary investigations account for benefits in building energy efficiency, and outdoor thermal comfort is a complex issue that needs an examination.

Considering the enforcement in the 20-year development plan set by EPPO and BMA, the design guideline integrating both urban planning and architectural design has not been proposed for practical applications. This lack of clarity on such design information could reduce the effectiveness and performance of building energy savings and outdoor thermal comfort conditions. It could slow down the progress to meet the strategic plan. To this end, this study aimed to understand the relationship between residential planning and architectural design, influencing the outdoor thermal comfort and building energy use. The investigation of efficient design, optimizing reductions of energy consumption and increasing acceptable outdoor thermal comfort conditions, sought to answer the following questions:

1. How does the planning of residential clusters and building designs impact the daily cooling energy and outdoor thermal comfort in that cluster?
2. How can those cluster designs decrease the residential cooling energy below the new energy efficiency standard and maximize outdoor thermal comfort conditions?

2. RESEARCH METHODOLOGY

Figure 1 presents the research framework. The first part of this work introduces the studied location and defined design parameters for cooling energy analysis. The second part presents the model setting in the energy modeling and validation method. Finally, the criteria used to evaluate the performance of cooling energy consumption and outdoor thermal comfort conditions are presented.

2.1. Site location and design parameters

This investigation selected Pathum Thani province, located north of Bangkok, as a studied location due to land availability for future housing development and easy accessibility from Bangkok. The expansion of housing construction in this area shows approximately 12.5% during the past 5 years [24]. In this study, urban typologies’ design characteristic for the row house cluster referred to the prior work [9, 25]. However, the design characteristics of a single house and window-to-wall ratios (WWRs) were observed from the model homes of four real estate agents. Figure 2 presents a combination of design parameters of the row house with a total of 128 design configurations, while the design for a typical single house has only eight configurations. The row houses with aspect ratios of 0.5, 0.7, 0.9 and 1.1 represent buildings with two, three, four and five stories, respectively. In contrast, only a two-story building is considered for a single house (H/W = 0.5). There are two different building block shapes considered: 1:1 represents a square shape comprising four housing units per block, while 1:2.5 is a rectangular shape with 10 housing units per block. In this study, the WWRs investigated from the row houses and single houses range from 20–80% and 20–40%, respectively.
2.2. Energy simulation and model setting

In this study, the energy simulation software eQUEST 3.64 [26] was used to simulate daily cooling energy consumptions in a cluster of row houses and single houses. This software is a user-friendly graphic interface for the DOE-2 engine, widely used for predicting building energy analysis. Since the sizes of the building blocks of the row house and the single house were not equal, the calculated cooling energy per floor area (Wh/m²·day) for an entire residential cluster, comprising 40 housing units, was used to assess energy-savings performance.

2.2.1. Building case studies

The typical single house had two stories with a living room, dining room and kitchen on the first floor and three bedrooms on the
second floor. However, the row house typically had a mixed-use function: a commercial function such as merchandise or office space was typically found on the first floor. The upper floors were used for residential space, as shown in Figure 3.

Table 1 shows the building materials and operation of air-conditioning units used in the energy model. The wall construction for both building types was masonry systems. The roof of the row house was a flat slab, while the single house had a gable roof. Both roof constructions had 8.5 cm. of polyurethane installed. The roof eaves of a single house were typically 1 m. in width. The calculation of the cooling load was from the building envelope heat gain. The heat generated from occupants, lighting and equipment did not account in this investigation. The hourly operation of air-conditioning units in the commercial area and residential area were different. The EER of the air-conditioning unit was 8.4, which was surveyed from the houses in 2015–2016.

2.2.2. Modified weather data file

Thailand is in a hot and humid climate, where the weather is warm all year round with average temperature ranging from 26 to 31°C. Prior analysis [25] used the ENVI-met modeling to calculate air temperature and mean radiant temperature in different street canyons on 26 April 2016. The energy simulation was extended from the prior work that the simulation was performed under the same date. On that date, the sun position is at the highest altitude angle as providing the shortest shadow length. The calculated monthly Cooling Degree Hours of this month showed a maximum of approximately 8,800 hours at the base temperature of 18.5°C [27]. As a consequence, it has an extreme condition for outdoor living and energy consumption in buildings.

In the energy simulation, the 24-hour weather data file is required in the energy model. This study exported the weather data from the ENVI-Met modeling investigated in the prior work [9]. However, their study’s limitation is that microclimate modeling was carried out from 6 a.m. to 6 p.m. This study used a trigonometric function shown in Eq. (1) to predict the air temperature profile from 7 p.m. to 5 a.m. From the microclimate output, the air temperatures near four-building envelopes were measured and averaged to modify the original IWEC weather file of Pathum Thani. At the same time, relative humidity and solar radiation used the initial values. The temperature fluctuation value ($T_{swing}$) was adjusted to obtain the curve fitting model between the modified weather data and the weather profile generated from the ENVI-met model. A total of 32 sets of hourly air temperatures were used as input weather data files in the eQUEST model:

$$\text{Hourly temperature} = T_{\text{mean}} - T_{\text{swing}} \left( \cos 2\pi \frac{t (\text{sec})}{86400 (\text{sec})} \right)$$

This study followed [28] to create an effect of shading from nearby buildings in the eQUEST model. The simplified way was to set the rectangular vertical plates having a setback from each side of the building block, as presented in Figure 4. The visible reflectance of nearby building’s shades and ground reflectance was 0.5 and 0.2, respectively.

2.2.3. Model validation

A two-story row house with 10 housing units per block surrounded by similar-sized buildings was selected as the studied model. The actual conditions of the studied house with 40% WWR, including building materials and operation schedules, were set in the model input. In this study, the calculated hourly cooling energy use in the commercial zone of a middle unit was compared with the data collected from the energy meter installed at the air-conditioning unit operating from 11 a.m.—6 p.m. The Coefficient of Variation of Root Mean Square Error (CVRMSE) was used to estimate the error between the simulation results and measured values. In this study, the calculated CVRMS values were 8.9% errors, which the ability of the simulation model can provide reliable results. The validated model was then used to perform the daily cooling energy consumption of 136 design configurations under 32 local microclimatic conditions.

2.3. Evaluation of the performance of cooling energy consumption and outdoor thermal comfort conditions

Srivanit and Jareemit [9] investigated microclimate conditions in 192 street canyon configurations and used the ENVI-met BioMET package to calculate hourly PET value (physiological equivalent temperature). The calculated hourly PET were determined comfortably hours within the comfortable summer condition ranging from 25.1–35.2°C, as investigated in a previous study [29]. They showed that acceptable comfortable hours ranged from 23–46%. This classified range was then used to access the design solutions, which maximized outdoor thermal comfort conditions. Regarding energy efficiency assessment, the cooling energy consumption in a single house and row house are classified in line with three performance levels following DEDE [8], as presented in Table 2.

The performances of cooling energy consumption of 136 design configurations were then plotted against the acceptable outdoor thermal comfort hours. Finally, the optimal design configurations, which considerably minimized cooling energy
Table 1. Initial settings for building construction, envelope materials and air conditioner’s operation schedule used as input in the energy modeling.

| Type                        | Parameters                  | Input value       | Thermal property |
|-----------------------------|-----------------------------|-------------------|------------------|
| Construction                | Floor to floor              | 3.0 m (9.8 ft)    | –                |
|                             | Floor to ceiling            | 2.6 m (8.5 ft)    | –                |
| Building envelope           | Roof type (row house)       | 10.5 cm. concrete slab | U-value = 1.7 W/m².K Roof absorbance = 0.55 |
|                             |                             |                   |                  |
|                             | Roof type (single house)    | Ceramic roof tile | U-value = 0.26 W/m².K Roof absorbance = 0.55 |
|                             | Roof insulation             | 8.5 cm. expanded polystyrene foam | U-value = 0.32 W/m².K |
|                             | Floor type                  | 10.5 cm. concrete slab | U-value = 1.7 W/m².K |
|                             | Wall paint color            | Light             | Absorbance = 0.4 |
|                             | Exterior wall               | 10 cm. brick wall | U-value = 2.6 W/m².K |
|                             | Interior wall               | 10 cm brick wall  | U-value = 2.6 W/m².K |
|                             | Exterior windows            | Single clear 6 mm | Solar Heat Gain Coefficient (SHGC) = 0.82 |
| Air conditioning system     | A/C System type             | Packaged single-zone DX | Energy Efficiency Ratio (EER) = 8.4 |
|                             | Cooling source              | DX coils          | –                |

| A/C operation schedule      |                             |                   |                  |
|-----------------------------|-----------------------------|-------------------|------------------|
| Row house                   | Commercial area             | Weekend           | 11 am – 6 pm     |
|                             |                             | Weekday           | 11 am – 6 pm     |
| Single house                | Residential area            | Weekend           | 8 pm – 7 am      |
|                             |                             | Weekday           | 8 pm – 6 am      |
|                             | Living room                 | Weekend           | 11 am – 6 pm     |
|                             |                             | Weekday           | 6 pm – 8 pm      |
|                             | Bedroom                     | Weekend           | 8 pm – 7 am      |
|                             |                             | Weekday           | 8 pm – 6 am      |

Figure 4. A model setting of shading effect from nearby buildings in the energy simulation.

3. RESULTS

3.1. Modified hourly air temperature profile

Figure 5 shows the hourly air temperature (Ta) profile modified from the microclimate simulation [25]. The simulated air temperature in different building’s arrangements varies depending on the street orientations and aspect ratios. The peak air temperature obtained from the weather station occurs at 2 p.m., which relates to the magnitude of solar radiation. In contrast, the highest magnitude of local air temperature from the microclimate simulation occurs at 5 p.m. That shift of the temperature profile might be the effect of the thermal storage of surface materials.

3.2. The impact of residential cluster designs on the cooling energy and outdoor thermal comfort hours.

The simulation of cooling energy of the single house cluster ranges from 117 to 140 Wh/m²-day, with an average of 129 Wh/m²-day.
Table 2. Classified groups of scenarios of building cooling energy levels (data are modified from [8]).

| Performance                        | Single house | Cooling energy consumption | Row house   |
|------------------------------------|--------------|----------------------------|-------------|
| Above-average performance          | Above 54 kWh/m²-year (148 Wh/m²-day) | Above 54 kWh/m²-year (148 Wh/m²-day) |
| Below-average performance          | 25–54 kWh/m²-year (68–148 Wh/m²-day) | 44–54 kWh/m²-year (121–148 Wh/m²-day) |
| New energy-efficiency performance  | Below 25 kWh/m²-year (68 Wh/m²-day)     | Below 44 kWh/m²-year (121 Wh/m²-day)     |

Figure 5. Distribution of hourly air temperature used in the energy model.

Figure 6. The calculated daily cooling energy consumption of single houses.

(shown in Figure 6). About 25% of row houses consume less cooling energy than those of the single houses (shown in Figure 7).

Figure 8 classifies the performance of calculated cooling energy in residential clusters, as defined by DEDE [8] and the percentage of outdoor thermal comfort hours obtained from the prior study [9]. The extreme cooling energy consumption is seen in the cases of a square-shaped row house. More than half of those cases consume the cooling energy above the average performance (148 Wh/m²-day), even when several designs are implemented. Design with a rectangular-shaped cluster (1:2.5) consumes 12% less cooling energy than those of the square shape (1:1). The building shape could considerably reduce the cooling energy in the residential cluster; however, it does not impact outdoor thermal comfort in the street canyon.

The cluster orientation induces notable improvements in both energy-efficient building and thermal comfort in the street canyon in the reverse direction. The lowest cooling energy consumptions (101.4–120.5 Wh/m²-day), highlighted with the blue color, occur mainly in the row house cluster on E–W elongated orientation. It is 20% lower than those for the N–S street orientation (121 to 191 Wh/m²-day). This is because the larger envelope area of the row houses is not exposed to direct solar heat on this arrangement. At the same time, this orientation facilitates the sun rays into the street canyon, leading to extreme thermal situations. In contrast,
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Figure 7. The calculated daily cooling energy consumption of row houses.

the N–S orientation delivers the highest degree of comfort hours at 46%, as seen in the aspect ratio of 0.9 and 1.1 (as seen in the red-dash border), but the cooling energy slightly over the new standard.

A decrease in WWR notably provides a higher saving degree of cooling energy use, which correlates to the increment of aspect ratio. However, this increment slightly affects the single house cluster, as the single house has only two stories with similar WWR for all buildings’ facades. For the row house cluster, the design for enhancing the maximum savings, up to 28–32%, could obtain by decreasing WWR with an increment of aspect ratio, as detailed in Figure 9. Regarding the comfortable outdoor conditions in the prior study [9], the number of comfort hours increases as the aspect ratio increases, except for the E–W orientation (see Figure 10). However, at the N–S and NE–SW orientations, the aspect ratio of 0.9 adequately delivers the maximum comfortable hours, as equal to that of 1.1.

3.3. Design solutions for encouraging outdoor thermal comfort and energy savings in residential clusters

Considering the effect of designs of residential clusters on cooling energy and outdoor thermal comfort, the design could be categorized into four scenarios, as seen in Figure 11. By enhancing the maximum energy performance and outdoor thermal comfort (Scenario 2), it was suggested that the building should elongate
Along on the NW–SE oriented street, H/W = 1.1, with a maximum WWR of 40%. This design scenario could deliver the highest energy-savings by up to 32% and outdoor thermal comfort up to 46%. Although the elongated buildings along with the N–S orientation consume the highest cooling energy consumption, reducing the glazed-window area and increasing aspect ratio could minimize the cooling energy nearly the new standard, as defined by DEDE [8].

The E–W orientation shows the best energy-savings performance, while the worst-case outdoor condition as seen in Scenario 4. Street tree plantings and building height could not increase comfort conditions. Overhead shade and canopy could provide an adequate shaded area to the pedestrian paths [9]. Either the lowest or highest cooling energy consumption could be seen in the rectangular-shaped row house on orthogonal orientation. Increasing the building height and decreasing glass area are suggested for minimizing the cooling energy use in this orientation.

The square-shaped clusters with lower aspect ratios and higher WWRs have the worst of outdoor thermal comfort and energy efficiency (Scenario 3). Additional designs, i.e., using higher performance windows, installed wall insulation, and adding external shading devices, are suggested for improving energy efficiency in that square-shaped clusters. By enhancing comfortable outdoor

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### Figure 8. Calculations of the daily cooling energy consumption and outdoor thermal comfort performance in different residential clusters.

| Orientation  | Square Shape | Cooling Energy (Wh/m²-day) | Rectangular Shape | Cooling Energy (Wh/m²-day) | Square Shape | Cooling Energy (Wh/m²-day) |
|--------------|--------------|-----------------------------|-------------------|----------------------------|--------------|----------------------------|
|              | Comfort hours (%) | WWR | H/W | 20 | 40 | 60 | 80 | Comfort hours (%) | WWR | H/W | 20 | 40 | 60 | 80 | Comfort hours (%) | WWR | H/W | 20 | 40 | 60 | 80 |
| N          | 31            | 0.5  | 151.1 | 165.0 | 176.9 | 192.0 | 31 | 0.5 | 135.3 | 149.5 | 164.2 | 178.2 |
| W          | 23            | 0.7  | 148.8 | 162.2 | 173.9 | 186.9 |
| S          | 46            | 0.9  | 142.3 | 154.0 | 166.1 | 178.1 |
| E          | 46            | 1.1  | 137.7 | 148.7 | 160.3 | 172.3 |
| N          | 31            | 0.5  | 135.6 | 141.7 | 152.0 | 160.0 | 31 | 0.5 | 113.3 | 119.6 | 126.2 | 132.2 |
| W          | 23            | 0.7  | 130.1 | 138.2 | 146.5 | 154.5 |
| S          | 23            | 0.9  | 126.1 | 133.9 | 142.0 | 149.6 |
| E          | 23            | 1.1  | 122.0 | 129.2 | 137.0 | 144.4 |
| N          | 31            | 0.5  | 147.6 | 159.8 | 171.7 | 183.6 | 31 | 0.5 | 128.6 | 141.8 | 155.4 | 168.6 |
| W          | 31            | 0.7  | 142.5 | 154.9 | 167.3 | 179.3 |
| S          | 38            | 0.9  | 136.8 | 148.3 | 160.0 | 170.9 |
| E          | 46            | 1.1  | 131.2 | 142.3 | 153.6 | 164.6 |
| N          | 31            | 0.5  | 149.3 | 161.3 | 173.2 | 184.9 | 31 | 0.5 | 130.2 | 143.4 | 157.1 | 169.8 |
| W          | 31            | 0.7  | 143.2 | 155.2 | 167.2 | 178.7 |
| S          | 38            | 0.9  | 136.7 | 147.8 | 159.2 | 165.6 |
| E          | 38            | 1.1  | 132.3 | 143.0 | 154.4 | 161.1 | 132.3 | 143.0 | 154.4 | 161.1 |

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conditions, planting street trees along the pedestrian paths could adequately deliver shaded areas.

4. DISCUSSION

To study an effect of modified weather data on the cooling energy consumption, one design scenario was selected and performed energy analysis under two different weather data files. In Figure 12, the modified weather data considerably affects the cooling energy use when the air-conditioning units were operated. From 12 a.m. to 3 p.m., the simulations with modified microclimate weather data show 0.5–7% lower cooling energy use than those performed under the original IWEC weather file. However, from 4 p.m. to 11 p.m., the modified weather data shows a higher cooling energy use up to 7%. It is because the modified air temperatures of that time are higher than those of the original weather file.

The single house consumes less cooling energy than the three-story to five-story row house. However, normalized by the total gross floor area, the row house is more energy efficiency, as compared to the single house. The five-story row house with a rectangular shape potentially provides a higher degree of energy efficiency, owing to the building’s compactness. The rectangular-shaped house has less ‘surface-to-volume ratio’ (S/V) than the square-shaped house. The lower S/Vs allow less heat gain through the building envelope, as presented in Figure 13. However, the less S/V would help only for buildings with major heat gain coming from the outside. For building with dominant internal loads, it can be less efficient in the use of daylight and natural ventilation.

Variations in the building’s geometry and WWR could significantly affect the building’s cooling energy use, as presented in the previous works [21, 30, 31, 32]. The higher degree of energy savings has a crucial link with the WWR and S/V in this work. At the aspect ratio of 1.1, decreasing WWR to 20% could reduce cooling energy up to 22% compared to those of aspect ratio of 0.5 (shown in Figure 14(a)). The energy savings increase alongside a decrease in S/V and an increase in WWR, owing to the magnitude reduction in glass areas (see Figure 14(b)). The higher degree of energy savings occurs in the rectangular-shaped clusters, as this shape has lower ratios of glass area to the building volume (see Figure 14(c)).

Furthermore, in the deep street canyon (higher aspect ratios), nearby buildings’ height could provide shade that reduces heat gain through the building envelope by approximately 130 kWh/m², as mentioned in Martins et al. [33]. The analysis of cooling energy efficiency and outdoor thermal comfort conditions in single house clusters shows a similar performance. It is because the single house only two stories that deliver insufficient shade for adjacent buildings and outdoor space. Providing shade is an essential basic design for improving energy efficiency and outdoor environment for the shallow street canyon lined with square-shaped buildings, as similar to the recommendations in previous works [20, 21, 23, 31, 34].
5. CONCLUSIONS

This study explores and examines the potential improvements of outdoor thermal comfort conditions and energy efficiency in low-rise residential clusters in Thailand's context. The eQuest modeling is used to perform the daily cooling energy consumption in various design configurations of residential clusters, including orientation, block shape, aspect ratio, and WWR, by integrating modified weather data from microclimate data generated from the ENVI-met model. The calculations of cooling energy consumption per unit of gross floor area are plotted against the acceptable outdoor thermal comfort hours investigated in prior work [9]. With the integrated design of residential planning and architectural design, the row house cluster design has more opportunities to become sustainable than the single house. By enhancing the maximum outdoor thermal comfort and energy-efficient buildings in the hot condition of Thailand, the row house should be on the NW–SE elongated orientations with a maximum WWR of 40 and an aspect ratio of 1.1. This recommended design improves the cooling energy consumption below Thailand's new energy efficiency standard and provides the highest number of comfort
The highest degree of energy savings in residential clusters correlates to the decrease in glass area and increase in aspect ratio. The energy savings notably increases by up to 28% and 32% for square-shaped and rectangular-shaped row houses, respectively. However, the extreme energy use and thermal situations are seen in the cases of a square-shaped row house and a single house, which requires further designs of shading elements and thermal envelopes to prevent incident solar radiation.

The study results provide a better understanding of a relationship between residential planning and architectural design, influencing the cooling energy consumption and outdoor thermal conditions. The potential improvements for sustainable residential clusters via several design techniques for particular situations have been proposed. This new guideline could help urban planners and designers successfully utilize the design information to enhance maximum energy efficiency and outdoor thermal comfort, especially in the hottest summer month.

Beyond the scope of this study, several parts require further investigations. Shading significantly contributes to energy savings and outdoor conditions. The critical factors, including complex urban typology and seasonal sun paths, influence the shaded area at the pedestrian paths and building envelope. This area, though, needs further investigation.

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5. CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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