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Resilient Residential Developments: Design Strategies for High-Density Cities

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ABSTRACT

Mega cities face the next 'global emergency' when the global population is projected to reach 9.7 billion by the mid-century, leading to interconnected web of concerns and challenges such as escalating built density, greenhouse gas emissions and climate change impacts, epidemic threats, liveability of cities, and the decline of natural habitats and biodiversity. Hong Kong population is projected to increase up to 8.96 million by 2050. Due to challenging topography, currently 7.49 million population occupies around 275sqm developed land area with densities in some areas exceeding 57,000 per sqkm. Due to high-rise high- densities, lack of urban open spaces, Urban Heat Island (UHI) effect, poor air quality and low wind velocity have become serios public health concerns effecting Hong Kong's liveability. This scenario certainly warrants revolutionary approaches. This paper focused on the aspects directly related to high-density cities and associated impacts such as limited land area for future developments, urban greenery, urban porosity, poor urban ventilation and daylight penetration to street levels to facilitate user comfort. This study compared existing residential typology with three proposed variations using simulation platforms for urban ventilation, shadow analysis and daylight performance analysis. Results were validated with district level microclimatic data, and literature reviews. Findings indicate the prospects for much higher vertical developments with no adverse impacts on daylight penetration, shading and wind flow. Wind flow and shading effect were improved with taller towers with wider spacing, improving microclimate around open podiums making them desirable for use during hot summer months.

1. Introduction

Humanity faces the next global emergency the 'density crisis' when the global population is projected to reach 9.7 billion by 2050, demanding twice the building stock and soaring urban densities within finite land resources. Such changes within a short span of time will inevitably accelerate strain on cities reducing their resilience to cope with subsequent impacts. Due to extreme high density with minimal natural ground cover and inadequate drainage reserves in Hong Kong have led to severe urban flooding in the recent years. Research predicts extreme rainfall events to increase by over 40% and hot nights to increase by 50% in 2040s. Vertical developments and compact residential units have become the response to limited land area. It is common to see the number of residential towers above 200m and nano flats as small as 11sqm.

Open space per capita is the lowest among other Asian metropolitan cities. Hong Kong's attractiveness among East Asian population dropped from 29th to 92nd position from 2017 to 2022 indicating downward spiraling livability.

To withstand and adapt swiftly to strains on cities, focus on resilient cities is growing. Despite the growing focus, the absence of analytical parameters has led to a unified scalable and adoptable urban resilience model (Rezvani et al., 2023). City Resilience Index (CRI) by ARUP (2014) encompasses 52 indicators responding to 156 questions, ranging from leadership in urban planning to infrastructural innovation. Climate Disaster Resilience Index (CDRI), reflects on the ability of people and institutions to respond to potential climate-related disasters (Joerin et al., 2014). Baseline Resilience Indicators for Communities (BRIC) provide significant variations in resilience levels on a regional scale, serving as a valuable tool for enhancing disaster resilience and crisis management (Scherzer et al., 2019). Rather than simple correlation between variables, some consider urban resilience as an equilibrium of multiple processes that involve diverse stakeholders, power dynamics and motivations in various contesting fields (Meerow et al., 2016). Among the most prevalent associations, resilience is being increasingly linked to sustainability (Milman and Short, 2008) and climate change adaptation. Progressive studies are being pursued on green infrastructure (Thiagarajan, 2018), sustainable development (Neumann Barbara et al., 2015), smart cities (da Silva et al., 2020; Shahrabani & Apanavičienė, 2022), governance (Frantzeskaki et al., 2016; Meyer & Auriacombe, 2019) and disaster risk management (Espada et al., 2017).

1.1 Livability Challenges in High-Density Environments

Sub-tropical climate of Hong Kong with hot, humid and wet Summers and its peculiar hilly terrain and proximity to sea surrounded by high-rise high-density built environment significantly influence microclimatic conditions in urban centres and hence the user comfort. Urban heat island effect, street canyon effect, shading from buildings, stagnant wind, air pollutant concentration and high humidity are unavoidable attributes of Hong Kong living. Key meteorological variables affecting outdoor thermal comfort are air temperature, wind speed, relative humidity and mean radiant temperatures (Jendritzky et al., 2012; Johansson, 2014). Rose et al., 2010opine that design interventions cannot modify all of the conditions related to thermal comfort in outdoor spaces and hence it is important to understand the influence from key meteorological factors. On average wind speed in most urban areas is approximately 1 m/s. Over the past five years humidity levels from 2018 June to 2023 September reported 77.87% average and 93% maximum with summer temperature reaching higher than 35oC (Hong Kong Observatory, n.d.). High humidity, hot weather, stagnant wind and air pollution are some of the key challenges towards the enjoyment of outdoor spaces. Urban open spaces are predominantly being used by elderly in the surrounding neighborhoods for passive recreation on a regular basis who are more vulnerable to heat stress and safety related issues.

Average open space per capita 1.6sqm is far below compared to many other metropolitan cities (Chow J, 2018). Open spaces attribute to human well-being and quality of life besides their benefits on microclimate. Open spaces have been defined as unbuilt spaces that consist of a high proportion of natural elements and permeable surfaces (Lo & Jim, 2010; Maruani & Amit-Cohen, 2007) cultural landscapes for social cohesion, well-being and recreation (Law, 2002; Thompson, 2002). Natural environments improve emotional and physical well-being by the nature connectedness (Mantler A. & Logan A., 2015) (Herzog et al., 1982).

1.2 Daylight Access in High-density Cities

Lu & Du, 2013 developed design guidelines based on a study on building orientations, layouts, and positions on facades affect the availability of daylight and sunlight in a high-density residential environment in North-East China. A study found the use of electrochromic glass windows in residential developments, contributing to higher daytime circadian-effective light levels, leading to earlier melatonin onset, earlier sleep onset, higher sleep regularity, and improved vitality and positive affect, compared to standard windows with blinds, demonstrating the importance of designing buildings to optimize daylight exposure for human health and wellbeing (Nagare et al., 2021). Studies also have concluded the importance of daylight access in work environments in reducing eye strains and depression and improving productivity and mental health (Woo et al., 2021, Boubekri et al., 2014). Besides studies also have demonstrated the contribution towards energy efficiency Yu & Su, (2015), Li, (2010).

1.3 Solar Radiation and Shading Effect

A study on high-density, high-rise buildings in Singapore reports reduction in daily photosynthetically active radiation (PAR) by nearly 50% in community green spaces, correlating with reduced growth in shrubs and trees compared to fully exposed conditions (Tan & Ismail, 2014). Providing comparable results from a similar climate to Hong Kong, a study from Taipei reports the impact of shading on outdoor thermal comfort; high sky view factor (minimal shading) causes discomfort in summer, while low sky view factor (heavy shading) causes discomfort in winter, recommending sufficient shading to improve summer comfort while avoiding excessive shading to prevent winter discomfort, emphasizing the need to consider local climate, environment, and resident preferences when designing shaded outdoor spaces (Lin et al., 2010). However, in high-density high-rise environments, shading and sky view factors are dictated by the height and built density. Less sky exposure is attributing to less solar radiation entering the urban canyon, thereby reducing the mean radiant temperature (Givoni, 1998). (Ojaghlou M. & Khakzand M., 2017) associated reduction in sky view factor (SVF) and reduction in mean radiant temperature by 3.04oC in Tehran. (Baghaeipoor & Nasrollahi, 2019) concluded a positive correlation between SVF and the air temperature between 11am and 3pm in open spaces in high-rise urban environments in Tehran. Analyzing 600m x 600m 18 test sites, (Yuan & Chen, 2011) established a positive correlation between SVF and the Urban Heat Island effect. (Unger, 2009)concluded a strong a relationship between SVF and the temperature based on a large number of areal means of SVF on a large sample area.

Due to extremely high density in Hong Kong, impact from the building envelopes albedo could be significant. Based on a study that compared thermal properties of material in a desert climate considering 24-hour average (Santillán-Soto N. et al., 2015) concluded that unlike concrete and asphalt, grass and poly material contribute to very low amount of thermal energy thereby reducing UHI. A study in Taipei recommends reducing unshaded paved areas to less than 50% and integrating at least 30% greenery and shading to alleviate negative effects from exposed hardscapes (Chang & Li, 2014). (Akbari et al., 2011; Santamouris et al., 2008, 2012) advocate the use of high albedo material for mitigating UHI effect. Cool paving materials have shown promising results in lowering surface temperature (Ferguson et al., 2008; Santamouris et al., 2008). (Shahmohamadi P. et al., 2010) opined that replacement of soil and vegetation by concrete and asphalt increases ambient temperature. A study conducted in Tokyo reported lower surface temperature on grass compared to asphalt and concrete surfaces. Air temperature at 1.2m above grass was also 2oC lower compared to asphalt and concrete (Ca et al., 1998). A study in Iran that compared surface temperature between grass and asphalt also concluded higher temperatures over asphalt compared to grass starting from 6am attributed to evapotranspiration in grass and low albedo of asphalt (Madjidi F. et al., 2013). These studies support the role of urban greening on reducing air and mean radiant temperature.

1.4 Urban Porosity and Ventilation

Urban morphology plays a crucial role in influencing air movement and thermal comfort (Palusci & Cecere, 2022). In a high-density urban setting, adequate urban ventilation plays a significant role in risk management during pandemics (Li et al., 2024). (Wong, 2001) has established strong correlations between poor air quality and increased number of hospital admissions and mortalities in Hong Kong caused by respiratory and cardiovascular diseases. (Ng et al., 2006; Yuan et al., 2014) established correlations between lack of urban permeability, stagnant wind and air pollutants concentration in high density cities. The same study also advocates the effectiveness of building separation, porosity, voids in podiums compared to building setbacks at higher elevations. (Yuan, 2018)emphasizes the need for appropriate urban design for high density cities to mitigate negative impacts on public health by reducing air pollutants concentration through increasing urban porosity to promote ventilation. Supplementing, (Ng, 2009) recommends aligning of gaps between buildings and voids within buildings for better effectiveness. (Yuan, 2018) shares number of approaches for increasing pedestrian level ventilation performance that includes reduced site coverage ratio, pedestrian level building porosity and aligning wind corridors with the street grid. Comparing porosity distribution patterns on mid-rise buildings (Saadatjooa, et al. 2019) conclude the effectiveness of porous residential blocks in enhancing ventilation compared to solid blocks. Comparing building heights and porosity sizes, (Du, et al. 2018)positive correlation between increased buildings heights and larger voids on improved wind comfort.

1.5 Effect of Building Geometries on Urban Ventilation

Pedestrian level wind velocities in Hong Kong have been adversely impacted by certain building typologies. Wind velocity is less than 2m/s due to lack of porosity, and increased urban roughness created by the high-rise high-density environments. (Van Druenen, 2019, Thilakaratne et al. 2016) concluded 0.6m/s wind speed reduction from 1968 to 1995 and 0.16m/s from 1996 to 2017 due to urbanization and high-rise developments. (Peng et al., 2018) predicted further 40% wind loss by 2050, if the current development trends continue. (Thilakaratne et al., 2016, 2017) reported pedestrian wind speed reduction due to large podiums. According to (Van Druenen, 2019)pedestrian level wind speeds drop significantly when high-rise buildings are located within a high-density environment. (Kubota, 2008) reported a strong relationship between building density and reduction in mean wind velocity ratio based on 22 urban areas in Japan. (Wise, 1971) (Y. Du & Mak, 2017; Liu, 2017)reported tall buildings inducing higher speed on low-rise surrounding areas. (Du, Y. and Mak, C. 2017; Liu, 2017)reported wind amplification effect at the immediate pedestrian zone around individual stilted building compared to the non-stilted buildings. (Blocken et al., 2007) report effective building separation widths for improving wind flow.

1.6 Role of Greenery in Modifying Urban Microclimate

Studies from Singapore, Taipei and Tokyo that represent similar urban morphological and climatological conditions to Hong Kong report correlations between greenery and air temperature. (Chau et al., 2016) reports 1.3°C temperature difference between areas with greenery and their surroundings in Hong Kong urban parks. (Honjo & Takakura, 1990) have established 300m as the optimum influenced distance from a 100m diameter green area. Supporting above recommendations, (Chen & Wong, 2006) reported positive contributions from greenery on microclimates within and surrounding two large urban parks in Singapore. Vertical greening is an effective solution for high-density cities. Studies have reported internal temperature reduction with vertical greening and bio-skin facades (Cheung & Luther, 2005; Dahanayake & Chow, 2017; Morakinyo et al., 2017). Through a life cycle impact study (Pan & Chu, 2016) reported 16% energy saving potential by vertical greening in Summer.

2. Methodology

2.1 Case Study

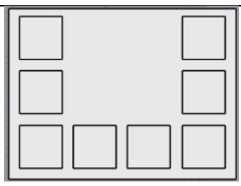
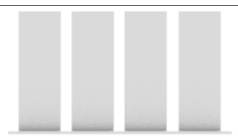
This paper intends to establish parameters for a resilient development proposal for an existing housing estate that was built in 1986. Increasing land premiums and development ratios in this district make this estate a prospective candidate for future redevelopment. This high-density residential development consists of 61 residential towers with 12,469 apartments, built on commercial and parking podiums. Tower heights range from 22-30 storeys or 85m - 87m with 8m distance between towers. This development built on 0.1877sqkm accommodating 18,008 residents leads to population density of 95,966/km².

Fig. 1. (a) Case study residential estate layout (b) open areas surrounded by residential towers

2.2 Test Parameters & scenarios

Considering the potential for redevelopment in this district to address demand for housing, the following scenarios were tested and compared with the existing development. Proposed scenarios represent increased tower heights which affords the possibilities of increasing spacing between towers, reduced numbers of towers on site allowing more open areas and greenery integration or accommodating more population in the future. Using simulation software Rhino CFD, Revit and VeLux, wind speed at pedestrian zone and upper zones, shadow analysis and daylight penetration at street level were examined. Simulation results were analysed based on published standards.

Test Scenarios

Option 1 Existing residential towers that are 85m tall and the current spacing of 8m between buildings			

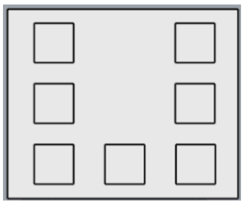
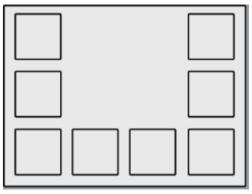
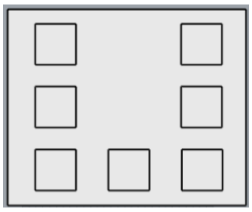
Option 2 Existing residential towers that are 85m tall and increased spacing of 16m between buildings			
Option 3 Modified residential towers that are 170m tall and the current spacing 8m between buildings			
Option 4 Modified residential towers that are 170m tall and twice the spacing 16m between buildings			

Fig. 2. Test scenarios adopting modifications to tower heights and spacing between towers

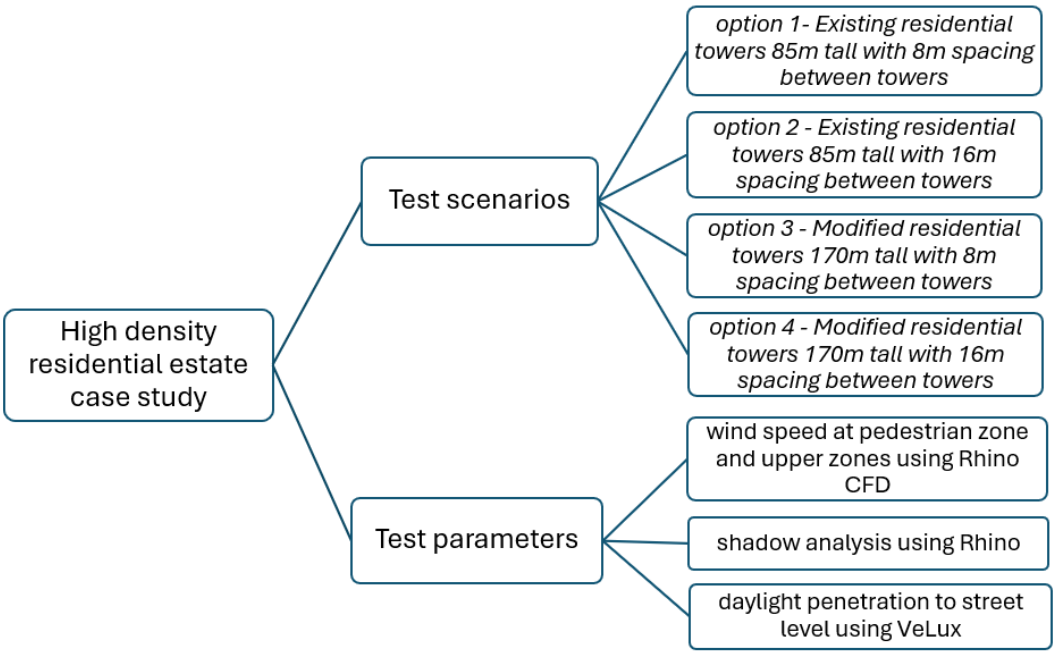


Fig. 3. Methodology diagram illustrating test scenarios, test parameters and analysis platforms

2.3 Wind, Daylight and Shadow Simulation

Real time wind speed of the site varied between 0.5m/s -1.5m/s with higher wind speeds closer to road level and much lower wind speeds around open podiums surrounded by residential towers. Wind simulation was conducted for the predominant summer wind direction South-East using Rhino

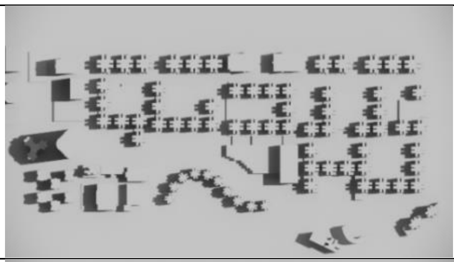
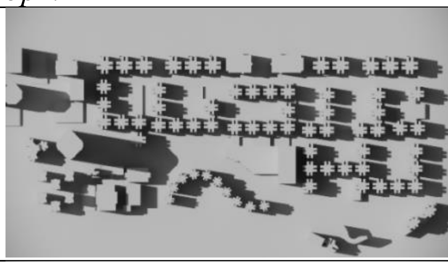
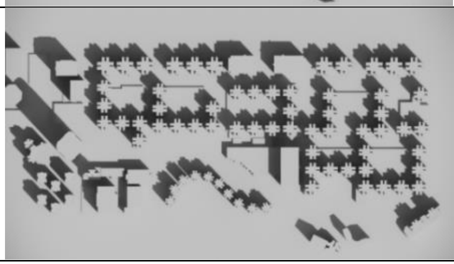
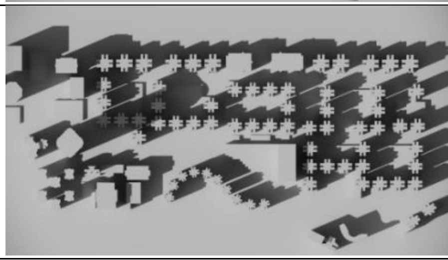
Computational Fluid Dynamics. In order for the calculation engine to capture wind flow changes and patterns, input wind speed was set to 10m/s amplifying the real time wind speed. Effective roughness heigh was set to 2m which corresponds to pedestrian wind zone. Test scenarios with increased distances between towers aimed at inducing wind speed and channeling wind towards open podiums.

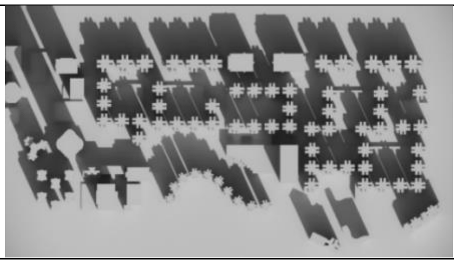
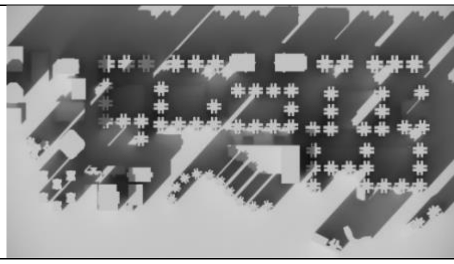
Daylight simulation was conducted using VeLux to investigate the amount of daylight and hence apparent solar radiation on open podiums. Test variations were experimented with increased heights and distance between towers. To observe the impacts from excessive solar exposure, shadow analysis was conducted using Rhino to examine the shading effect on exposed podiums during important solar days of the year; June 21, September 21 and December 21. Residents often use these open podiums sit out areas in the morning around 11am and afternoon around 3pm.

3. Results & discussion

3.1 Shadow Analysis

Given that there are fewer taller towers on the West direction and in the absence of taller trees within the estate, shadow effects mainly resulted by the residential towers within the estate. 85m residential towers within the existing estate are not tall enough to cast shadows onto open podiums on June 21 and September 21, 11am and June 21, 3pm effecting the usage of these open spaces during hot summer months when the afternoon temperature often rises over 31^{o}C. According to Physiologically Equivalent Temperature (PET) classification for sub-tropical regions, PET between 26°C and 30°C is considered neutral for high-density high-rise contexts (HKGBC, 2017). In December these podiums are too shaded when daylight is important to reduce the effect of cold air temperatures. Whereas extended heights to 170m contributed to providing adequate shading on these podiums during hot summer months due to low sky view factor lowering solar radiation and hence the air temperature (Baghaeipoor & Nasrollahi, 2019; Givoni, 1998; Ojaghlou M. & Khakzand M., 2017; Unger, 2009; Yuan & Chen, 2011). Since increased spacing between towers did not have any effect on shadow patterns, we only use options 1 and 4 to illustrate. Filed observations on weekend between 2-4pm confirmed the lack of usage of these open spaces.

Option 1: 85m tall towers with 8m spacing between towers		
	11am	*3pm*
June 21		
September 21		

December 21		

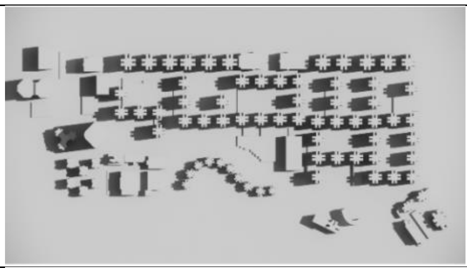
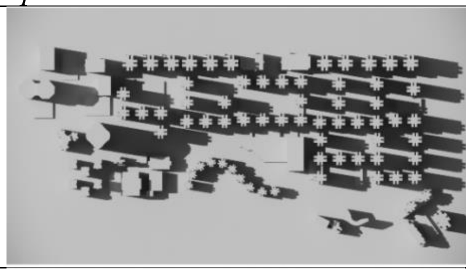
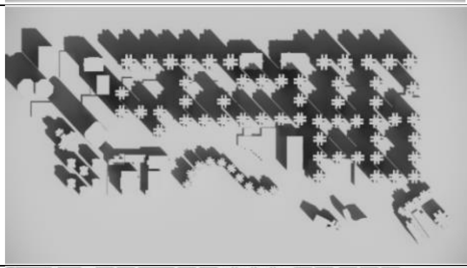
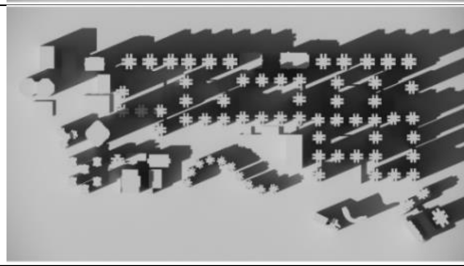
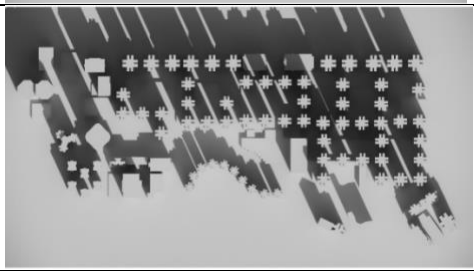
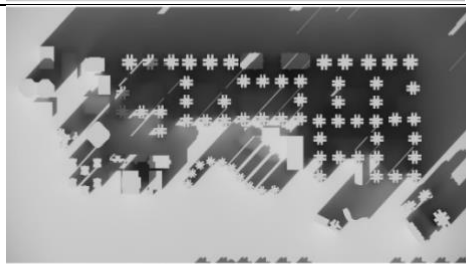
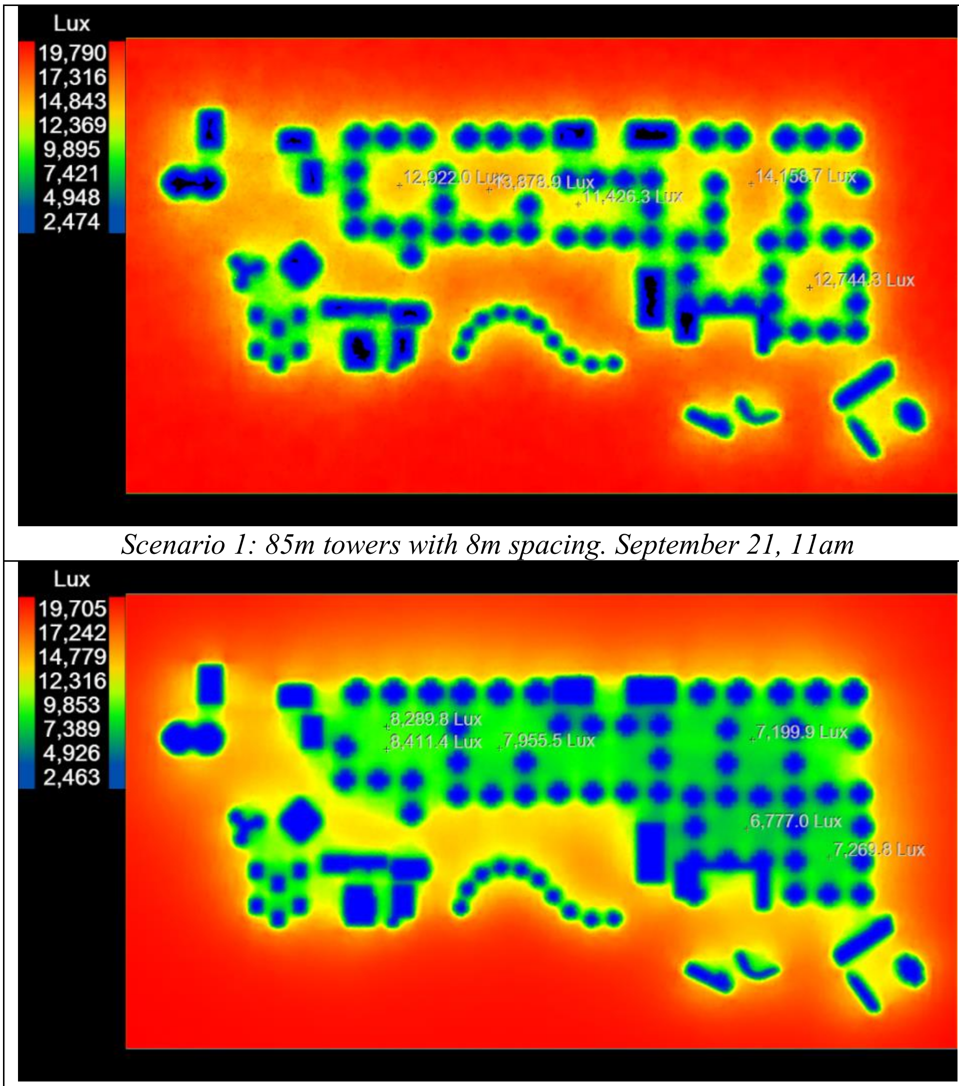
Option 4: 170m tall towers with 16m spacing between towers		
	11am	*3pm*
June 21		
September 21		
December 21		

Fig. 4. Shadow analysis effect on open spaces in June, September and December

3.2 Daylight Performance

With increased tower heights from 85m to 170m, daylight levels reduced by approximately 4000 lux in open podiums. Using rule of thumb conversion of 0.0079W/m^2 equals to 1 lux led to 31.6 watts/m^2 reduction in solar irradiance and hence radiant temperature (Baghaeipoor & Nasrollahi, 2019; Givoni, 1998; Ojaghlou M. & Khakzand M., 2017). Findings correlate with the shadow analysis comparison between taller and shorter towers. Taller towers did not block daylight access to pedestrian zone.



Scenario 1: 85m towers with 8m spacing. September 21, 11am

Scenario 4: 170m towers with 16m spacing. September 21, 11am

Fig. 5. Daylight analysis of scenario 1 and senario 4

3.3 Wind Performance

Wind performance in all four scenarios reported lack of wind passing through the open spaces.

Sectional wind flow diagram shows desirable wind speeds reaching 170m tall towers indicating the possibility for cross ventilation even at higher elevations. Validating the field data, wind flow did not reach open podiums among the towers, even with increased spacing between towers. However, 170m towers with 8m and 16m spacing seem to have improved the wind flow through open podiums at the centre. These findings correlate with studies of (Y. Du et al., 2018) that established positive correlation between increased buildings heights and larger voids on improved wind comfort. Wider and aligned spacing seem to have facilitated better air movement and wind speed. These findings are confirmed by other studies conducted in Hong Kong (Ng et al., 2006; Yuan, 2018).

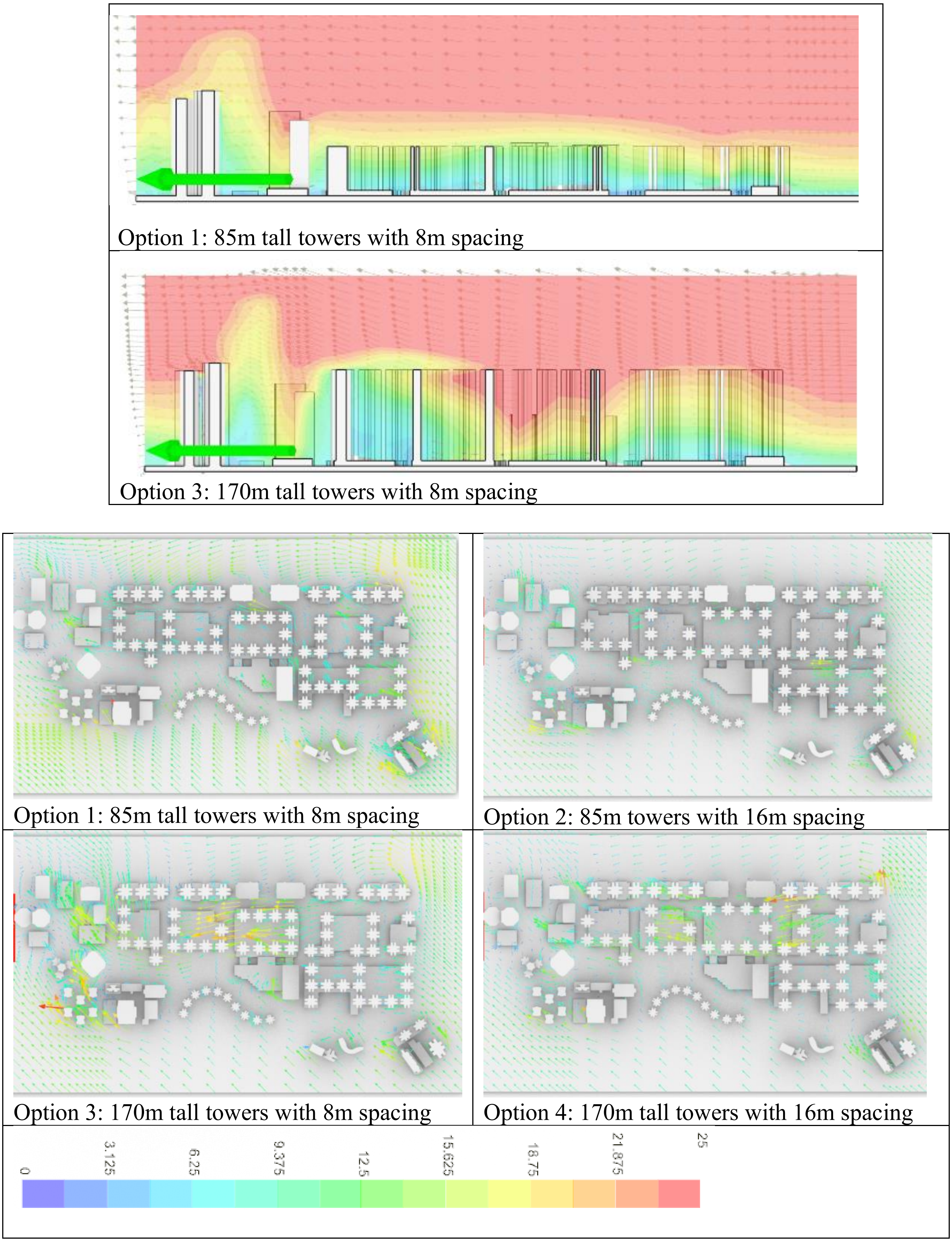


Fig. 6. (a) comparison of wind flow analysis between 85m and 170m towers (b) comparison of wind flow analysis of test scenarios with existing estate conditions

4. Conclusions

This paper investigated aspects that are directly related to high-density cities such as lack of urban greenery, lack of urban porosity, poor urban ventilation and lack of daylight penetration to street levels that effect user comfort and liveability. An existing high-density residential estate that is nearly 40years old was considered as the case study. Three different design scenarios were compared with the existing scenario and tested for improving the microclimate for evaluating potentials for future developments. Findings indicate prospective directions for improving microclimatic conditions and potential design strategies that could be adopted during revitalization programmes and when planning new developments in this area. Results indicate the potential for taller vertical developments with no adverse impacts on daylight penetration, shading and wind flow at the tested height of 170m. Wind flow and shading effect improved with 170m taller towers improving the microclimate around open podiums creating desirable conditions for users during hot summer months. Increased spacing between towers to 16m contributed to improved wind flow towards open podiums. Increased heights demonstrated their effectiveness in terms of reducing solar exposure and hence solar radiation of the excessively hard paved open podiums. Current footprint of the estate could be reduced to 50% by increasing the tower heights from 85m to 170m to accommodate the current population. This scenario suggests potential directions for future developments such as greenery integration on open areas and vertical surfaces, land for future developments. Greenery integration is a priority to reduce solar radiation and related environmental and health impacts (Tan & Ismail, 2014). However impacts from greenery integration on vertical surfaces on microclimatic conditions and improving energy efficiency could not be validated at this stage. These findings and limitations could be further explored for high-density cities with limited land area for future developments.

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