Spatial Analysis of the Development Potential of a Commercial District: A Case of Hong Kong

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Abstract

With large-scale urbanization globally, the world is facing environmental problems brought about by high-density cities. To achieve sustainable development in Hong Kong, especially for the heavily loaded Cross Harbour Tunnel district, The Hong Kong Polytechnic University proposes a Green Deck over the Cross Harbour Tunnel to enhance the neighbouring environments. Green belts, buildings, and a new exhibition centre are planned for this deck. This will require an increase in the guest capacity of nearby hotels in the Tsim Sha Tsui East (TSTE) area. This study therefore investigated the development potential of the 23 existing buildings in TSTE and the environmental impact brought about by the increase of PR/BH in that area. Spatial analyses of solar exposure, wind ventilation, and air temperature were conducted based on four different scenarios with various PR/BH; human thermal comfort brought about by PR/BH changes were also measured. A comparison of different scenarios revealed no significant changes in the surrounding environment. The study concludes that there is potential for PR/BH relaxations in TSTE to increase spaces to meet increased population flow.

Keywords: Development potential, Green Deck, High-density city, Spatial analysis, Urban microclimate, Thermal comfort

1. Introduction

With the continuous growth of global urban areas, they are facing enormous challenges in terms of land supply and the heat island effect, as well as environmental problems such as traffic noise and exhaust pollution. Hong Kong is a typical densely populated city with high-rise buildings. To achieve sustainable development in Hong Kong, particularly for the heavily loaded Cross Harbor Tunnel district, The Hong Kong Polytechnic University (HKPU) has proposed an innovative solution that involves constructing a Green Deck (HKPU, 2015) over the Cross Harbor Tunnel plaza to enhance the immediate and neighboring environments. A comparison of the Green Deck blueprint and the current Cross Harbor Tunnel plaza is presented in Fig. 1. The Cross Harbor Tunnel is a cross-sea tunnel connecting Hong Kong Island and Kowloon Peninsula, which is one of the busiest tunnels in the world. While providing convenient transportation in the Hung Hom district, the Cross Harbor Tunnel also brings huge traffic congestion, environmental pollution, and noise problems. The proposed 43,000m^2 deck will accommodate various entertainment, cultural and sports facilities, including a convention and exhibition center, while solving existing problems in this area. It will not only provide people with a green resting space, but also help to promote the sustainable development of Tsim Sha Tsui, especially Tsim Sha Tsui East (TSTE) and Hung Hom. As a result of the proposed Green Deck and the convention and exhibition center, more tourists, participants in conferences and other activities, and local residents will visit this area. Since most visitors will choose to stay in nearby hotels, TSTE will undoubtedly be their first choice. This study therefore rigorously examines the development potential of TSTE with its current carrying capacity of 23 existing buildings, including six hotels.

Development potential in Hong Kong is mainly controlled by Lease Conditions, Outline Zoning Plans (OZPs) and Building (Planning) Regulations (BPR), all of which inevitably impose restrictions on the plot ratio (PR) and building height (BH) of individual land zones. Hong Kong has been struggling to develop every piece of land in downtown areas to its maximum potential and so the development of the Green Deck project will bring unprecedented opportunities to TSTE. To meet the increased high passenger flow, it is necessary to ensure enough living and working spaces in TSTE, which currently has a building gross floor area (GFA) of 842,585.105m^2 for 23 buildings. Elevating the development potential of built-up region through minor relaxation of the maximum PR/BH restrictions is a viable option for increasing living and working spaces within a short timeframe. Although minor relaxation of PR/BH restrictions may be a possible way to accommodate more people, its impact on the surroundings must be carefully analyzed.

Development intensity is generally explored through an Environmental Impact Assessment (EIA), as it is subject to the public's tolerance to changes in the environment. The TSTE area is a tourist check-in point, which is close to the Victoria harbor, Avenue of Stars, Hong Kong Coliseum, and famous shopping malls. Therefore, the extent to which this relaxation to the area will be acceptable to the public is rigorously analyzed in this study.

This paper investigates the development potential of the 23 existing buildings (including six hotels) in the TSTE area and the environmental impact brought about by the PR/BH increase in this area. Various spatial analyses including solar exposure, wind ventilation, and air temperature are conducted through 3D building models of four different scenarios with various PR/BH, and the thermal comfort of different scenarios is also calculated and compared. A comparison of the four scenarios leads to a discussion and conclusions. The results of this study provide vivid design sketch and science-based suggestions for urban planners or decision makers in relation to the development of TSTE, and assist them in making better informed decisions. Moreover, 3D visualization and scenario analysis in our study could help the non-professional public understand the developing land and its future development, which is beneficial to the community engagement. The same or similar planning model can be easily applied to urban renewal projects in other districts of Hong Kong or similar initiatives in other high-density cities such as New York and Tokyo.

2. Literature Review

The development potential of urban areas is one of the most important study topics in urban planning. Most relevant studies are dedicated to providing scientific findings to support and to guide the proper consideration of land use, building and facility renewal/development, culture, and heritage preservation for improving social benefit without damaging the environment. In this regard, some scholars have focused on the use of fundamental data (e.g., spatial characteristics, financial data, political documents, environmental data and socio-economic data) to explore the impact of urban development on the environment and to analyze the development feasibility of a city or urban area. This study adopts the same focus and has a few relevant studies on exploring the surrounding environmental impact after minor relaxation of the maximum PR/BH restrictions.

Although previous similar studies have integrated geographic information systems (GIS) for assessing air ventilation and visual permeability etc., they have mainly focused on the use of 2D GIS. Since the spatial distribution of land units in the real world is three-dimensional, 3D GIS can help us to see the real world portrayed in true perspective and thereby make better-informed decisions. One such research by Terzi and Bölen (2012) focused on the feasibility of urban development strategies (i.e. market-led development, conservative-led development and fiscal incentives-led development) for dealing with urban sprawl while preserving the environment in Istanbul. Three other studies (Stevens et al., 2007; Tayyebi et al., 2011; He et al., 2018) were dedicated to the modelling of urban expansion. All four studies made use of 2D spatial analysis technology to deal with the potential of urban sprawl rather than 3D spatial analysis technology (3DSAT). The latter technology was developed from the former by adding a vertical dimension to the original two horizontal dimensions in spatial analysis. Since three dimensions enable representation and visualization of real-world space better than two dimensions, many urban development studies have been conducted using 3DSAT. The viability of using 3DSAT to study urban development has been touched upon by Ranzinger and Gleixner (1997), Pullar and Tidey (2001), Zhang et al. (2004), Mak et al. (2005), Thill et al. (2011), Leszek (2015), and Guo et al. (2017, 2020), all of whom achieved effective results that help with making urban planning decisions. The increased application of 3DSAT for urban development has resulted in the following proposed tools based on 3DSAT: a GIS tool for urban climate evaluation (Li et al., 2004) and for community engagement in urban planning (Foth et al., 2009); an original 3D GIS methodology developed by Wong et al. (2011) for investigating the wall effect caused by the proliferation of tall buildings along the coast of Kowloon in Hong Kong; a platform for assisting decision making in urban development projects (Isaacs et al., 2011); an integrated approach for assessing residential development (Xu & Coors, 2012); and a framework for assessing the development potential of Liuzhou city in China (Xia et al., 2016). Although the above mentioned researchers tried to introduce 3D GIS to their studies, however, they only applied this technology into urban planning, landscape, and development control. Few people used 3D modelling and GIS technology to do the research focus on the changes of PR/BH for the buildings and their related impacts to the environment nearby. The tool used in Xia’s study is similar to the one used in this study, however, they only considered land use suitability, economic feasibility, and landscape visibility. There are obvious differences in respect of the urban situation, socio-economic conditions, and the scale of the study area. Hong Kong is a high-density city with many skyscrapers and so the development of its urban areas involves different environmental issues. Although TSTE is a relatively small-scale urban region, it is nevertheless important that the proposed development be implemented as soon as possible in order to help maintain Hong Kong as one of the world's leading financial centers.

Studies have shown that an urban microclimate is affected by many factors, such as the interrelated elements of air temperature and wind ventilation. Croker found that wind could bring hot air to shaded areas to increase the air temperature in those areas, and at the same time wind can bring cold air to exposed areas, thereby reducing the air temperature there (Croker,1956). As the density of urban development increases, urban canyons usually appear in densely populated urban areas with high-rise buildings (Wang et al., 2011). Air temperature and ventilation influence heat exchange and consequently affect the comfort of pedestrians (Bottillo et al., 2014).

People are subject to the combined effects of meteorological elements and use temperature to indicate whether the environment is hot or cold. Energy exchange continuously occurs between humans and the atmosphere, and the body maintains a constant temperature through its own temperature regulation centre; if the human body feels uncomfortable it will lead to a corresponding stress response (Zhang, 2015). However, few studies have focused on assessment of the thermal comfort of people subjected to urban microclimate change. The exemplar of such studies was conducted by Mayer who used ENVI-met to simulate the spatiotemporal distribution of different levels of thermal comfort within the Rieselfeld quarter of the city of Freiburg in Germany on a typical summer day in 2007 (Mayer et al., 2008). Therefore, human thermal comfort is also a key factor considered in this study.

Development of the Green Deck project and its environmental influence can be addressed in terms of solar exposure, wind ventilation, air temperature, and human thermal comfort changes.

Similar research was conducted by Guo et al. (2017, 2020) on PR/BH relaxation and related analyses using 3D spatial analysis technology in the Kai Tak Development Area (KTDA) of Hong Kong. However, since most of the KTDA was still under construction, all the 3D building models of different scenarios were generated based on the blueprints (EKEO, 2012). TSTE is a very different situation in that it is an existing commercial and tourism district and as such all the simulated renovations are based on existing buildings. Therefore, in addition to paying special attention to environmental impact factors and microclimate changes, insolation radiation energy and human thermal comfort analysis are added in this study to understand the energy changes and human feelings changes respectively after relaxation of the PR/BH in the study area. This will help with better adapting to sustainable development.

Although many previous related studies applied 3D GIS and related software to the development potential of urban areas, only a few of them focused on relaxation of PR/BH. The success of the KTDA study provides a useful insight into the application of 3D GIS and spatial analyses for assessing the development potential of TSTE. This research therefore investigates the development potential of relaxing PR/BH restrictions of the existing 23 buildings, especially the six hotels, in the TSTE area through 3D GIS and spatial analyses.

3. Research Methodology

3.1 Framework of this Study

The research framework, shown in Fig. 2 below, is in two major parts: 1) Data collection and 3D modelling and, 2) 3D spatial analyses. The 3D building models of the TSTE study area are generated using Digital Terrain Model (DTM) and building and infrastructure models according to the OZPs and BPR. To meet the needs of the research, four scenarios of the models with various PR/BH are created. In particular, 3D spatial analyses include effects on solar exposure, wind ventilation, and air temperature based on various 3D models. Based on the results of wind ventilation and air temperature for different scenarios, thermal comfort is calculated. For each analysis, a comparison is made among the four scenarios to lead the final discussion and conclusion.

3.2 Study area and data collection

The study region and DTM is shown in Fig. 3. The inner boundary is the focus study area including TSTE, HKPU, and Hung Hom Station areas. The outer area is the potential boundary of the affected adjacent area within a 500 m radius covering Tsim Sha Tsui, Jordan, Whampoa and Victoria Harbor. Refer to the previous study, Wang et al., Alexakis and Sarris (2010) also applied 500 m butter area in their studies. Therefore, considering the area of the TSTE, surrounding land use types, and the area affected by the study area, a 500-meter buffer area is created. There are six hotels out of 23 buildings in the study region. In this study, the six hotels are the focus objects to check the carrying capacity after the Green Deck has been built.

The 3D spatial data including 3D buildings, roads, and DTM can be obtained from the Lands Department in Hong Kong (Lands Department, 2016). However, as some of the available data is not up to date, the data does not always identically match the current situation. For example, the data for some parts of the Royal Garden Hotel and the New World Centre do not match the actual current situation. Such 3D buildings are developed based on the current latest situation. The other non-spatial collected data relates to the updated approved building plans including Site Class, Zone, Site Area, PR, GFA, Site Coverage (SC) and BH of the existing six hotels in TSTE (see Table 1), which are available from the Buildings Department (BD, 2017). The data is considered when relaxing the maximum PR/BH restrictions and make appropriate determinations of designing and developing effective scenarios for 3D spatial analyses.

3.3 Generation of four scenarios

The maximum PR/BH restrictions are shown in the Lease Conditions proposed by The Land Registry (LR, 2017), OZPs proposed by the Town Planning Board (TPB, 2016), and the BPR proposed by the Buildings Department (BD, 2012). Specifically, the OZPs are statutory plans prepared by the TPB under the Town Planning Ordinance and show land zonings and major road systems for each planning scheme area. The OZPs (S/K1/28) are one of the most important regulations when considering PR/BH relaxation. There are four major types of zones in the study area: Commercial (C), Open Space (O), Government, Institution or Community (G/IC), and Other Specific Uses (OU). The use of each zone is also restricted by the maximum BH. The BPR is made under the Buildings Ordinance, which statutorily governs the planning, design and construction of buildings. The BPR is another important regulation in the consideration of the PR/BH relaxation. The BPR regulates the sites of buildings. These regulations classify the sites of buildings into three classes - Classes A, B, and C with different definitions. These regulations restrict the maximum PR/SC in terms of a building's site and height (described in regulations 20 and 21).

With careful consideration of the maximum PR/BH/SC restrictions, the relaxation of the maximum PR restrictions in OZPs is increased from 12 to 15 under the BPR, and the maximum BH restriction in the Lease Conditions is modified from the current BH (prevailing 51.5 meters) to the maximum under OZPs (80 to 95 meters). With consideration of the foregoing, four hypothetical scenarios with different PR/BH of the 23 buildings in TSTE are developed as shown in Fig. 4. Scenario 1 (S1) is the current situation, which uses the current PR/BH of the buildings; Scenario 2 (S2) is developed by maintaining the current SC, only partially increasing the PR to the maximum under BPR and by increasing the BH to the maximum under OZPs; Scenario 3 (S3) is developed by increasing the PR to the maximum under BPR with maintaining the current SC; and

Scenario 4 (S4) is developed by rebuilding all the buildings to the maximum PR under BPR and the maximum BH under OZPs. By following the four hypothetical scenarios, the 3D buildings are developed. The three scenarios S2, S3, and S4 are all reach the maximum PR and BH only with the different building shape, roof shape, SC, and the complexity and difficulty of reconstruction. The completed building models are shown in Fig. 5. However, the roof shape in S2 is difference form other three scenarios. The reason is that only part of the current building (one of the building facades) has been increased to the maximum PR/BH. The side facing the southeast was chosen to be raised to the maximum PR/BH, because it faces Victoria Harbor and so most of the rooms could have a sea view, which has extremely high commercial value.

3.4 Simulation model for solar exposure analysis

The effects of solar exposure in terms of time (hourly) on the direct insolation (excluding the diffused insolation) and the radiation energy of the insolation around the surface (land and building facades) of TSTE are investigated by using a simulation model. The solar exposure for each of the four individual scenarios is simulated. The parameters of the simulation include the date and time of simulation, coordinates of TSTE, and the solar azimuth and altitude (see Table 2).

Based on these parameters, the simulatoin model is applied in generating the footprint of shadow volume, which is represented by a bundle of sunlight (see Fig. 6a) blocked by the buildings. The generated footprints of building shadow are used as the impact boundaries (Fig. 6b) respectively in the summer and winter solstices. All the 3D buildings/roads within these boundaries are used as input for the simulation. The simulation is implemented based on Ecotect analysis software, which is an environmental analysis tool widely used in the study of daylight assessment, thermal performance, and acoustic simulation for building planning and design (Yang et al., 2014; Thuesen, 2010; Wang et al., 2011; Peng, 2016). The results of the simulation include the cumulative exposure time and radiation distributed on the 3D surface within the impact boundaries in the summer and winter solstices.

3.5 Microclimate model for analysing wind ventilation

Wind flow significantly impacts the living environment and plays an important role in urban climates, renewable energy development, and crisis management related to outward wind flow. Airflow Analyst (version 1.4) is software that helps to analyze wind ventilation, which is based on GIS and spatial data to simulate complex surrounding airflow movements. It uses a fluid dynamics algorithm, 3D Computed Fluid Dynamics (CFD), which is a core element for a highly accurate airflow analysis and was developed and tested at Kyushu University. It is the first software to integrate CFD with GIS and is available as third-party extension software of the ArcGIS (version 10.6.1). Therefore, terrain and 3D building datasets prepared in ArcGIS can be directly used in Airflow Analyst without any re-modelling of spatial data. Airflow technique of wind flow estimation is used and validated in different studies to simulate wind speed (Li, 2011; Uchida et al., 2011a, 2011b, 2011c; Uchida & Ohya, 2008, 2011).

A Digital Elevation Model (DEM) with a 2-meter spatial resolution and 3D models were used to simulate airflow in the study area using Airflow Analyst. The monthly means of wind direction and wind speed from Star Ferry Automatic Wind Station were acquired from the Hong Kong Observatory (HKO). Three computational grids were generated, corresponding to 3D scenarios (S1, S2, S3, and S4), and then subsequent fluid analysis, visualization and analysis of the results were performed.

3.6 Microclimate model for analysing air temperature

Simulation of air temperature is conducted by ENVI-met, which is a popular microclimate model that can simulate the microenvironment of a study region and is widely applied in the study of the relationships between urban design and microclimates (Toggweiler & Key, 2001; Emmanuel & Fernando, 2007; Fahmy & Sharples, 2009; Ng et al., 2012; Li et al., 2016; Jamei & Rajagopalan, 2017; Morakinyo et al., 2017). The simulation of ENVI-met considers the interaction among soil, vegetation and atmosphere based on theories of fluid dynamics and thermodynamics, with a few pre-requisites including a steady temperature and no heat storage in the buildings (ENVI-met, 2017). These conditions result in a simulation that focuses only on the physical influence instead of the anthropogenic effect. The capability of ENVI-met in simultaneous calculation of meteorological conditions, soil and vegetation processes, and surface energy fluxes with a broad range of urban configurations can also improve the simulation of an urban micro-climate (B.M, 2011; Jamei & Rajagopalan, 2017). Therefore, in this study, ENVI-met 4.1 was applied to simulate the spatial patterns and air temperature distribution in the TSTE region with different building designs (S1, S2, S3, and S4). The completed ENVI-met model of the study area is shown in Fig. 7. The expected results of the research will provide the basis for future development that take a climate conscious urban design method. This model requires initial weather information, including the direction and speed of wind, relative humidity, air temperature, and special humidity at a specific date and time (see Table 3). Two seasons (summer and winter) were examined according to the meteorological parameters and the climatological database of Star Ferry Automatic Wind Station. Two typical days 11-July-2016 and 13-Jan-2016, which represent normal weather conditions in summer and winter respectively, were selected to represent the two seasons.

The average air temperatures were 29.8°C for summer, and 16.0°C for winter (see Table 4). During the comparison of scenarios, S1 acts as a reference, while S2, S3, and S4 act as observations. Comparison values are calculated by deducting the reference values from the observation values.

3.7 Thermal comfort to the surrounding environmental changes

Thermal comfort is an important scientific basis for measuring the rationality of building/urban planning. The factors affecting thermal comfort mainly include four environmental factors (air temperature, air velocity, air relative humidity, and mean radiant temperature) and two human factors (the rate of metabolism of human body and the body clothing thermal resistance). This study analyzed the changes in thermal comfort environmental factors brought about by various building design scenarios with different PR/BH. To measure the degree of perceived changes in the surrounding environment by the residents living in and nearby the area, three related indexes were introduced: mean skin temperature (MST), apparent temperature (AT), and thermal comfort index (TCI). All three indexes are related to air temperature, wind speed, and relative humidity, but only air temperature and wind speed were changed according to the different PR/BH for various scenarios.

3.7.1 Mean skin temperature

Under naked conditions, the temperature of the human skin surface responds well to the comfort of weather. When the surface temperature is between 35℃ to 37℃, people will feel hot. It is commonly considered that 33℃ to 34℃ is most suitable, while 31℃ to 32℃ will cause a cold feeling. The formula for calculating the body surface temperature can be obtained by the following estimation process.

When the human body temperature T is 37℃, skin layer thickness d is 5mm, T_s is skin surface temperature, and T_a is air temperature, the heat transferred from the human body to the skin Q should be (Koichiro, 1961):

$$Q = k \times \frac{T - T_s}{d} \times S \tag{1}$$

Where k is coefficient of heat conductivity, which is approximately equal to 2.0921 x 10-3J/(cm-1·s·℃), and S refers to an area of skin equal to 1 m^2. The heat generated by the human body (Q) needs to be transmitted to the atmosphere to stabilize the body temperature and may include radiation, transmission and evaporation. Therefore, the following formulas can be established.

$$Q = Q_{radiation} + Q_{transmission} + Q_{evaporation} \tag{2}$$

$$Q_{radiation} \approx 20.92 \times (T_s - T_a)$$

$$Q_{transmission} \approx 87.03 \times \bar{V} \times (T_s - T_a)$$

$$Q_{evaporation} \approx 18.74 \times \bar{V} \times (E_s - r \times E_a)$$

Where the unit of temperature is ℃, V is the wind speed at the height of the human body, E_s is the saturated water vapour pressure on the surface of the human skin, E_a is the saturated water vapour pressure corresponding to the temperature, r is the relative humidity of the air, and the unit of Q is kJ/m^2·h.

Based on equations (1) and (2), equation (3) can be calculated as follows:

$$T_s = T - Q \times d/k \tag{3}$$

3.7.2 Apparent temperature

AT is the temperature equivalent perceived by humans, which is a heat index invented in the late 1970s and extended in the early 1980s by an Australian researcher named Robert Steadman who took four environmental factors into consideration: temperature, vapour pressure, wind speed, and relative humidity. According to Steadman's study (Steadman, 1984), the formula (4) for calculating AT is:

$$AT = 1.07T + 0.2e - 0.65V - 2.7 \tag{4}$$

$$e = \frac{RH}{100} \times 6.105 \times exp\frac{17.27T}{237.7 + T}$$

Where AT is apparent temperature (℃), T is temperature (℃), e is vapor pressure (hPa), V means wind speed (m/s), and RH is relative humidity.

3.7.3 Thermal comfort index

TCI is another topic that reflects human's satisfaction with the surrounding environment. When the heat produced by human metabolism is allowed to consume or dissipate, thermal neutrality is maintained, thereby maintaining a balance with the surrounding environment. Although there are great differences from individual to individual in terms of physiological and psychological satisfaction, main factors that directly affect thermal comfort can be divided into two categories. One category is personal factors, which are characteristics of the occupants such as metabolic rate and clothing level; the other category is environmental factors, which are conditions of the thermal environment, namely air temperature, air speed, and humidity. Based on Wu and Deng's study (2001), the equation for calculating TCI is:

$$I = 1.8 \times T + 0.55 \times (1 - RH) + 32 - 3.2V^{0.5} \tag{5}$$

Where I means the thermal comfort index, T means temperature (℃), RH is relative humidity, and V means wind speed (m/s).

4. Impact analysis and results

4.1 Solar exposure analysis and results

The solar exposure analysis for both summer and winter was investigated for the study area. Compared with winter, the solar exposure effect in summer is more obvious. Therefore, only the analysis and results for summer are presented and discussed in this paper; winter results can be found in the research monograph (Shen et al., 2017). Fig. 8 shows the patterns of solar exposure on 3D surfaces (shadow footprint and building facades) in terms of ten hourly sections (from cold to warm colours) of direct insolation. The findings show that the buildings' roofs are exposed to the sun for a longer time (around 9 to 10 hours) than the ground surfaces are (around 4 to 5 hours). The reason is that the ground is shaded by the surrounding high-rise buildings for most of the time during the day. To quantify the difference between four scenarios, the differences of the corresponding pattern areas and the value of each individual pattern area of the four scenarios are shown in Fig. 9. The difference between S2 and S1 is in the range of -10% to 2.5% for the time of exposure. The reduced area is mostly in the (9, 10) hourly section. Specifically, the area exposed by (9, 10) hour insolation in S1 is decreased by 10% with increasing PR/BH in S2, and the area exposed by (8, 9) hour and (4, 5) hour insolation in S1 is increased by 2% and 2.5% in S2, respectively. Similarly, the difference between S3 and S1 is in the range of -3% to 2% for the time of exposure and the difference between S4 and S1 is in the range of -4.2% to 1.5% for the time of exposure. All the trends of change are similar for the three difference lines. And the changes show no significant impact of the PR/BH relaxation on the summer solar exposure. It is noted that the difference between S2 and S1 is larger than others, a reasonable explanation being that the roof area is much smaller than the other three scenarios due to differences in design among the four scenarios; the additional increased building height in S2 also blocks the original roof area in S1. Therefore, the roof areas that received the longest sunlight hours (around 9 to 10 hours) were significantly reduced in S2 compared to S1. However, the roof shape is similar in S1, S3, and S4 because the increased buildings block part of the roof of the buildings that are lower than them and part of the ground, meaning that the areas exposed by the longest sunline hours was slightly decreased and the middle sunlight hours increased.

Fig. 10 shows ten sections of cumulative solar radiation energy in summer, while Fig. 11 show the differences of the corresponding pattern areas and the value of each individual pattern area of the four scenarios. The difference between S2 and S1 is in the range of -11% to 2% for the cumulative radiation energy. The reduced area in S2 is mostly in (5760, +∞) the Wh radiation section, which corresponds to the longest sunlight hours. The area exposed by (2340, 2910) Wh insolation in S1 is decreased by 2% compared to S1. The difference between S3 and S1 is in the range of -3% to 1% and the difference between S4 and S1 is in the range of -5% to 2% for the cumulative radiation energy. Both of the differences are similar, and they are smaller than the difference between S2 and S1, with the trend similar to the sunline exposure.

The above results showing the overall situation of insolation in terms of time and radiation, indicate that the shading effect phenomenon becomes larger after PR/BH relaxation. The shading effect exists after mid-day and enhancement of the shading effect from the PR/BH relaxation has a positive impact on the life extension of facade materials. Furthermore, the shape and area of the building roof plays an important role in exposing the longest sunline hours.

4.2 Wind Ventilation Analysis and Results

Wind ventilation analyses were conducted and compared for both winter and summer. Since wind speed in summer is relatively slower than in winter, only winter results are shown in this paper. Accordingly, Fig. 12 shows the differences of four scenarios of winter wind speed at the corresponding locations. The differences are mainly in the range of -1 m/s to 1 m/s between S2, S3, S4, and S1 and only a small portion falls within the range of -5 m/s to -4 m/s or 4 m/s to 6 m/s. As indicated by the shades near the buildings, wind speed is slightly increased in S4 in the TSTE area. Compared to the other three scenarios, S4 is designed by rebuilding all the buildings to the maximum PR/BH leading to a decrease in the area of most of the buildings and a subsequent reduction in the SC. Therefore, the space between each building has increased accordingly and the extra space can be used for green plants. This shows that widening the distance between buildings in S4 permits more air flow in TSTE, which increases the wind ventilation in the area. Although the wind speed patterns are similar for the four scenarios, increases of wind speed are more prominent during the winter season when the wind is entering TSTE. However, since most of the difference is within 1m/s, it can be concluded that there is no significant impact of the PR/BH relaxation on the winter wind ventilation.

Distributions of wind flow direction during the winter season are shown in Fig. 13. As shown in the figure, wind comes from the east and enters the TSTE area from gaps between the buildings and circulates into the northern TSTE area (ellipse A), which is primarily located at the Urban Council Centenary Garden area. This garden provides a significantly important corridor of wind inflow to the TSTE regions during winter. However, the area highlighted with ellipse B indicates that wind could not enter the TSTE area through the narrow gaps and would bounce back from the buildings to become wind flow along the harbour rather than flowing into the area; this phenomenon is enhanced in S2, S3, and S4. On the other hand, wind circulations inside the TSTE area creates a strong outward wind flow from west to northeast and southeast, highlighted with ellipse C, which seems to be reflected by the closely spaced building on the western side of Nathan Road. It is evident that wind circulation is improved in S4 as compared to S1, S2, and S3 due to the wider spaces between buildings.

4.3 Air temperature analysis and results

The simulation results of air temperature for each scenario were extracted at 1:00 am and 1:00 pm on the representative day of winter and summer seasons. Due to the high air temperature on summer afternoons, only the analysis and results during this time are presented in this section. In summer, the prevailing wind direction is from the west. As shown in Fig. 14, air temperatures on a summer afternoon range from ≤ 30.0°C to > 38.0°C and the spatial patterns of the air temperature indicate warm to cold fringes from the southwest to the northeast. And, temperatures in TSTE, and most of the study areas (around 95%), lie in the temperature range of 32.0°C and 36.0°C in all scenarios.

Spatial patterns and distribution analysis of air temperature on summer afternoons are shown in Fig. 15. A colour legend is designed to present changes in air temperature due to the changes in building dimension corresponding to the different scenarios. The temperature range (-0.20°C to 0.20°C) is considered as insignificant, while changes in air temperature beyond this range, i.e., below -0.20°C or above 0.20°C, are deemed as significant changes. There is no notable change in S2 and S3 temperatures when compared to S1, with most of the area within an insignificant range of -0.20°C to 0.20°C respectively. However, compared to S1, there is an uncharacteristic pattern of change in S4 as a relatively higher temperature is observed in the southeast of the study area. This might be due to the fact that the prevailing wind direction in summer is from the west and the increased height in building increases and expands the air temperature regime. However, most of the regions with increased temperature lie over the coastal region, away from the core study area.

4.4 Thermal comfort analysis of the surrounding environmental changes

Three related thermal comfort indexes were calculated to measure the reaction of human feelings to the surrounding environmental changes brought about by minor relaxation of the maximum PR/BH in the study area. The air temperature and wind speed for various scenarios was obtained from the CFD simulation results in sections 4.2 and 4.3. The air temperature and wind speed of S1 and S4 were obtained from CFD simulation results and are shown in Table 5. S1 and S4 were taken as examples, because S1 is the original lowest PR/BH and S4 is a hypothetical case with the maximum RP/BH. The relative humidity for the winter and summer in 2016 are available on the Hong Kong Observatory website at Star Ferry Automatic Wind Station, which is near the study area (HKO, 2016). Three human feelings indexes, MST, AT, and TCI were calculated using the equations listed in section 3.7 with the results shown in Table 6. The human comfort index classification is shown in Table 7.

As can be seen from the human feeling indexes, AT is the most sensitive indicator. Therefore, AT is referred to as the main index to verify the changes in human feelings brought about by PR/BH changes of surrounding buildings. AT is much larger in summer (about 8^{o}C) than the air temperature, while the difference between AT and air temperature is small in winter (about 2^{o}C). The large difference between AT and air temperature is mainly related to the high air temperature in the summer, while the air can hold much more specific humidity due to the high air temperature (see the term of e in Equation 4). After comparison, the difference between S1 and S4 on MST, AT, and TCI are very small both in winter and summer. In short, there is a minor effect on human feelings when the PR/BH of buildings are increased to the maximum. In Hong Kong, people will feel comfortable in winter, while people will feel very hot or extremely hot in summer. This is the reason why air temperature, wind ventilation, and heat island effects need to be considered when conducting urban development or redevelopment.

5. Discussion

Solar exposure, wind ventilation, and air temperature were all analyzed in this study, along with a comparison of calculated human thermal comfort in relation to surrounding environmental changes. Some of the analyses in this study are similar to the ones in the pilot study of PR/BH relaxation for residential/mixed use buildings in KTDA. However, the results represent the development potential in TSTE where existing buildings, including six hotels, are in densely built commercial zones rather than in residential zones that are still under construction as in the KTDA. Therefore, the findings of this study are more representative of the issues in the compact development of a high-density city and also more supportive of maintaining social-economic development in a suitable manner.

This study used ENVI-met for simulating air temperature and wind ventilation in the TSTE and surrounding areas. Notwithstanding the promising results, there are nevertheless limitations to this study: (i) the study simulated the influence of PR/BH on air temperature and wind ventilation only, we did not consider the impact of water bodies, vegetation, transport, and human activities in this study. However, water bodies, vegetation, transportation and human activities will have corresponding impact on the thermal environmental changes. Through verification and application research with various configurations, the evaporative cooling effect from water surfaces in a micro-environment was evaluated by Tominaga et al. in 2015. Finally, a numerical analysis was carried out combining CFD and radiative heat transfer analysis to predict the thermal environment around residential neighborhood with a pond. The results showed that the maximum temperature decrease due to the water body was around 2 °C at the pedestrian level. Besides, Park et al. (2012) investigated the mitigating effect of vegetation on the urban microclimate for decades. The results revealed that the presence of four sidewalk trees reduces the wind speed inside the canopy by up to 51%. Trees along the sidewalk also decrease the globe temperature; the reduction is attributed mainly to the decrease in radiation flux resulting from the shade they cast. The development of Green Deck project and its influence can also be addressed in terms of transportation. In the past, the relationship between “built environment” and people’s travel behavior has been explored and confirmed (Ni and Loo, 2012). To express the built environment, one way is to adopt the yellow boundary 3Ds (Density, Diversity, and Design) first advanced by Cervero and Kockelman (1997).

Furthermore, Yue et al. (2008) used remote sensing and GIS technologies to research on the relationship between the spatial-temporal change of thermal environment and human activities in Shanghai. They applied Spatial Principal Component Analysis (PCA) methodology to analyze the spatial pattern of the urban thermal environment and its influencing factors. The results revealed urban construction density, population density, industry distribution, types of underlying surface, and urban landscape diversity were the main factors affecting the urban thermal environment in downtown area of Shanghai; (ii) meteorological data were obtained from the nearest observation stations in the TSTE area instead of from the specific sites being considered; and (iii) default rather than specific values were applied for soil properties and water content. Although as a consequence of the limitations the simulation results may not be accurate enough for absolute quantification, they are sufficiently accurate for studying relative differences. Furthermore, although ENVI-met may not be capable of deriving rigorous quantitative results at a specific time, it can nevertheless accurately depict the trend of changes (Maggiotto et al., 2014).

The findings show that the potential of GFA increases among TSTE's 23 buildings is 208,493.297 m^2, as shown in Fig. 16. Taking the six hotels as an example, the GFA increased from 207,220m^2 to 260,261m^2 after PR/BH relaxation, with a net increase of 53,041m^2. The number of rooms for the six hotels increased by 892, which together can hold 1,784 more guests. It should be noted that the effects of traffic capacity and noise were not analyzed in this study.

6. Conclusions

This study was carried out against the background of the Green Deck plan. It investigated the development potential of TSTE in terms of the PR/BH relaxation of buildings for increasing the capacity of living and working spaces to meet the increased population flow whilst preserving the environment. The impacts of the PR/BH relaxation on the environment of the study area were assessed in respect of solar exposure, wind ventilation, and air temperature. The analyses and the corresponding results are as follows.

(1) In summer and winter solstices, the effect of the PR/BH relaxation on solar exposure was analyzed, both of which have extreme duration of solar exposure. However, for representative purposes only the results in summer were shown in this paper. The patterns of solar exposure in terms of sections of time and cumulative radiation energy were generated for S1, S2, S3, and S4. The differences (S1 vs S2, S3, and S4) of the corresponding pattern areas indicate the enhancement of shading near the building footprint areas and this effect is positive for the life extension of facade materials; it was also found that the shape and area of the building roof seriously affect the longest sunline hours and corresponding radiation energy. Compared to S1, the areas exposed by sunline hours between 9 to 10 hours sharply declined in S2, while slightly decreasing in S3 and S4. Correspondingly, the areas exposed by sunline hours between 3 to 5 hours are slightly increased in S2, S3, and S4. The trend of radiation energy is similar.

(2) Wind ventilation was simulated in S1, S2, S3, and S4 respectively in summer and winter. However, only the results in winter were shown in this paper. The comparison (S1 vs S2, S3, and S4) shows a small range of wind speed change from -1 m/s to 1 m/s for both seasons and the S4 is more ventilated (higher wind speed) for the wind as the SC of the buildings is narrowed, which release more space between buildings. The wind direction is not significantly changed after the relaxation.

(3) Air temperature was analyzed in S1, S2, S3, and S4 respectively in both day (1:00 pm) and night (1:00 am) and in both summer and winter. Similarly, only the summer afternoon results were present in this paper. The differences (S1 vs S2, S3, and S4) imply a minus

range of air temperature change [-0.2°C, 0.2°C], which is a not insignificant zone of change, for both time and seasons from S1 to S2, and S3. The southwest area has a change by more than 0.4°C from S1 to S4 in summer as the speed of the west wind carrying heat to TSTE is improved by the widened spacing between buildings. A relatively higher temperature is observed in the southeast of the study area which is close to Victoria Harbour.

(4) MST, AT, and TCI were indexes used to represent the human thermal comfort reaction to changes in the surrounding environment of the study area. There is no significant difference between S1 and S4 for all three indexes both in winter and summer. However, a large difference was found between AT and the initial air temperature in summer, since the temperature and specific humidity are much higher at that time. It can therefore be concluded that AT is the most sensitive of the three indicators.

In summary, an appropriate relaxation of the PR/BH in the study area has no significant negative impact on environmental issues or people. On the contrary, the increased GFA and associated hotel rooms could alleviate the problem of increased tourists in the area resulting from construction of the proposed Green Deck. Furthermore, the research methodology employed in this study is suitable for application to other districts in Hong Kong or other high-density cities with the similarity throughout the world.

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Data availability statement

All the data support the findings of this study are available from the corresponding author upon rational request.

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Figure captions list

Fig. 1. Comparison of Green Deck blueprint (a) and Cross Harbour Tunnel plaza (b)

Fig. 2. Framework of this study

Fig. 3. Study area (a) and DTM covered Kowloon and Hong Kong islands (b)

Fig. 4. Four hypothetical scenarios

Fig. 5. 3D buildings in the four scenarios

Fig. 6. Shadow and corresponding footprints of exposure in summer and winter solstices, (a) building shadow in summer and winter solstices, and (b) footprints of building shadow

Fig. 7. ENVI-met 3D model of the study area (a) and corresponding footprint (b)

Fig. 8. Patterns of summer solar exposure in terms of hourly sections of insolation

Fig. 9. Differences of corresponding pattern areas in relation to time of exposure in summer

Fig. 10. Patterns of summer solar radiation energy (Wh)

Fig. 11. Differences of corresponding pattern areas in relation to radiation energy in summer

Fig. 12. Differences of winter wind speed at corresponding locations

Fig. 13. Wind speed and prevailing wind direction in each scenario in winter

Fig. 14. Spatial patterns of summer (1:00 pm) air temperature in each scenario

Fig. 15. Spatial patterns of differences in summer (1:00 pm) air temperature

Fig. 16. GFA before and after the PR/BH relaxation for the buildings in the study area

Tables list

Table 1. Buildings plan for the six hotels in the study area

No.	**Building name**	**Site class**	**Zone**	**Site area (m^2)**	**PR (total)**	**GFA (m^2)**	**SC (%)**	**BH (m)**	**OZPs (Max)**		**BPR (Max)**	
									PR	**BH (m)**	**PR**	**SC (%)**
1	Kowloon Shangri-La	C	C	4000.000	11.599	46383.644	74.079	47.10	12	80.0	15	65
2	InterContinental Grand Stanford			2479.000	10.540	26128.660	75.000	47.00				
3	New World Millennium			2850.000	11.832	33718.948	74.253	47.96				
4	The Royal Garden			2219.600	14.993	33278.630	74.960	62.60		95.0		
5	Regal Kowloon Hotel			2560.000	12.401	31746.004	74.767	49.00				
6	Hotel ICON		G/IC	4000.000	8.991	35964.050	64.960	107.00	-	111.5		

Table 2. Parameters of simulating the solar exposure in TSTE

Parameter	Winter Solstice (22-Dec-2013)	Summer Solstice (21-Jun-2013)
Time	8:40 - 16:00	7:15 - 17:32
Coordinates	22.30° for Latitude	114.10° for Longitude
Azimuth	127°SE - 232°SW	72°ENE - 288°WNW
Altitude	20°	20°

Table 3. Configuration setting in ENVI-met

Initial Configuration	11-Jul-2016 (Summer)	13-Jan-2016 (Winter)
Start Time of Simulation	7:00am	7:00am
Total Simulation Time (Hour)	24	24
Wind Speed in 10m Above Ground (m/s)	2.70	3.42
Wind Direction (degree)	West (260°)	East (100°)
Initial Atmosphere Temperature (°C)	27.50	15.45
Specific Humidity in 2500m (g water/kg air)	10.42	5.24
Relative Humidity in 2m (%)	83	85

Table 4. Meteorological elements and climatological database by HKO in 2016

Meteorological elements	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Average Wind Speed (km/h)	29.4	21.3	22.8	17.1	20.2	18.0	19.2	17.1	18.9	26.3	27.0	26.7
Prevailing Wind Direction (degree)	60	20	50	40	70	220	230	60	80	70	70	70
Average Air Temperature (°C)	16.0	15.5	17.5	23.6	26.7	29.4	29.8	28.4	27.9	26.8	22.3	19.6
Date	13-January-2016						11-July-2016					
Average Wind Speed (m/s)	3.42						2.70					
Prevailing Wind Direction (degree)	100°						260°					

Table 5. Initial values of air temperature, wind speed and relative humidity

Date	Air temperature (°C)		Wind speed (m/s)		Relative Humidity (%)
	S1	S4	S1	S4	
13 January 2016 (Winter)	19.798	19.79	0.9352	1.0325	85
11 July 2016 (Summer)	33.6725	34.062	0.7325	0.7534	83

Table 6. Human feelings indexes - MST, AT, and TCI

Date	MST (°C)		AT (°C)		TCI		Human feelings	
	S1	S4	S1	S4	S1	S1	S1	S4
13 January 2016 (winter)	19.32	19.30	21.81	21.73	66.84	66.83	Comfortable	Comfortable
11 July 2016 (Summer)	32.69	33.06	41.55	42.14	89.37	90.01	Very hot, people feel very uncomfortable	Extremely hot, people feel extreme uncomfortable

Table 7. Human comfort index classification [Bai et al., 2009]

Thermal comfort index	Grade of physiological stress	Thermal perception
>=90	Level 9	Extremely hot, people feel extremely uncomfortable
[85-90)	Level 8	Very hot, people feel very uncomfortable
[79-85)	Level 7	Hot, people feel uncomfortable
[70-79)	Level 6	A little hot, some people feel uncomfortable
[60-70)	Level 5	Comfortable
[50-60)	Level 4	Cool, some people feel uncomfortable
[40-50)	Level 3	A little cold, most people feel uncomfortable
[25-40)	Level 2	Cold, people feel uncomfortable
<25	Level 1	Very cold, people feel very uncomfortable