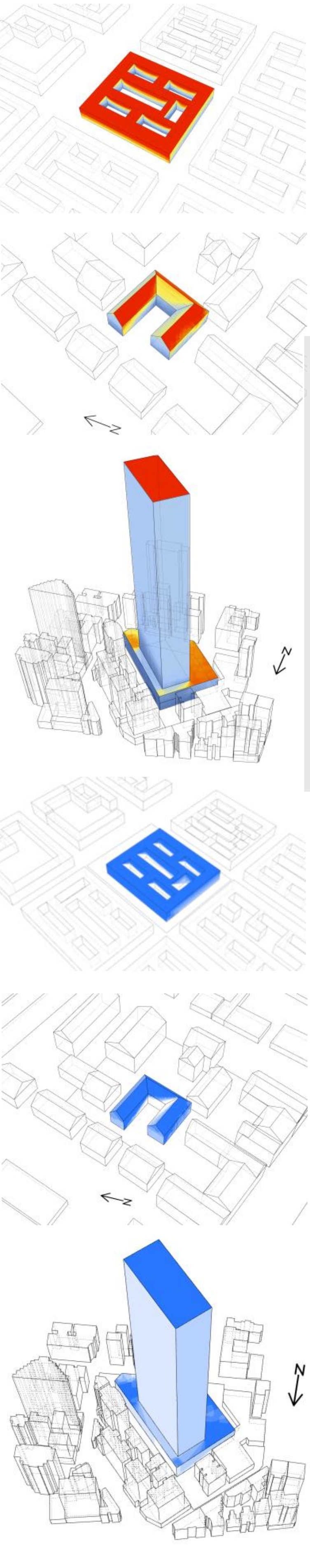

SOLAR ACCESS POTENTIAL AFFECTED BY URBAN PLANNING AND BULIDING DESIGN

A parametric study in the urban context

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Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

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The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Keywords: Daylight, urban planning, solar access potential, sun hours, vertical sky component, vertical daylight illuminance, solar irradiation, parametric analysis, Berlin, Copenhagen, Hong Kong

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Abstract

In the initial stage of planning, considering the solar impact of urban layout on the building can effectively avoid some irreversible design issues, improve the indoor environment, and reduce energy demand. The typical architectural models of three representative cities (Copenhagen, Berlin and Hong Kong) were selected as the analysis cases in this study. By analysing several sunlight and solar metrics via Grasshopper in Rhino, at first, we can know if they meet local regulations. Those mentioned metrics included annual solar irradiation, heating season irradiation, vertical illuminance, sun hour, vertical daylight factor, vertical sky component and shadow cast aerial view. Then a few urban parameters with greater influence on passive and active solar potential were selected to carry out a parametric study. By comparing the results, we can know how building geometry and urban layout affect the solar potential and which parameter contributes the most in these three cities. Through this research, we can provide suggestions to urban planners or architects that help them make decisions in the early stage of city planning about passive and active solar potential considering building shape, density, roof inclination and material of building envelope.

Acknowledgements

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Nomenclature

VSC	Vertical Sky Component [%]
VDF	Vertical Daylight Factor [%]
VDI	Vertical Daylight Illuminance [lx]
SI	Solar Irradiation [kWh/m^2]
HSI	Heating Season Irradiation [kWh/m^2]
SH	Sun Hours [h]

Abbreviations

BBR	Boverkets Byggregler
BREEAM	BRE (Building Research Establishment) Environmental Assessment Method
CIE	Commission Internationale de l′ Éclairage
LEED	Leadership in Energy and Environmental Design
CBDM	Climate-based Daylight Modelling
WMO	World Meteorological Organization
FAR	Floor Area Ratio

1 Introduction

1.1 Background

Nowadays, around 55% of the world's population lives in urban regions and this proportion is predicted to rise to 68% by 2050 (United Nations, 2019). This circumstance indicates that more buildings will be constructed in cities in the future. However, the limited available urban space has already led to the form of new neighbourhood configurations, which only set awareness to the population density increase (Fernández-Ahumada et al., 2019). For example, narrower streets, more buildings, smaller courtyards appear in modern cities. These dense and compact urban settlements make the environment complex, where daylight availability and solar access can be scarce (López et al., 2016).

In regard to the importance of daylight, two aspects must be stated: human and energy. Firstly, daylight has a positive effect on human's emotional and physical well-being and also the efficiency of the occupants (Edwards & Torcellini, 2002). Also, the passive daylight acquirement has favourable social impacts as well (Dogan et al., 2012). Then in terms of the energy perspective, sufficient daylight access has the potential to reduce the electricity consumption for artificial lighting by 20–30% in office buildings (Chirarattananon et al., 2002) and by 10% in residential buildings (Lam, 1996).

Utilising solar energy actively through Photovoltaic panels (PV) and solar thermal systems (ST) is an effective measurement to produce renewable energy and to cut carbon dioxide emissions. In European countries, buildings account for around 40% of the total energy use (Allouhi et al., 2015). Therefore, solar energy plays a fundamental role in lowering energy consumption especially in building industry.

Studies show that architects became more interested in daylighting in 1970's after the oil crisis (Nasrollahi & Shokri, 2016), and currently, lots of architects participate in the practice of solar-integrated architecture design stated by (Kanters et al., 2013).

Nevertheless, architects always only contribute to the building design phase but the decisions taken during the early stages of urban planning, where building design is not the focus, have a greater impact on the following phases and the further building performance (Kanters & Horvat, 2012). This is due to that solar and daylight availability and potential is strongly related to buildings' geometry and configuration which are decided to a large degree during the urban design process (Chatzipoulka et al., 2018). Specifically, according to (Kanters & Wall, 2014), early design decisions are normally made when the zoning plan is structured. A zoning plan is a legal instrument for urban planners to set up certain boundaries of the land use, open spaces, street dimensions, buildings' density, function and rough geometry.

For all these reasons, a thorough knowledge of the available daylight level and solar irradiation on the roofs and façades of buildings together with that of open areas in urban context including courtyards, key streets and city gardens is necessary at the early design phase. This research focuses on this issue and attempts to conduct a comprehensive parametric study based on different case studies of urban context producing general knowledge and experience to urban planners that help them to make early decisions for the purpose of enlarging daylight access and solar harvest.

1.2 Objectives and aims

The overall aim of this research was to provide the involved urban planners with some support and recommendations regarding daylight access and solar energy implementation potential at the early design phase, which were expected to help them to take well-informed decisions in the future work. It was achieved by assessing several daylight metrics and solar irradiation parameters through a multi-objective parametric analysis in typical city forms and at last some regularities were found.

Main research questions were listed:
1) Does the building daylight standard fit its corresponding urban status quo?
2) How does the building geometry and urban layout affect the passive and active solar energy potential?
3) Which parameter contributes the most to the solar potential? Is it different for different city cases?

1.3 Scope and limitations

The research limited its scope to investigating the daylight and active solar energy (PV/ST) availability of selected typical building blocks in three cities: Copenhagen in Denmark, Berlin in Germany and Hong Kong in China. This is because that these three cities are distinct and representative in regard to their urban planning (building form) styles. Specifically, Copenhagen is a city with low-rises in a scattered distribution, Hong Kong is quite compact with numbers of skyscrapers and Berlin's urban form is in between: moderate-width streets and regular building configuration. Moreover, some urban public space was chosen to conduct passive solar access evaluation. For the PV/ST part, only architecture-integrated systems were considered while solar plants or ground-mounted solar systems were excluded.

Further limitations were:

- This research was adaptable for the circumstances of studied cities mentioned above indicating that the results can only be applicable in the regions with similar climate characteristics and urban planning style. However, the methodology of the daylight and solar potential studies can be applied globally.
- The urban context model was theoretical and did not consider any adjacent vegetation or other obstructions such as urban infrastructure facilities or terrain conditions. Only buildings were included in the model.
- The buildings' geometries were simplified and abstract in box-shaped without any protrusions like balconies or shading devices or any detailed façade designs.

2 Literature review

The literature review contains two parts: independent variables and dependent variables. The former is about the parameters of the building itself, and the latter is about the parameters of daylight performance.

2.1 Review of independent variables

These independent variables were the ones chosen for the parametric analysis in this study, which can affect the daylight performance parameters from the urban perspective. The following are the independent variables that were investigated in this project.

2.1.1 Density of the urban context

Planning a group of buildings in a city is not as simple as putting them together with a distance. In other words, the pursuit is not density itself, but the quality that dense urban environments provide in the form of work, sports, cultural activities, etc.

With the rapid population growth in cities and larger communities, housing shortages have appeared in many cities around the world. To solve this problem, it is necessary to build more houses, but before that, the life quality of the residents should be considered in the planning of a city or community.

According to a survey on urban life (Boverket, 2017), maintaining an appropriate distance between the open spaces and the residence is considered the main comfort factor affecting the lives of urban residents. At the same time, dense building groups will make it difficult to meet the daylight requirements of a building, while having sufficient access to daylight is a very important part of the later architectural design.

Therefore, a good urban planning not only ensures a good large environment of the buildings, but also provides a good foundation for achieving the design goals of the architecture design (Boverket, 2017).

Regarding how to measure the building density of a city or community, the concept of floor area ratio is widely used. The floor area ratio (FAR) is a measure of the size of a building related to the plot on which it is located. FAR is expressed as a decimal number. FAR is an effective method for calculating the total volume of buildings on a development site, and is widely used in combination with other development standards (such as building height, plot coverage, and plot area) to encourage the layout and development forms that communities expect. It is calculated as shown in (eq.1). In this case, a higher FAR indicates a larger building volume (Metropolitan Council, 2015).

$$\mathrm{FAR} = \frac{\mathrm{G}}{\mathrm{B}} \qquad \text{(eq.1)}$$

In which
Total floor area (G) = Sum of floor area of all floors above ground
Total buildable land area (B) = Constructible land area

To calculate the FAR using the total building area and buildable land area, should follow these steps:
Step 1. Determine the total buildable land area of the site in square meter. The constructible land area is the part of the development site that can be legally and reasonably constructed, so public streets, wetlands and sewers, and other restrictions will not be included.
Step 2. Determine the floor area of each floor of the building. Calculate the total floor area of the building, which is the sum of the floor area of each floor.
Step 3. Calculate the floor area ratio. Divide the total floor area by the total buildable area.

2.1.2 Shape of the building

Daylighting planning has different goals at each stage of the architectural design, and for the conceptual design phase, daylighting design will affect or be affected by the shape of the building, including the proportion of the building dimension, location and size of the inner courtyard, etc.

Studying the shape of the surrounding buildings on the building site can enable designers to know the solar potential of the building envelope, and can help architects to design the shape of the building itself and allocate floor area according to the daylight condition. In many cases, the building is self-blocking, so the physical design of the building itself and the surrounding buildings are important factors affecting the daylight conditions (Reinhart, 2018).

2.1.3 Material of the envelope

The façade material of surrounding buildings affects the reflected sunlight distribution can be obtained. For the study of Vertical Daylight Factor (VDF) and Vertical Daylight Illuminance (VDI) in this report, the material reflectance of the surrounding building facades has an important effect on the results. Therefore, by analysing the influence of different building materials on lighting conditions, it can help architectural designers optimize the form and material selection of building envelopes.

2.1.4 Roof inclination

As the fifth facade of the building, the roof surface plays an important role in providing sufficient building interior lighting as it is more difficult to be blocked than the building facades. Proper roof inclination is an important factor affecting indoor lighting. It can not only provide a better lighting environment for designing atriums or roof windows, but also provides the possibility of installing PV solar panels or solar hot water systems on the roof. In addition, whether there is an inclination angle and the specific inclination angle should also consider the actual situation in the local area. For example, flat roofs are popular as an accessible space for drying foods in some relatively dry areas of China. But people from the south part who live in humid environments prefer a sloping roof that doesn't collect water. In this study, only the effect of roof slope on the indoor lighting environment is considered.

2.2 Review of dependent variables

The key daylight performance indicators are mainly divided into two parts: illuminance and irradiation. The different mentioned performance metrics come from different handling methods of these variables.

The followings are the dependent variables that were investigated in this project.

2.2.1 Illuminance metrics

Illuminance measures the amount of light that a surface can receive. The unit of it is in SI-unit [lx] or lumens per m^2 [lm/m^2]. Illuminance is one of the most widely used measurements of light currently to determine daylight availability in both interior and exterior. These measurements were assessed under overcast Commission Internationale de l′ Éclairage (CIE) standard sky, which influenced by location, climate, and orientation. Thus, they are mostly adopted as static metrics.

2.2.1.1 Vertical daylight illuminance

In photometry, illuminance [lx] is defined as the density of luminous flux incident on a surface (King, 2002), and daylight illuminance measures the illuminance with the sun and the sky as the main lighting sources. Eq.2 (Tregenza &Wilson, 2011) illustrates the contribution to the illuminance on a point of a surface from a sky patch:

$$\mathrm{E_{ki}} = \mathrm{L_i} \cdot \mathrm{s_i} \cdot \mathrm{d_{ki}} \;\; [lx] \qquad \text{(eq.2)}$$

In which
k: receiving area; *i:* sky zone number; L_i: luminance of the sky zone; s_i: angular size of the sky zone; d_{ki}: daylight coefficient.

The majority of current studies focuses on the daylight illuminance of the interior horizontal workplanes during the building design stage. A certain level of indoor illumination is suggested, for example 300 lx and 500 lx on office tables for computer-based and paper-based work respectively (Konis & Selkowitz, 2017). However, in the urban planning phase, without detailed architectural layout, an overall prediction of the future indoor illuminance is still needed, which can be achieved by establishing a relationship between the indoor and outdoor daylight illuminance levels. *Figure 1* (Tregenza & Wilson, 2011) describes the construction of vertical daylight illuminance.

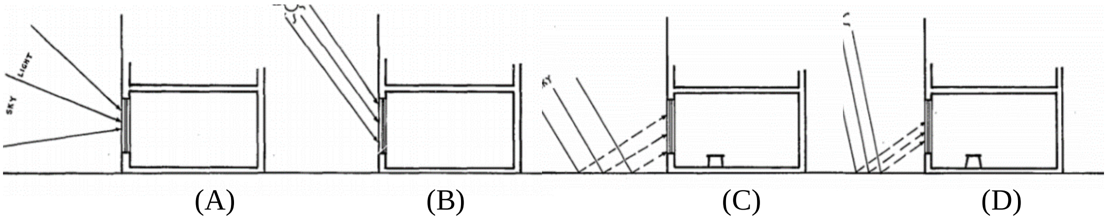


Figure 1 Illumination on vertical surfaces from sky vault (A), direct sunlight (B), ground-reflected skylight (C) and ground-reflected sunlight (D).

A simplified method (eq.3) to estimate the exterior daylight illuminance threshold is proposed by (Compagnon, 2004). It means that the imagined indoor work plane can be sufficiently lit by sunlight solely if the vertical illuminance exceeds the calculated threshold. In this method, all constructive details including room size, window-to-wall ratio, glazing transmittance and indoor surface reflectance are not necessarily specified.

$$E_{threshold} = \frac{E_W}{CU}\ [lx] \qquad \text{(eq.3)}$$

In which
E_W: the required illuminance on the indoor work plane, which is typically 500 lx.
CU: the coefficient of utilization taking into account all construction parameters mentioned above, which is commonly set as 0.05 for vertical openings.

2.2.1.2 Vertical Sky Component

The Building Research Establishment has defined the Vertical Sky Component (VSC) as the ratio of illuminance received directly from a standard CIE overcast sky at the sample points' locations to illuminance received on a horizontal unobstructed plane (Helliwell, 2012). The reflected light was not included in VSC, either from the ground or surrounding constructions.

The VSC can show how the amount of daylight that reaches the facades of the buildings which can be affected by the environment. The maximum VSC value of a roof surface is 100% and close to 50% of a vertical wall. The formula was shown below in (eq.4).

$$VSC = \frac{Es}{Eh} \times 100\%\ [\%] \qquad \text{(eq.4)}$$

In which
E_s =the light directly from the sky [lx]
E_h=the horizontal illuminance of an unobstructed sky [lx]

2.2.1.3 Vertical daylight factor

The vertical daylight factor (VDF) is defined as the ratio of the total amount of illuminance that falls onto a vertical surface to the illuminance of a horizontal surface under CIE standard overcast sky (Li et al., 2009). It considers the Sky Component (SC), Obstruction Reflected Component (ORC) and Ground Reflected Component (GRC) which is calculated as (eq.5).

$$VDF = \frac{Es + Erb + Erg}{Eh} \times 100\%\ [\%] \qquad \text{(eq.5)}$$

In which
E_{rb}= the reflected light from buildings around [lx]
E_{rg}= the reflected light from ground [lx]

2.2.2 Irradiation metrics

2.2.2.1 Heating season irradiation

The heating season irradiation [kWh/m^2] represents the surfaces' average irradiation level during the buildings' heating period which serves to assess the potential for passive solar heating techniques such as thermal-stored walls and floors (Liu et al., 2019). Compagnon (2004) introduces a formula (eq.6) that defines the heating season irradiation threshold. This threshold stands for the amount of solar energy [kWh/m^2], which required to compensate the heat losses through glazing in the heating period, that needed to be collected by the building's roof and facades.

$$G_{pa\_threshold} = \frac{24DDU}{1000g\eta}\ [kWh/m^2] \qquad \text{(eq.6)}$$

In which
η : utilisation factor considering the dynamic behaviour of the building and its users that is normally estimated as 0.7.
DD: the heating degree days of the city.
g: solar energy transmittance coefficient for a common double pane window is 0.75.
U: thermal transmittance coefficient for a common double pane window is 1.2 W/m^2K.

This theory is then verified by Nault, Rey, and Andersen (2013).

2.2.2.2 Solar irradiation

Solar radiation toward a surface varies depending on latitude and the three cities in this study are very representative. Through the solar irradiation analysis of the building facades in these three typical cities, solar irradiation can be understood well via comparison. It can be calculated by the (eq.7) shown below.

$$S = S_t + S_d\ [kWh/m^2] \qquad \text{(eq.7)}$$

In which
S_t is the measured direct component incident on a surface.
S_d is the measured diffuse component incident on a surface.

A large amount of solar irradiation can be used in passive ways to obtain sunlight and passive solar energy, and can also be actively used through PV panels and ST collectors. *Figure 2* and *Figure 3* show a generalsolar electricity potential for Denmark and Germany roughly.

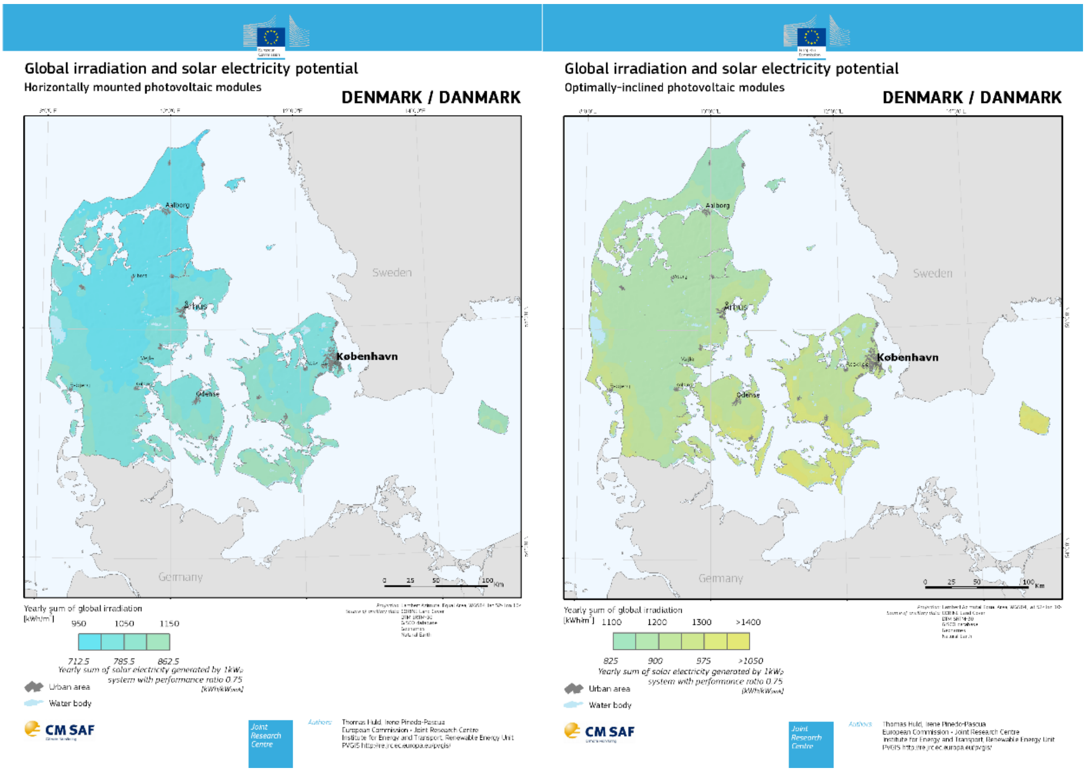


Figure 2 Solar irradiation and solar electricity potential on horizontal and optimally inclined surfaces in Denmark.

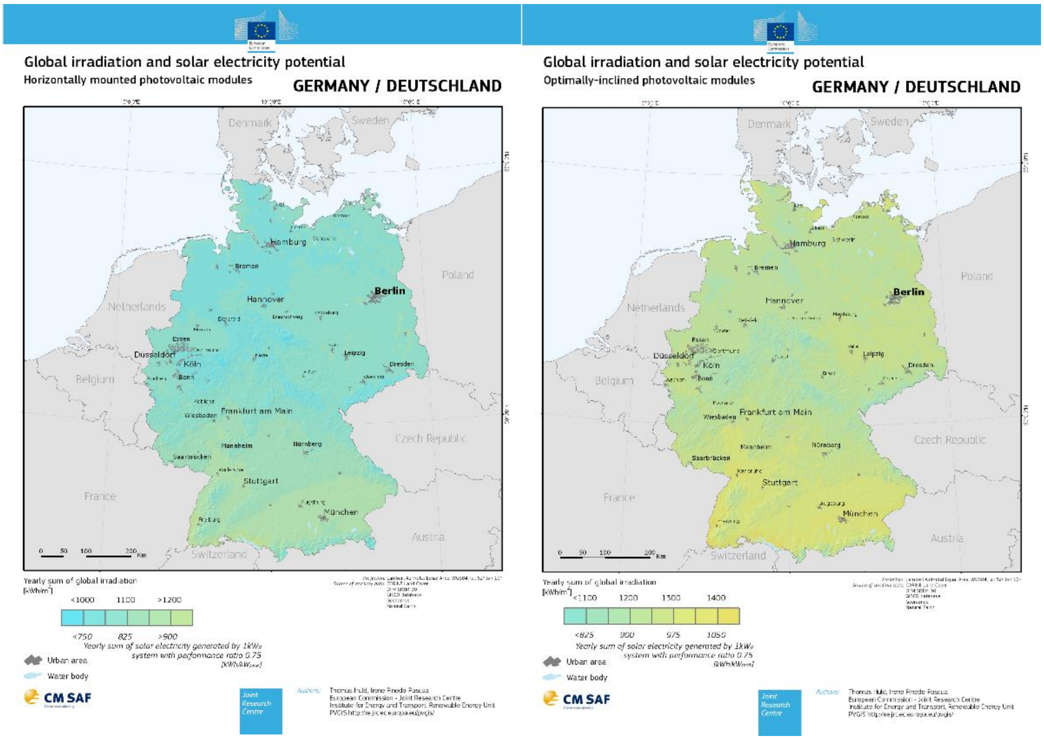


Figure 3 Solar irradiation and solar electricity potential on optimally inclined and horizontal surfaces in Germany.

2.3 Visual performance study

2.3.1 Shadow range analysis

High density areas with tall buildings influence the available solar radiation to surroundings (Jose R. et al., 2011). Studies (Lau et al., 2011) (Al-Qeeq, 2008) showed that shadows of unplanned high-rises have adverse impacts on human health, comfort living and even the economic value of land. Additionally, (Islam, 2015) states that a dark alley or a comparative shaded public space can be a place for anti-social activities. Thus, how and to what extent does the buildings' shadows affect the sunlight access to the neighbouring open spaces is necessary to explore. This information helps urban planners to decide whether to establish a public utility, which should be daylight assured, if the shadow effect is great for a long time during the year.

3 Methodology

The workflow was divided into three main parts. At first, a typical building block was selected in each studied city: Berlin, Hong Kong and Copenhagen which was then modelled by computer software: Rhinoceros. Then, these three base models were assessed with the help of simulating tools to consider their daylight and solar potential by comparing the metrics results with the current regulations. After that, some variations of each building block were made including shape, material, roof type and density. These new cases were assessed then compared with their base counterparts to investigate the contribution of each variation type and to find the most contributory factor in different cities.

3.1 Modelling and simulation software

3.1.1 Rhinoceros

Rhinoceros is a 3D computer graphics and computer-aided design (CAD) software utilised for modelling various products. Therefore, all the buildings' geometries were modelled by Rhinoceros in this study.

3.1.2 Grasshopper

Grasshopper plug-in is a graphical algorithm editor integrated within Rhinoceros (Tedeschi, 2010). It allows the users to create and modify complex geometries directly by combining some Grasshopper components. Most importantly, several environmental analyses on buildings could be carried out with the implementation of other plug-ins for Grasshopper.

3.1.3 Ladybug & Honeybee

Two open-source Grasshopper-based plug-ins were applied in the study, which were Ladybug and Honeybee that belongs to the 'Ladybug Tools' collection. They were designed to perform comprehensive environmental analysis integrated with several validated simulation engines (Bates, 2015).

Ladybug imports standard EnergyPlus weather files into Grasshopper and supports detailed climate data analysis such as wind, radiation, view and thermal comfort studies (Sadeghipour et al., 2013). In this research, the impact of weather data, irradiation analysis and sun hour analysis were achieved by Ladybug.

Honeybee particularly runs daylight simulations (e.g. illuminance, glare and annual daylight studies) and visualizes the results using the engine RADIANCE (Ringley & Heumann, 2017). It was employed to simulate and evaluate all the daylight metrics in this study.

3.2 Simulation inputs

In the Ladybug and Honeybee tools, the simulation settings regarding the grid and material properties are shown in *Table 1*. The Honeybee radiance parameters were set to an error-acceptable quality instead of the most accurate level in order to achieve shorter computational time which are presented in *Table 2*. These values were acquired from a previous study (Todorov, 2015).

Table 1 Material optical properties and other simulation inputs applied in Ladybug and Honeybee simulations.

Component reflectance / transmittance			
Ground	**Surrounding buildings (Base case)**	**Light-coloured concrete (Material 1)**	**Glass curtain (Material 2)**
0.2	0.4	0.6	0.64
Other simulation inputs			
Grid size		**Sensors offset**	
0.5 x 0.5 m		0.001 m	

Table 2 Honeybee radiance parameters.

Ambient bounces (-ab)	Ambient divisions (-ad)	Ambient super-samples (-as)	Ambient resolution (-ar)	Ambient accuracy (-aa)
3	2048	512	256	0.1

3.3 The generic cases and variations

The original models were acquired from CADMAPPER, an online tool providing CAD files for any selected location over the world. These models were then simplified by the authors.

3.3.1 Copenhagen

The residential communities chosen for this study is around the city centre (55° 40' N, 12° 33' E), which are the Denmark typical urban layout. Both the building blocks and constructions are not in a regular way. Most buildings are not connected to each other with different orientation of pitched roof. There are also public open spaces within the block enclosed by the scattered buildings. This is shown below in *Figure 4*.

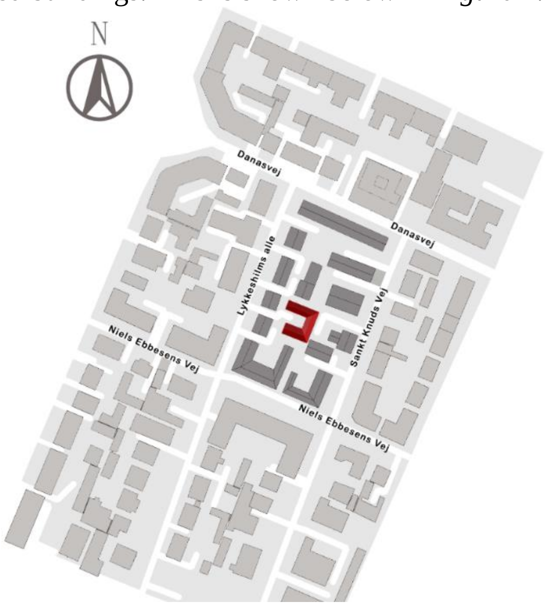


Figure 4 Communities around the street: Niels Ebbesens Vej in Copenhagen.

The base case chosen for this study was the building block in dark grey. The main buildings in this block were in linear and U shape and two to four storeys. The test construction (in red) was in the middle of this block with height of 6 m and footprint of 273 m^2, which is shown in *Figure 5*. The surrounding building were all the same height except the one on the south of it in U shape, which was 3-storey. The opening direction of the studied building (in red) was west. Based on this shape, a large part of the pitched roof was south facing, which can be analysed for PV potential.

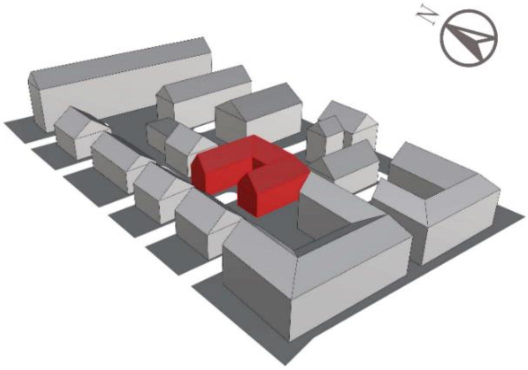


Figure 5 Studied base building block and its surroundings in Copenhagen.

3.3.1.1 Independent variables

3.3.1.1.1 Density variations

Two varied cases with the same density and floor area were compared to base case in the city centre of Copenhagen, which are shown in *Figure 6* below. The only independent variable was the footprint of the cases. Study case 1 with the smallest footprint had the highest total building height, and study case 2 with the second smallest footprint had the second highest building height as well.

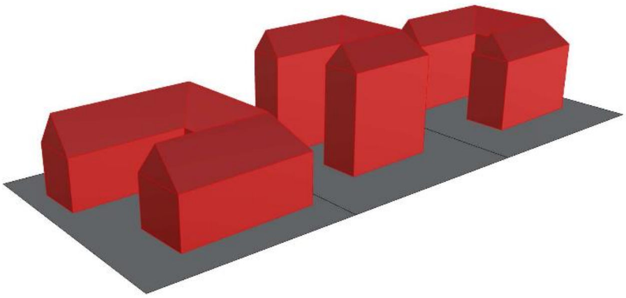


Figure 6 Studied base case (left), density 1 case (middle) and density 2 case (right) in Copenhagen.

The parameters are shown below in *Table 3*.

Table 3 Parameters of threes cases of density analysis in Copenhagen.

	FAR	Block area / m^2	Foot print / m^2	Height / m	Storeys
Base case	0.71	772	273	6	2
Study case 1	0.71	772	136.5	12	4
Study case 2	0.71	772	182	9	3

3.3.1.1.2 Shape variations

The original building was U-shaped. The other two shapes of the building with same roof inclination, density and floor area were chosen for this analysis. They were L-shaped and linear, which are shown in *Figure 7* below.

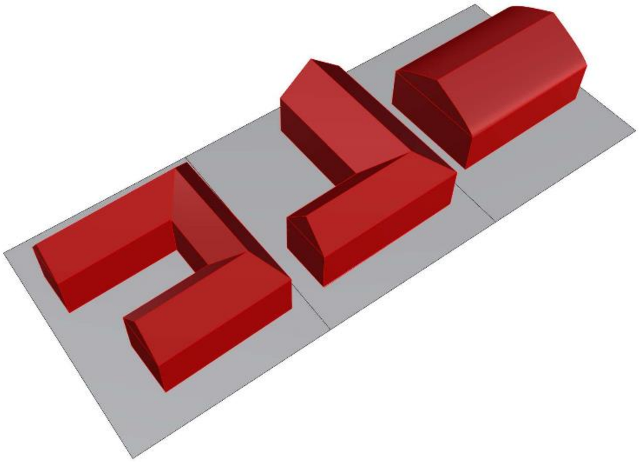


Figure 7 Studied base case (left), shape 1 case (right) and shape 2 case (middle) in Copenhagen.

3.3.1.1.3 Roof variations

In northern Europe where the sun is not very abundant, the roof surface can well complement the indoor lighting performance. The original roof inclination was almost 60 degrees. The other two roof inclination were chosen as shown in *Figure 8* and *Table 4* below.

Figure 8 Studied base case (left), roof 1 case (middle) and roof 2 case (right) in Copenhagen.

Table 4 Parameters of threes cases of roof inclination analysis in Copenhagen.

	Roof inclination / °
Base case	60
Study case 1	0
Study case 2	30

3.3.1.2 Dependent variables

3.3.1.2.1 Sun hours

For the Copenhagen case, an European standard (EN 17037:2016-08) recommends that on any day (which is supposed to be cloudless) between 1st February and 21st March, buildings should meet the requirement in *Table 5*. In this study, only the 1st February and 21st March conditions were simulated so that the overall performance during the mentioned entire period could be estimated roughly.

Table 5 Suggested sun hours from EN 17037.

Sun exposure condition	Daily sun hours
Minimum level	1.5 h
Middle level	3 h
High level	4 h

Independently studying the sun hour condition for the public city space, BRE's 2011 guidance document 'Site Layout Planning for Daylight and Sunlight' states in Section 3.3.17 that for a space to appear adequately sunlit throughout the year, it should obey the guideline that having more than 2 hours sunlight at least half of a garden or amenity area on 21st March. The three base cases' surrounding open space were assessed by this regulation since there was no corresponding domestic guideline.

3.3.1.2.2 Vertical daylight illuminance

The percentage of the building vertical surfaces that got stronger illuminance than the result from (eq.3) was checked and compared between each variation. Specifically, this simulation was done for only one day in the whole year: 21st June, which is supposed to be the sunniest day. During this day, 10.00, 12.00, 14.00 and 16.00 conditions were studied. Then the potential for the rooms at the building edges to be illuminated entirely by daylight was able to be estimated.

3.3.1.2.3 Vertical sky component

In order to ensure median Daylight Factor (DF_{med}) 1% indoors, VSC value was found that should be more than 29%. Following the guideline, in the façade areas where VSC is below 15% it would be difficult to reach the target DF_{med} (Olina & Zaimi, 2018). *Table 6* shows the VSC guideline in Sweden. Due to the similar geographical locations, this guideline could also be applied in Copenhagen.

Table 6 The VSC guideline in Copenhagen.

Storage space	<15%
living rooms, studies and dining rooms	15% to 29%
all other room types	> 29%
At the centre of the window surface	

3.3.1.2.4 Heating season irradiation

The heating degree days of Copenhagen is 4118.8 K·day (Weatherbase, n.d.). According to (eq.6), the heating season irradiation benchmark for Copenhagen is 226 kWh/m^2. In addition, (Lipeng et al., 2015) mentioned that the heating period for Copenhagen is from 1st October to 15th April.

The accumulated solar irradiation during this heating season was compared with its corresponding threshold in order to evaluate if the building had a good potential for passive heating strategies or not.

3.3.1.2.5 Annual solar irradiation

A method presented by (Compagnon, 2004) quantifies the solar potential of the external envelope of buildings located in urban areas for photovoltaic electricity production and daylighting. The study also presented the minimum level of solar radiation for installing Solar Thermal (ST) and PV systems. However, Compagnon's methods are based on a specific location. But they would probably differ in other regions of Europe. Based on categories used in Lund's solar map, (Kanters & Wall, 2014) introduced thresholds applicable in a Swedish context (that is similar to Denmark), which is shown in *Table 7*.

Table 7 The thresholds of solar radiation in a Swedish context.

	Unsuitable	**Suitable**		
		Reasonable	**Good**	**Very Good**
Facades	650 kWh/m^2	651-899 kWh/m^2	900-1020 kWh/m^2	>1020 kWh/m^2
Roof	800 kWh/m^2	800-899 kWh/m^2	900-1020 kWh/m^2	>1020 kWh/m^2

3.3.1.2.6 Shadow cast study

The casted shadows and the shadow domain of building blocks on their nearby open spaces for some certain days of a year: 21st March, 21st June and 21st December were investigated. According to 'BRE – Site Layout Planning for Daylight and Sunlight (2nd edition)', the shadow range aerial images for all cases were simulated every 2 hours from 10.00 to 16.00, which provided with a visual representation of any potential that may arise from the existing scheme.

The shadow cast analysis method was the same for all these three cities.

3.3.2 Berlin

Around 'Schillerpromenade' (52° 48′ N, 13° 45′ E) there is an area that consists of several communities located in Neukölln, southern central Berlin. It represents the traditional Berlin urban pattern: building blocks stand alongside the streets with several small courtyards inside seen in *Figure 9*.

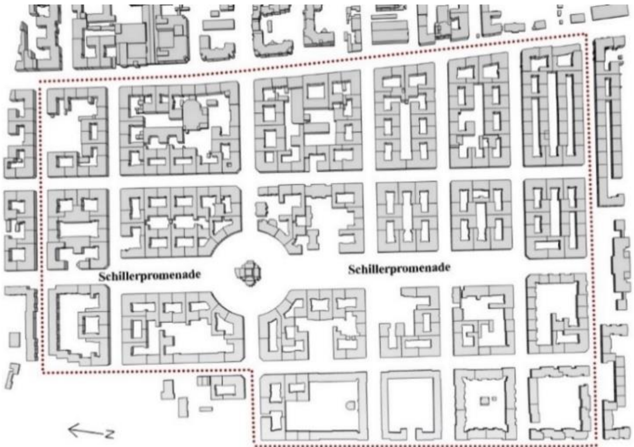


Figure 9 Communities beside the street: Schillerpromenade in Berlin.

One building block within this area was selected as the base case as shown in *Figure 10*. Its height was 15 m with the floor area 5487 m^2. It was surrounded by building blocks of similar height in all directions but the western street was as wide as 50 m (with a public activity space in the centre) while other roads' width was 19 m.

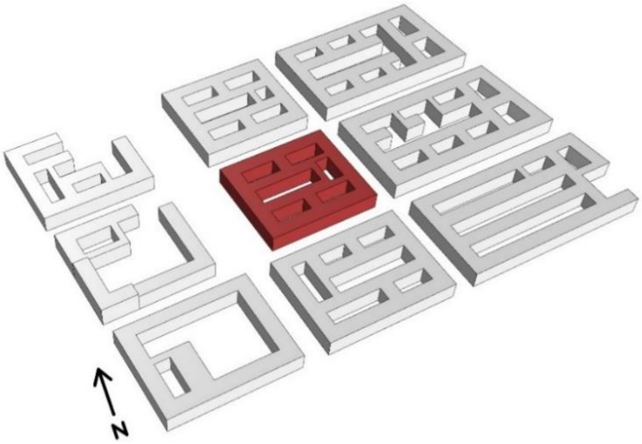


Figure 10 Studied base building block and its surroundings in Berlin.

3.3.2.1 Independent variables

3.3.2.1.1 Density variations

Two variations were proposed that they had the similar density as the base case where the building storey and footprint area was varied proportionally. The parameters of each case are illustrated in *Table 8* and the building forms are seen in *Figure 11*.

Figure 11 Studied base building block (left), density 1 case (middle) and density 2 case (right).

Table 8 Parameters of threes cases of density analysis in Berlin.

	FAR	**Block area / m^2**	**Footprint / m^2**	**Height / m**	**Storey**
Base case	2.05	13412	5487	15	5
Density 1 case	2.05	13412	6640	12	4
Density 2 case	2.05	13412	2793	27	9

3.3.2.1.2 Shape variations

Two shape variations were adjusted in *Figure 12*. Case 1 had simpler courtyard layout and the building was separated into two parts with a central road as wide as 14 m. Case 2, a much more open inner courtyard was put forward which contributing to a lower density.

The detailed information for these types of variations are displayed in *Table 9*.

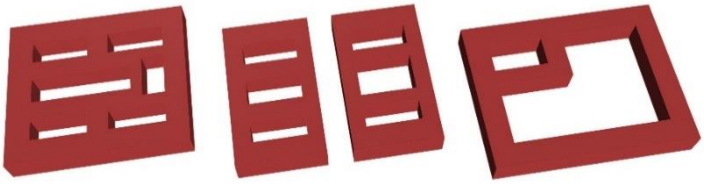


Figure 12 Studied base building block (left), shape 1 case (middle) and shape 2 case (right).

Table 9 Parameters of threes cases of shape analysis in Berlin.

	FAR	**Footprint / m²**	**Block area / m²**	**Height / m**	**Storey**
Base case	2.05	5487	13412	15	5
Shape 1 case	2.05	5499	13412	15	5
Shape 2 case	1.94	5203	13412	15	5

3.3.2.1.3 Roof variations

When the roof degree was increased, the wall height was reduced as well seen in *Figure 13* and the detailed size of all cases are shown in *Table 10*.

Figure 13 Studied base building block (left), roof 1 case (middle) and roof 2 case (right).

Table 10 Parameters of threes cases of roof inclination analysis in Berlin.

	Roof inclination / °	**Wall height / m**	**Roof height / m**
Base case	0	15	0
Roof 1 case	30	13.3	3.5
Roof 2 case	60	9.6	10.3

3.3.2.1.4 Material variations

Material variations were only analysed for the vertical illuminance performance. Specifically, the original material was imagined as general concrete finishing, then other two materials including more reflective concrete finishing and glass curtain whose properties were shown before in *Table 2*.

3.3.2.2 Dependent variables

3.3.2.2.1 Sun hours

For the Berlin case, German standard DIN 5034-1 asks for the building's minimum sun hour at certain days. This regulation is shown in *Table 11*.

Table 11 Compulsory sun hours from DIN 5034-1.

17th January	**21st March**
1 h	4 h

3.3.2.2.2 Vertical sky component

The standard SD5072 - 2012 - 3.2 from BREEAM quotes the guideline for vertical sky component to ensure enough sky light through the window, which was set out in chapter 2.2

of BRE Report 'Site layout planning for daylight and sunlight: a guide to good practice' (BR 209). The guideline is that VSC value is more than 27% at the centre of the window surface. The maximum VSC for a completely unobstructed vertical window is 39.6%.

3.3.2.2.3 Heating season irradiation

The heating degree days of Berlin is 3878.3 K·day (*Weatherbase,* n.d.). According to the (eq.6), the heating season irradiation benchmark for Berlin is 213 kWh/m^2. In addition, the heating period season for Berlin is 1st October – 30th April.

The accumulated solar irradiation during the heating season was compared with its corresponding threshold in order to evaluate if the building had a good potential for passive heating strategies or not.

3.3.2.2.4 Correlation between shadow cast range study and sun hour analysis

The same shadow coverage domain analysis was carried out for the Berlin building cases with the method mentioned in the Copenhagen section above. However, since the shadow range views could only show graphical results for the target audience, a tentative study in regard to the comparison and correlation between the shadow study and daily sun hour analysis was practised. In this paper, the 21st March condition for the surrounding open space of the base case in Berlin was selected for this experimental study. In specific, 0 sun hour was equal to fully shaded circumstance that the percentage of the open space area receiving no sun hour during 10.00 – 16.00 on 21st March, 21st June and 21st December were compared with those of the fully shaded area in the shadow aerial image.

3.3.3 Hong Kong

Hong Kong is famous for its high floor area ratio (FAR), which is the ratio of a building's gross floor area to the land area (Metropolitan Council, 2015). Tsim Sha Tsui (22° 17' N 114° 10' E) is one of the most representative and prosperous area in Hong Kong shown in *Figure 14*. Due to the high population density and tight land area, some buildings are connected together or have a relatively small distance. Most of the constructions in Hong Kong have flat roof.

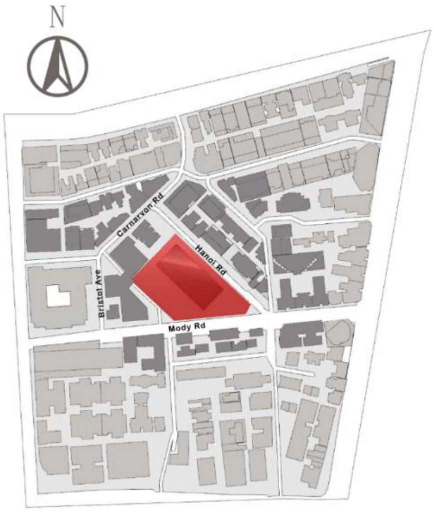


Figure 14 Communities around the street: Mody Rd in Hong Kong.

The chosen base case in this study consists of a skyscraper (shown in red in *Figure 15*) with a height of 261 m and many buildings over 50 m in height. The test building is the skyscraper with the first 6^{th} floor of podium and another 79 floors above. The footprints of the podium and high-rise sections are 5168 m^2 and 1806 m^2. There is one open space on the west-south side of the test building, which is enclosed by another 6-storey building.

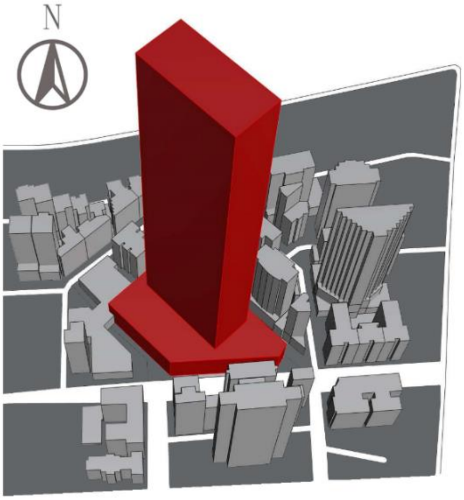


Figure 15 Studied base building block and its surroundings in Hong Kong.

3.3.3.1 Independent variables

3.3.3.1.1 Density variations

Based on the city status of Hong Kong, density is the most prominent problem. In order to analyse impact of urban density on Hong Kong's central area, two study cases with the same density and floor area were compared to base case, which are shown below in *Figure 16*. The only independent variable one was the footprint of the high-rise part for study case one and the footprint of the podium for study case two. Study case two had the highest total building height, while study case one had the lowest. The parameters are seen below in *Table 12*.

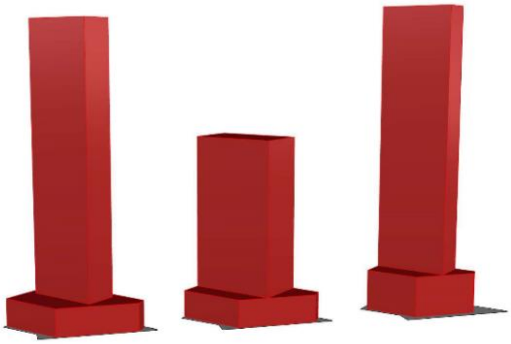


Figure 16 Studied base case (left), density 1 case (middle) and density 2 case (right) in Hong Kong.

Table 12 Parameters of threes cases of density analysis in Hong Kong.

			Height / m		Storey		Footprint / m²	
	Block area / m²	**Density / %**	**Podium**	**Tower**	**Podium**	**Tower**	**Podium**	**Tower**
Base case	5662	30.68	24	237	6	79	5168	1806
Study case 1	5662	30.68	24	135	6	45	5168	3171
Study case 2	5662	30.68	36	237	9	79	3450	1806

3.3.3.1.2 Shape variations

The original podium was similar in shape to the block area and almost occupied the entire area. In order to control variables in comparisons, the footprint of the podium was stable in shape analysis. So, the podium was same in these three cases. The shape of the high-rise part is the independent variable of this analysis, but the total building area remains the same. The shape of these three cases are shown in *Figure 17*.

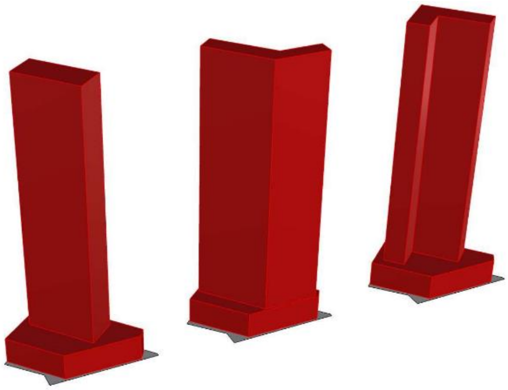


Figure 17 Studied base case (left), shape 1 case (middle) and shape 2 case (right) in Hong Kong.

3.3.3.2 Dependent variables

3.3.3.2.1 Sun hours

For the Hong Kong case, Chinese GB legislation requests that the buildings should gain at least 3 sun hours on the building surface parts where 0.9 m above the ground on 20th January.

3.3.3.2.2 Vertical daylight factor

Based on the regulations from 'Practice Note for Authorized Persons, Registered Structural Engineers and Registered Geotechnical Engineers APP-130', the standards of VDF in Hong Kong was shown in *Table 13* referred from (Buildings Department of Hong Kong government, 2010). But a threshold was found despite of a low standard, which can provide 80% satisfaction rate (Ng, 2005).

Table 13. The standards of VDF for habitable building in Hong Kong.

Habitable Room	> 8%
Kitchen	> 4%
On the centre of the window pane	

3.3.3.2.3 Heating season irradiation

The heating degree days of Hong Kong is 74.5 K·day (*Weatherbase*, n.d.). According to (eq.6), the heating season irradiation benchmark for Hong Kong is 4 kWh/m^2, which was quite low. Also, the heating period for Hong Kong was much shorter than the other two cities as 1st December – 28th February (Lipeng et al., 2015).

The accumulated solar irradiation during the heating season was compared with its corresponding threshold in order to evaluate if the building had a good potential for passive heating strategies or not.

3.4 Combined comparison between three cities

Since all three cities have local standards for sun hours, this study specifically compared the percentages of the three cities that met local sun hours regulations.

3.4.1 Density study

In the density parametric study, there was a clear gap between the FAR of these three typical cities. At the same time, the FAR value of study cases and base cases in each city was consistent. The variables were building height and footprint.

In this section, the first part was comparison between different cities, which can show how the building density influenced the sun hours results. Then the cases with different building height in the same city were also compared, which was a supplement to illustrate the effect of building height on sun hours with the same density in the same city.

3.4.2 Roof inclination study

In the roof inclination parametric study, only two cities, Berlin and Copenhagen, were analysed. Because of the actual situation, it is difficult to see buildings with sloping roofs in Hong Kong.

This section compares the sun hours results for different roof inclination cases in Berlin and Copenhagen.

4 Results and Discussions

The results are composed of two parts: the daylight metric results of base cases in three cities and the parametric study. The parametric study contains the longitudinal comparison of each city and the comparison of different cities. As for the comparison of the same city, it mainly involves the parameters of building density, building shape, roof inclination and material of the facade.

4.1 Base case study

4.1.1 Copenhagen

4.1.1.1 Sun hours

In Copenhagen, 61% of the surrounding courtyard got more than 2 sun hours on 21st March which achieved the BRE regulation. The sun hour distribution is shown in *Figure 18*.

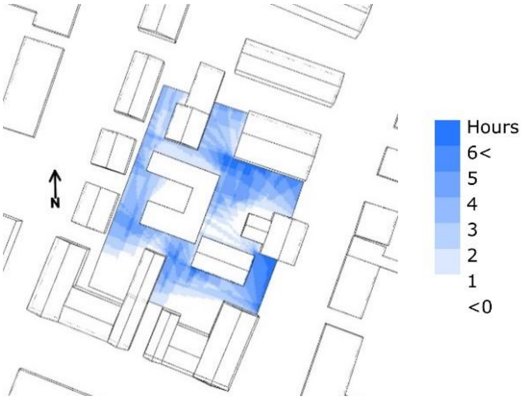


Figure 18 Sun hour conditions for the open space in Copenhagen on and 21st March.

Then for the building block, the north surfaces were hardly to get any direct sun hour on neither day because of the geographic location while the west façade facing the yard ranked the second worst due to the building's self-occlusion (*Figure 19*).

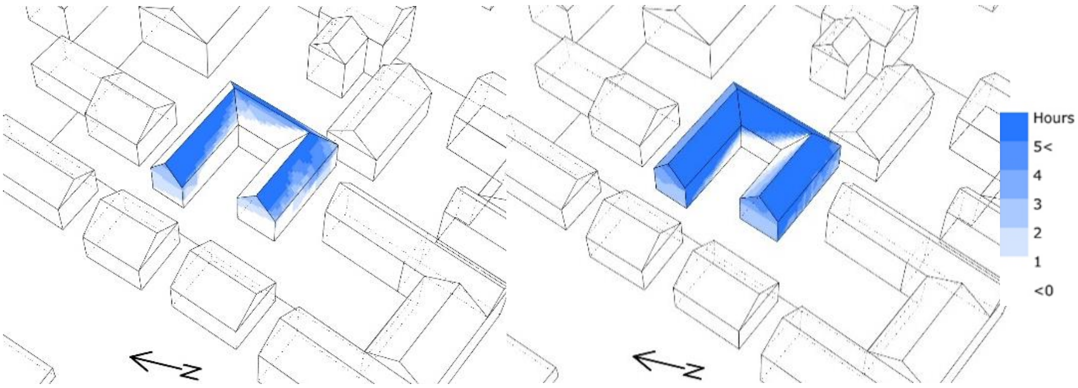


Figure 19 Sun hour conditions for the building block in Copenhagen on 1st February (left) and 21st March (right).

Specifically, on 1st February, 53% of the surface did not reach the recommended sun hour, 7% area lied in the minimum level, 5% area ranged from 3 to 4 sun hours and 35% area got high level of sun light. And on 21st March, only 26% surface area was below the minimum level, 13% area was in minimum level scale, 17% area was in middle level and 44% area was in the high level. *Table 14* presents the percentage of surface area in each sun hour scale for different orientations in detail.

Table 14 The building façade area percentage of the base case that met the sunlight recommendation in Copenhagen.

		North	West	South	East	Roof
21.03	< 1.5 h	82%	31%	10%	26%	9%
	Minimum level	18%	40%	8%	6%	5%
	Middle level	0%	16%	23%	10%	23%
	High level	0%	13%	59%	58%	63%
01.02	< 1.5 h	100%	84%	82%	84%	43%
	Minimum level	0%	15%	11%	5%	7%
	Middle level	0%	1%	6%	10%	7%
	High level	0%	0%	1%	1%	43%

It was found that the for the Copenhagen base case, 99% ground floor facade area could not get 1.5 hours on 1st February. And on 21st March, the situation became better especially the percentage of '< 1.5 h' whose sun hour distribution can be seen in *Table 15* and *Figure 20*.

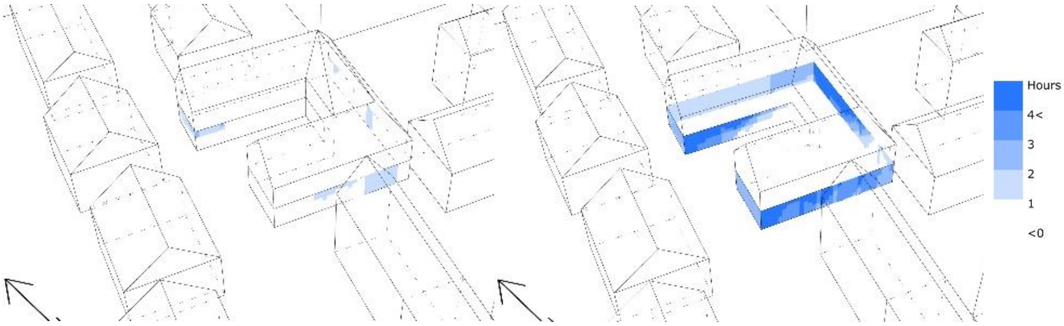


Figure 20 Sun hour conditions for the building ground floor facade in Copenhagen on 1st February (left) and 21st March (right).

Table 15 The ground floor facade area percentage of the base case that met the sunlight recommendation in Copenhagen.

		Percentage
21.03	< 1.5 h	46%
	Minimum level	23%
	Middle level	13%
	High level	18%
01.02	< 1.5 h	99%
	Minimum level	1%
	Middle level	0%
	High level	0%

4.1.1.2 Vertical daylight illuminance

As stated in the Methodology section, if the building surface got 10 000 lx at any time, the rooms on the building facades were able to be fully illuminated by the natural sunlight. For the Copenhagen building, on 21st June the best illuminance condition was on 12.00 for most cases and the worst condition was various on 10.00 and 16.00.

The Copenhagen base case (*Figure 21*) showed that the outer west facade always got more than 10 000 lx during 21st June. Also, the south facade facing the courtyard had acceptable illuminance for all checked hours even in the morning and afternoon. Additionally, the building's outer north façade was illuminated sufficiently for most time due to the high reflectance originating from short surrounding building distance. Considering the whole building, the worst VDI performance was at 10.00.

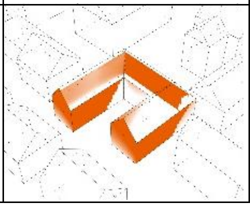
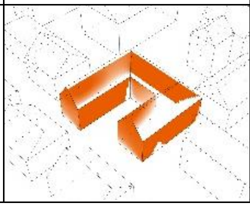
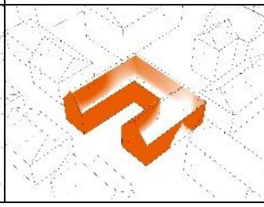
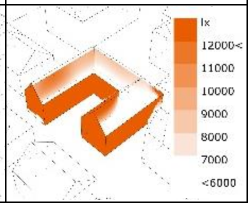
	10.00	12.00	14.00	16.00
21.06 (Base case)				

Figure 21 The VDI distributions for four selected hours on 21st June – base case of Copenhagen.

4.1.1.3 Vertical sky component

The original building shape of base case was U-shape. The open space enclosed by the envelope was on the west side. The VSC results of the envelop are presented in *Figure 22* in two different perspectives. As shown below, due to the closest building distance to the southeast of base case, the east facade is the most severely blocked part. Due to mutual obstruction, the occlusion of the facades that enclosed the inner yard were relatively severe.

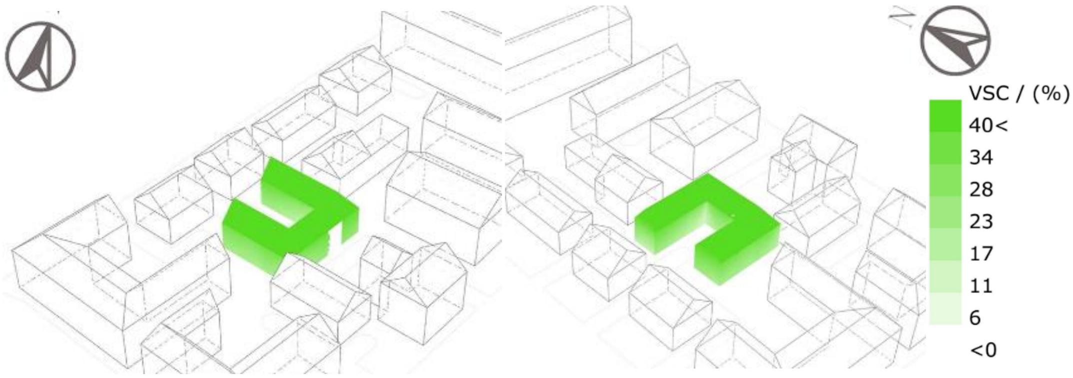


Figure 22 The VSC results of base case in Copenhagen.

The ratio of different façades that meets the recommendation in Copenhagen are shown in *Table 16* below. The roof surface fully met the recommendation, which was good for all kinds of rooms. Most of west, south and north façade were suitable for living rooms, studies and dining rooms. Only around one quarter of west and south façade met the recommendation for all rooms which was 29%. North surface was slightly worse in this threshold. The proportion of east facade which was suitable for three kinds of thresholds were basically the same.

Table 16 The ratio of each surface that meets the VSC recommendation in Copenhagen.

	North	West	South	East	Roof
<15%	18%	4%	5%	33%	0%
15% to 29%	68%	71%	75%	39%	0%
> 29%	14%	25%	20%	28%	100%

4.1.1.4 Heating season irradiation

Unfortunately, the investigated case in Copenhagen had quite bad heating season irradiation accumulation as the qualified surface percentage was only 16% shown in *Figure 23*. Its west roof's potential was lower than expected resulting from the roof inclination and mutual-shading.

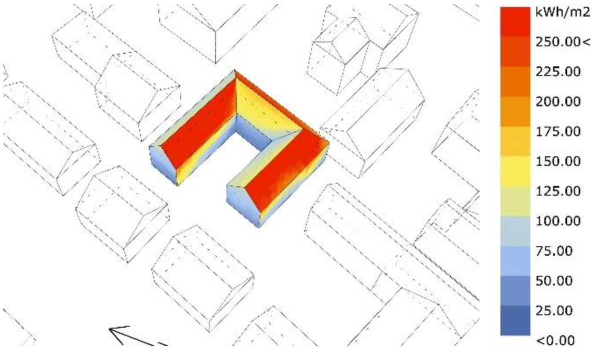


Figure 23 The heating season irradiation result of base case in Copenhagen.

4.1.1.5 Annual solar irradiation

The annual solar irradiation of the facades of base case in Copenhagen is shown in *Figure 24* below. In fact, the solar irradiation result of the Copenhagen base case was much better than that of Berlin. It can be seen from the above that under the unfavorable latitude conditions of the city, through the design of the building shape, density, roof inclination, etc., the solar irradiation of the building facades can be effectively improved.

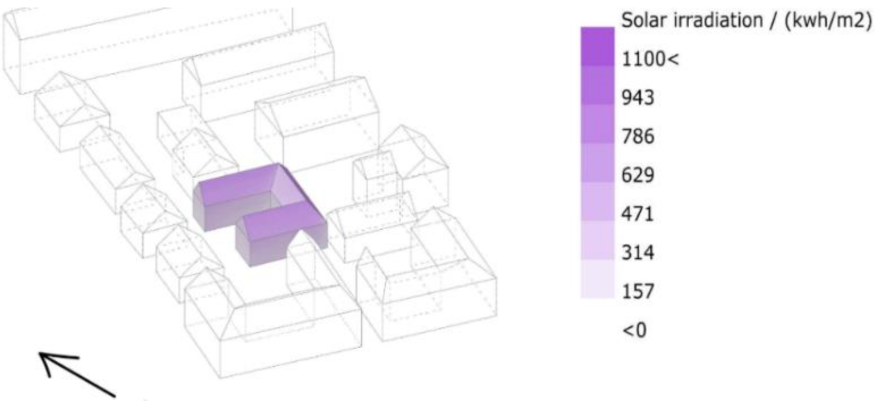


Figure 24 The annual solar irradiation of base case in Copenhagen.

Based on the further monthly analysis shown in *Figure 25*, the time period between May and August had the greatest potential for PV system.

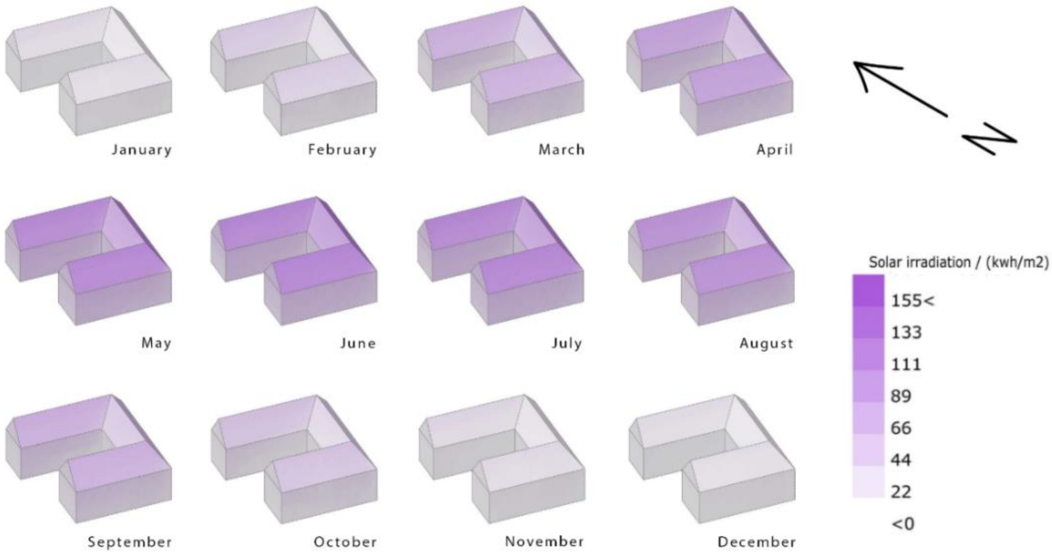


Figure 25 The monthly solar irradiation of base case in Copenhagen.

Even though the results of Copenhagen were better than Berlin, it was not enough to meet the standards for installing PV systems in Copenhagen detailed in *Table 17*.

Table 17 the threshold of annual solar irradiation for installing PV system in Copenhagen

	Threshold
North west facade	Unsuitable
South west facade	Unsuitable
South east facade	Unsuitable
North east facade	Unsuitable
Roof	Unsuitable < x > Reasonable

4.1.1.6 Shadow cast study

There was no shadow which meant no sun at 16.00 21st December because of the city's high latitude. On 21st December, the courtyards were black nearly during the whole day while on 21st June, residents were able to take sun bath for the whole day as well. The shadow aerial images are shown in *Figure 26*.

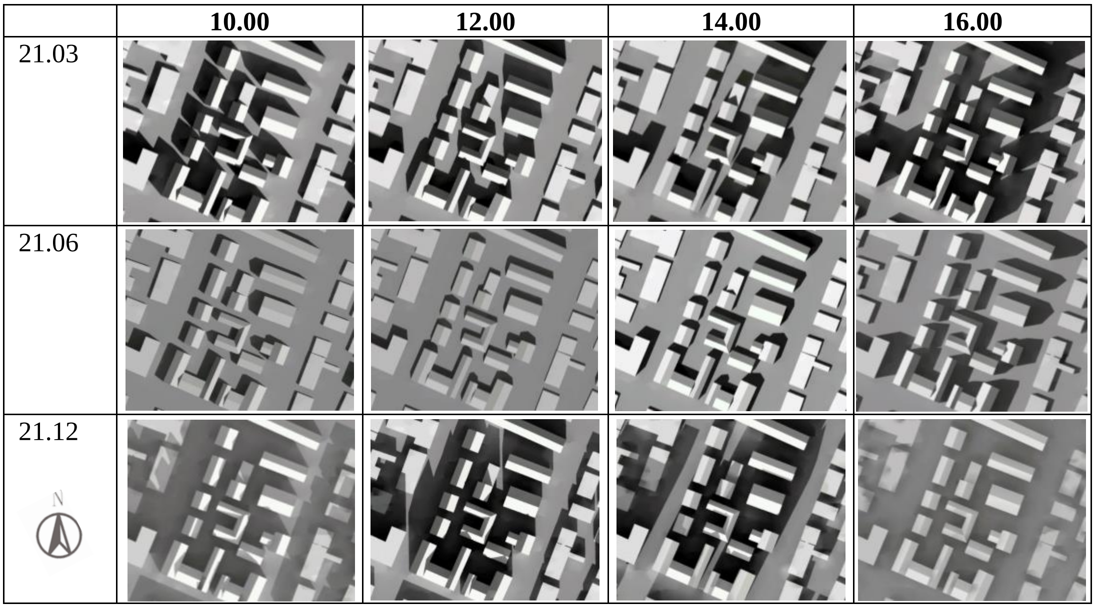


Figure 26 The building shadow cast for four selected hours on 21st March, 21st June and 21st December – Base case of Copenhagen.

4.1.2 Berlin

4.1.2.1 Sun hours

For the open space, the western public activity area acquired the longest direct sun hours. On 21st March, some parts of the open space were able to receive direct sunlight for more than 9 hours. Moreover, 82% of the studied public area was adequately shined by sunlight for longer than 2 hours displayed by *Figure 27* which obeyed the BRE guideline.

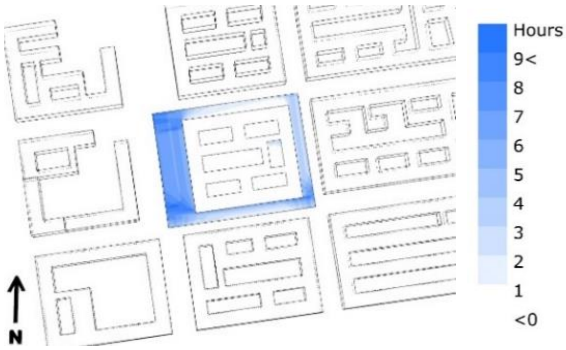


Figure 27 Sun hour condition for the open space in Berlin on 21st March.

For the building surfaces, 59% of the façade area met the 4 h requirement on 21st March while only 51% façade area complied to the 1 h requirement on 17th January. It is worth mentioning that none of the north façades ever accomplished the standard. The detailed values of the qualified surface percentage of each façade are seen in *Table 18*. In addition, the lower floor façade was much more difficult to fulfil the regulation than the upper floors especially for those surfaces facing courtyards seen in *Figure 28*.

Table 18 The building façade area percentage of the base case met the standard in Berlin.

	North	West	South	East	Roof
Outer façade (21.03)	0%	100%	100%	49%	100%
Inner façade (21.03)	0%	37%	62%	23%	100%
Outer façade (17.01)	0%	99%	45%	100%	100%
Inner façade (17.01)	0%	16%	28%	14%	100%

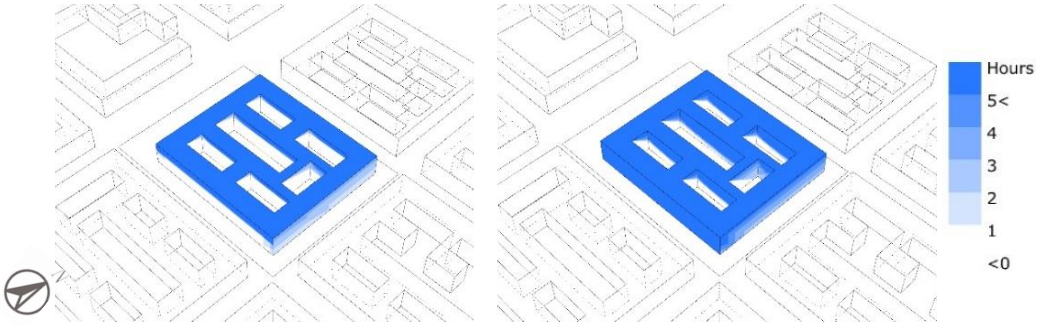


Figure 28 Sun hour conditions for the base building block in Berlin on 17th January (left) and 21st March (right).

For the ground floor sun hour investigation, on 17th January, it was surprising that only the east façade facing street met the standard which indicated 10% of the ground wall surface. On 21st March, the percentage was similar: 11% but some inner facades also got 1-3 sun hours even if they were not sufficient enough to achieve the regulation seen in *Figure 29*. This was because that some part of the sunlight was reflected several times by the inner walls due to the too small size of the courtyard.

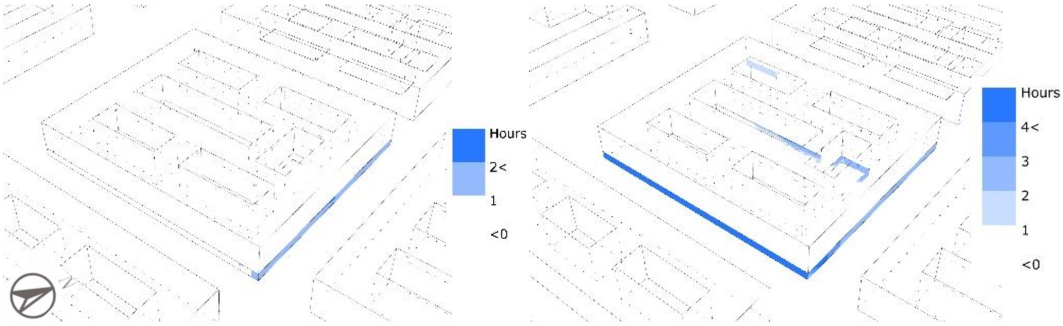


Figure 29 Sun hour conditions for the building ground floor facade in Berlin on 17th January (left) and 21st March (right).

4.1.2.2 Vertical daylight illuminance

The best VDI condition was on 12.00 noon while the worst condition was on 16.00 on 21st June for the investigated cases in Berlin.

Figure 30 shows that more than half of the inner courtyards' facades had VDI value above 10 000 lx during morning hours but in the afternoon, the qualified surface area decreased significantly. Additionally, for the outer surfaces, the full west façade and south facade acquired more than 10 000 lx during the whole day after 10.00 and before 16.00 respectively.

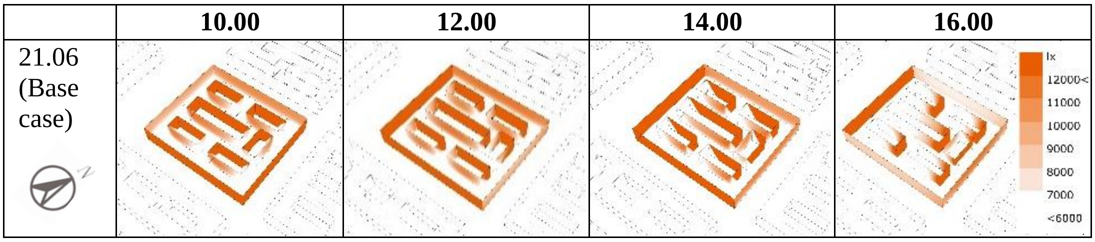


Figure 30 The VDI distributions for four selected hours on 21st June – base case of Berlin.

4.1.2.3 Vertical sky component

Most of the building's inner courtyards run east-west, so the north and south facades are more heavily shielded. And the distance between the base case and the building on the left is larger than other sides as shown in *Figure 31*.

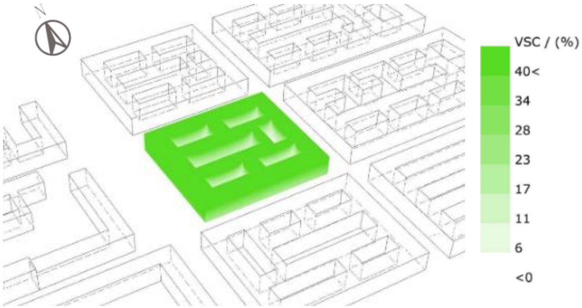


Figure 31 The VSC results of base case in Berlin.

For the ratio that meets the requirement in Berlin seen in *Table 19*, roof surface performed the best, which was completely satisfactory. North, south and east façade were almost the same, which was around 45%. West surface was better which was around 63%.

Table 19 The ratio of each surface that met the VSC requirements (*>27%*) *in Berlin.*

North	**West**	**South**	**East**	**Roof**
46%	63%	45%	48%	100%

4.1.2.4 Heating season irradiation

For the base case in Berlin, 47% surface area received the suggested 213 kWh/m^2 irradiation in the winter heating season seen in *Figure 32*. This percentage was higher than that of Copenhagen case mainly due to the high performance of roof.

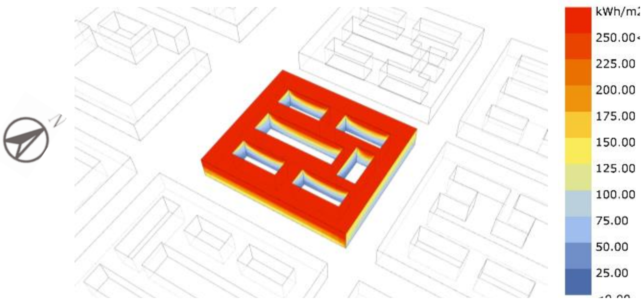


Figure 32 The heating season irradiation results of base case in Berlin.

4.1.2.5 Annual solar irradiation

The annual solar irradiation of the facades of the base case in Berlin is shown in *Figure 33* below. The overall situation was that it cannot meet the solar irradiation suggestion for installing PV in Berlin. One of the reasons was that the self-occlusion of the Berlin building is more serious.

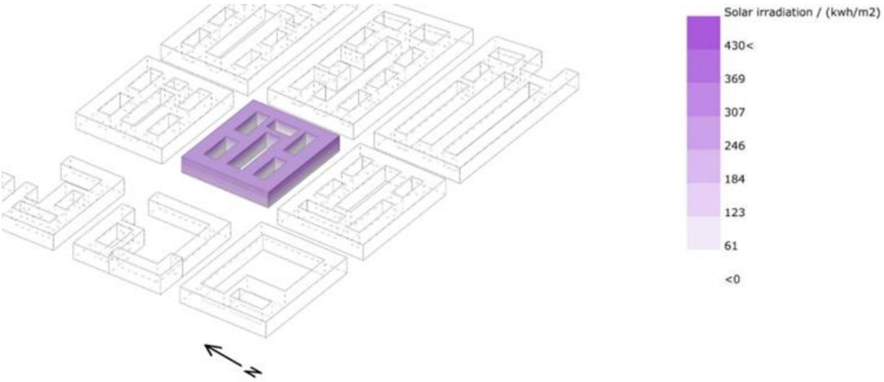


Figure 33 The annual solar irradiation of base case in Berlin.

Based on the further monthly analysis in *Figure 34*, the time period between May to August had the greatest potential for PV system. But the specific situation must be analysed according to German standards.

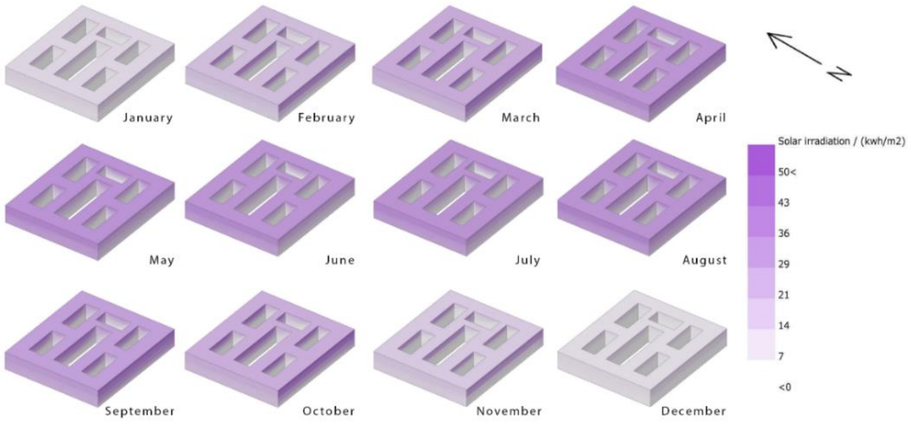


Figure 34 The monthly solar irradiation analysis of base case in Berlin.

4.1.2.6 Shadow cast study

On 21st June, only a few parts of the inner courtyards were shaded by the buildings and the shadow range of the streets was small during the whole day except dusk hours. While on 21st March and 21st December, the shadow covered the whole area of east-west streets for more than 4 hours and 6 hours respectively shown in *Figure 35*.

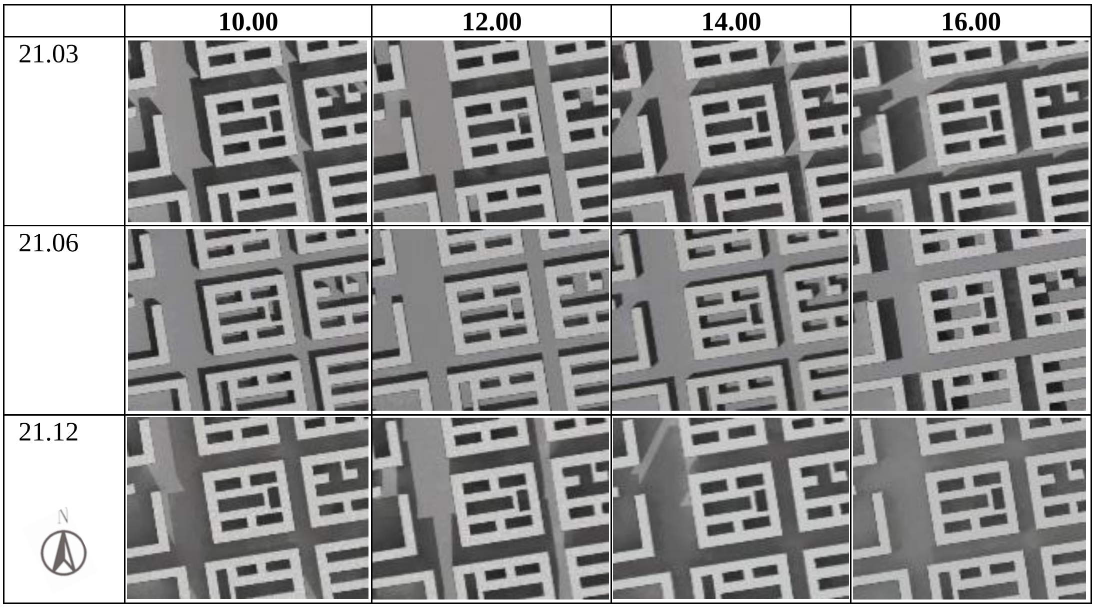


Figure 35 The building shadow cast for four selected hours on 21st March, 21st June and 21st December – Base case of Berlin.

4.1.2.7 Correlation between shadow cast study and sun hour analysis

In *Figure 36*, *Figure 37* and *Figure 38* where the area in white colour of the sun hour distribution graph and the area in black colour of the shadow range study was expected to be the same if the shadow range study is as accurate as the sun hour simulation. This kind of comparison was aimed to see if the BRE shadow standard matched with normal daily sun hour estimation and whether any numerical support can be provided by the BRE shadow range views.

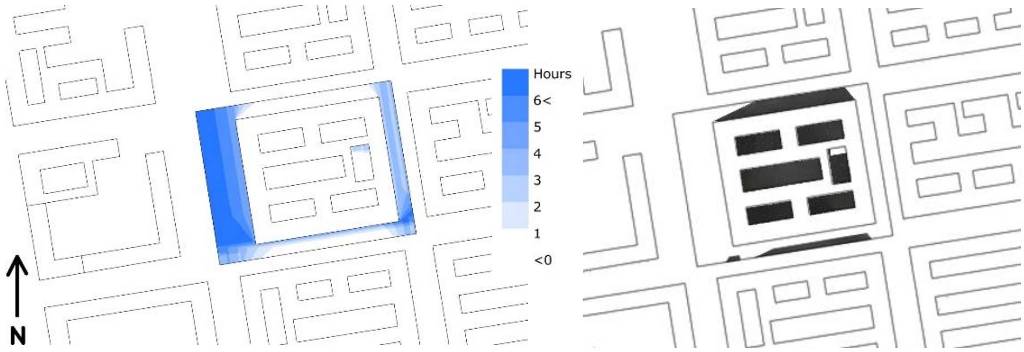


Figure 36 Sun hour condition from 10.00 to 16.00 on 21st March (left) and the fully shaded area derived from the overlapped shadow domain according to the study in 4.1.2.6 (right).

Figure 36 show that the shape of the targeted areas was quite similar for the 21st March case that a slight difference appeared on the south part of the restricted open space.
However, on 21st June, the entirely shaded area derived from the shadow cast image was noticeably smaller than that of sun hour study especially the courtyard condition seen from *Figure 37*. While the result of 21st December presented by *Figure 38* was on the contrary that the shadow range was much larger than the 0 sun hour area where the east part of the

open space experienced the most obvious distinction.

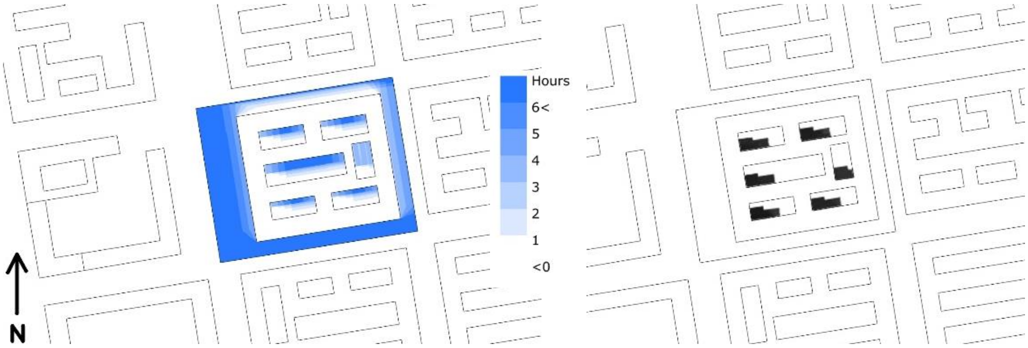


Figure 38 *Sun hour condition from 10.00 to 16.00 on 21st June (left) and the fully shaded area derived from the overlapped shadow domain according to the study in 4.1.2.6 (right).*

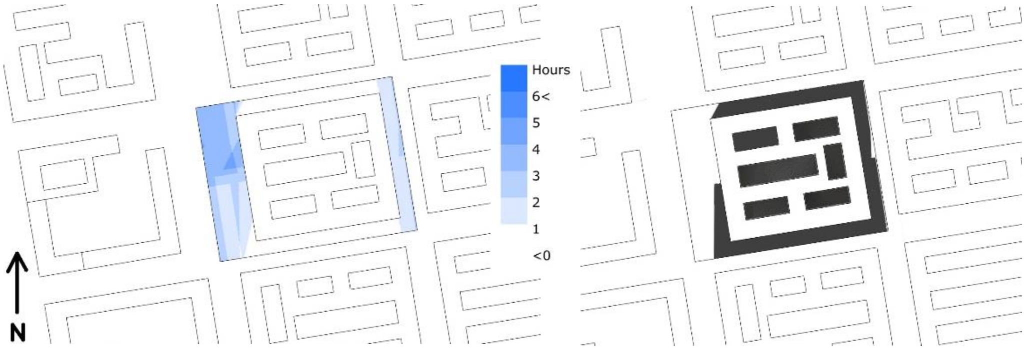


Figure 37 Sun hour condition from 10.00 to 16.00 on 21st December (left) and the fully shaded area derived from the overlapped shadow domain according to the study in 4.1.2.6 (right).

Table 20 shows the detailed numerical results which were corresponded with the above graphs. It was found that large discrepancies appeared on 21st June and 21st December cases, i.e. -17% and +15% respectively. This was due to the fact that the BRE standard asked for the shadow check in every 2 hours between 10.00 and 16.00 during the day while the sun hour study was hourly. It was reasonably inferred that the sun movement was more active on June and December than March that the shadow condition changed more quickly which resulting in the above results.

Table 20 The open space area percentage that obtained 0 sun hour or was fully shaded from 2 type of studies.

	21st March	**21st June**	**21st December**
Sun hour study	47%	27%	55%
Shadow range study	46%	10%	70%

4.1.3 Hong Kong

4.1.3.1 Sun hours

On the Hong Kong site, the building north facades were unable to get 3 sun hours on 20th January, even the tower. *Table 21* shows that the tower obviously performed better than the podium building. However, the south façade of the podium did not achieve the regulation because of the high dense of surrounding urban context. In total, 51% of the studied building surfaces received more than 3 sun hours.

Then for the open space, 77% of the whole area acquired more than 2 sun hours during the day where the southern street performed the best and even the western building canyon achieved the BRE standard seen *Figure 39*. This was because that the sun position was high.

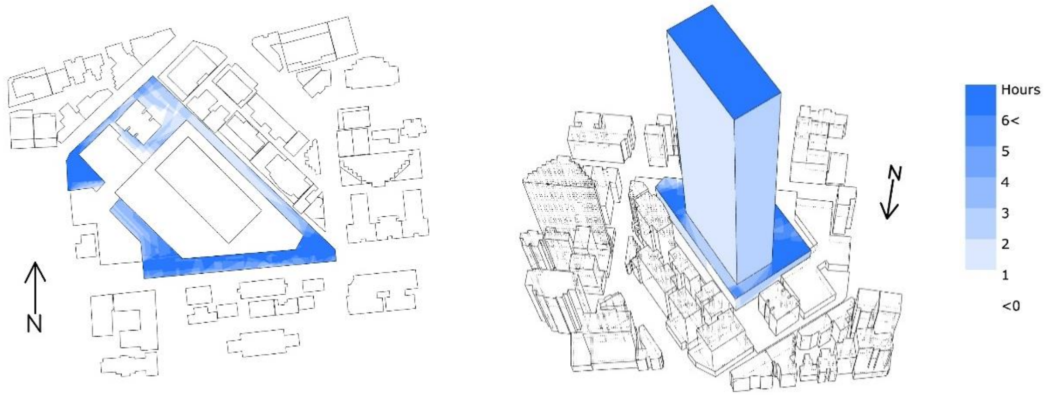


Figure 39 Sun hour conditions for open space (left) on 21st March and building block (right) on 20th January on the Hong Kong site.

Table 21 The building façade area percentage of the base case that met the standard in Hong Kong.

	Northeast	Northwest	Southwest	South	Southeast
Podium	0%	0%	94%	9%	19%
Tower	0%	0%	100%	No sharp south facade	100%

In regard to the ground floor façade, only 4% area received more than 4 sun hours on 20th January which presented in *Figure 40*. It was hard to improve this situation since the street was too narrow and the city was too dense.

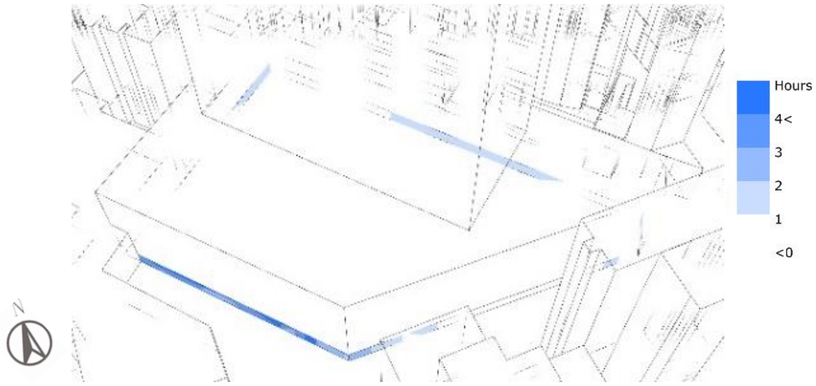


Figure 40 Sun hour condition for the building ground floor facade in Hong Kong on 20th January.

4.1.3.2 Vertical daylight illuminance

The Hong Kong building had the highest VDI performance among the three cities. On 21st June the building performed the best in terms of the vertical illuminance potential on 12.00 noon while that on 10.00 and 16.00 were similarly the worst.

On 12.00 and 14.00, nearly all building facades were illuminated by 10 000 lx sunlight or even stronger seen in *Figure 41*.

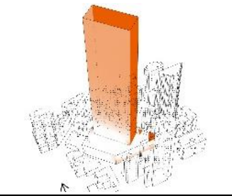
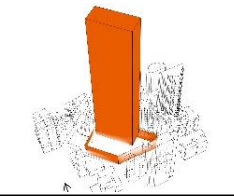
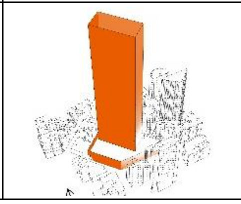
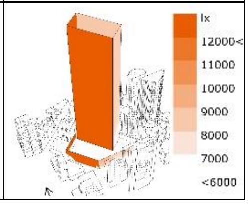
	10.00	12.00	14.00	16.00
21.06 				

Figure 41 The VDI distributions for four selected hours on 21st June – base case of Hong Kong.

4.1.3.3 Vertical daylight factor

Unlike Copenhagen and Berlin, Hong Kong does not have VSC building codes, but there are VDF standards for residential buildings. VDF contains reflected light based on the formula, so it should be larger in value than VSC. In the base case, the reflectance of the studied building façade was 0.64, which was assumed as glazing. And the reflectance of surrounding buildings was 0.6. However, the VDF standard in Hong Kong is even lower than the VSC standard of BRE. The VDF results of the base case in Hong Kong are shown below in *Figure 42* and the north-west façade as well.

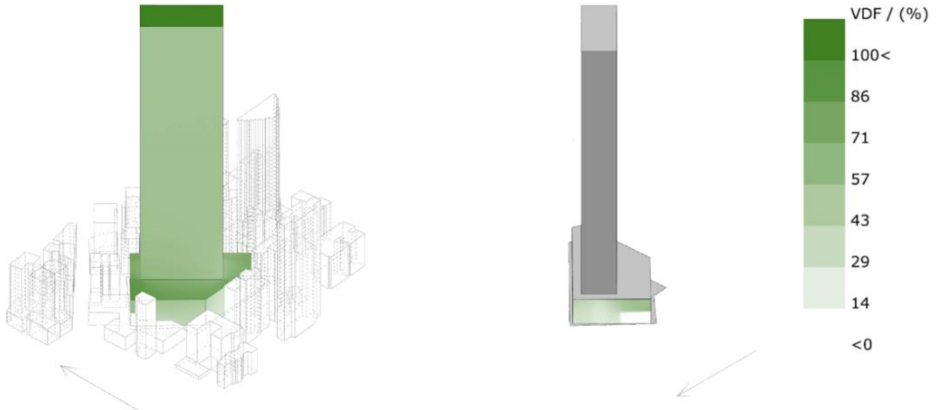


Figure 42 VDF results of base case in Hong Kong (left) and the result of north-west façade (right).

The ratio of each surface that can meet the VDF standard for kitchen and habitable room in Hong Kong are shown in *Table 22* and *Table 23* below. All surfaces of tower and façades of podium except north-west and south-west can meet the VDF standard requirements in Hong Kong.

Table 22 The ratio of each surface that met the VDF standard for kitchen in Hong Kong.

	Northeast	Northwest	Southwest	South	Southeast	Roof	Total
Podium	100%	84%	96%	100%	100%	100%	97%
Tower	100%	100%	100%	-	100%	100%	100%
Total	-	-	-	-	-	-	100%

Table 23 The ratio of each surface that met the VDF standard for habitable room in Hong Kong.

	Northeast	**Northwest**	**Southwest**	**South**	**Southeast**	**Roof**	**Total**
Podium	100%	82%	96%	100%	100%	100%	97%
Tower	100%	100%	100%	-	100%	100%	100%
Total	-	-	-	-	-	-	99%

4.1.3.4 Heating season irradiation

The surface area that achieved the recommended heating season irradiation in Hong Kong was around 100% (98% in specific) seen in *Figure 43*.

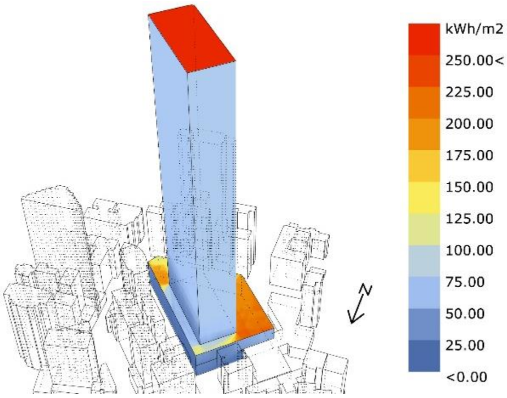


Figure 43 Heating season irradiation result of base case in Hong Kong.

4.1.3.5 Annual solar irradiation

The annual solar irradiation of the facades of base case in Hong Kong is shown in *Figure 44* below. The results were much better than other two cities. Hong Kong is located at a lower latitude, and the building height is also much higher than that of the other two cities. However, specific analysis of which planes are suitable for installing PV systems also requires local standards in Hong Kong.

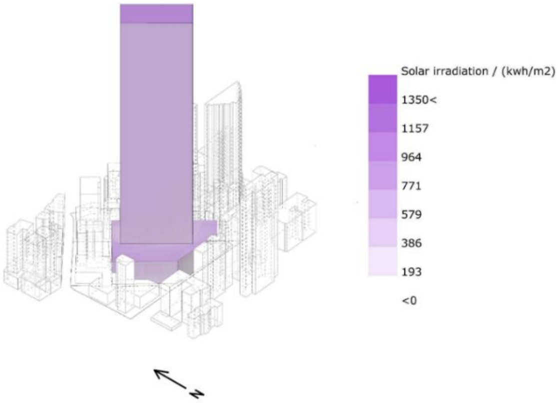


Figure 44 The annual solar irradiation of base case in Hong Kong.

Based on the further monthly analysis, the time period between August to October had the greatest potential for PV system displayed in *Figure 45*. However, the specific situation must be analysed according to local standards.

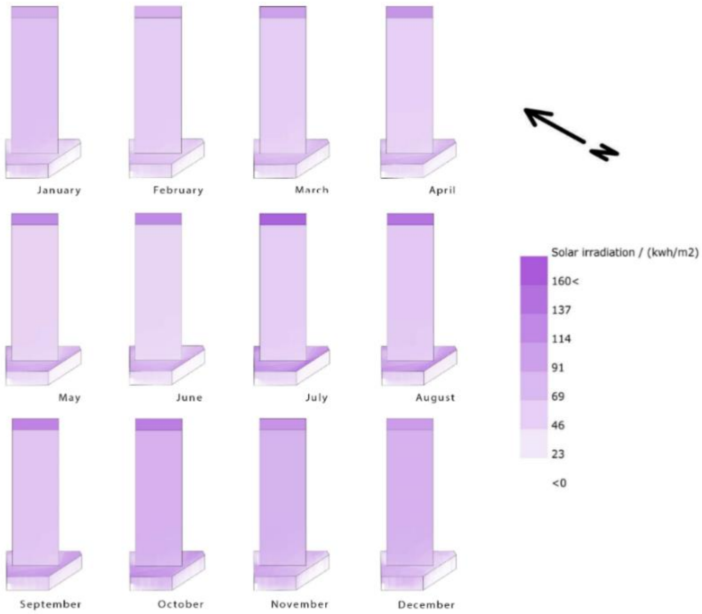


Figure 45 The monthly solar irradiation analysis of base case in Hong Kong.

4.1.3.6 Shadow cast study

It can be found that at 12.00 on 21st June, there was nearly no shadow at the surrounding open space whereas the eastern street was shaded for almost all the time except 10.00 21st December (*Figure 46*). Also, on 21st June, the tower's shadow was located on the south side which was distinct among the three cities. This was account on its sun position due to the low latitude.

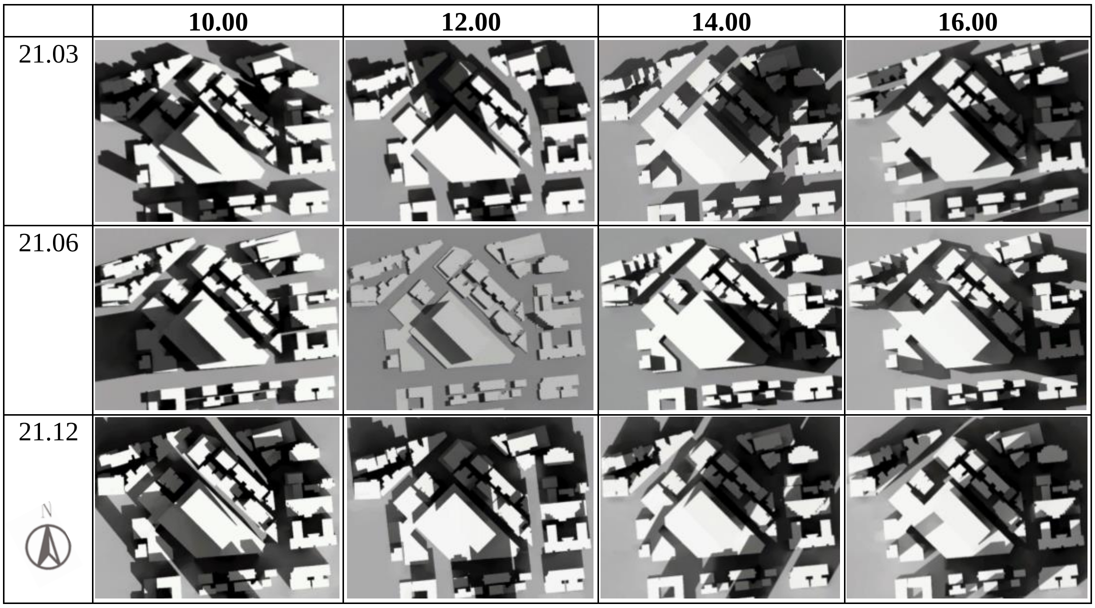


Figure 46 The building shadow cast for four selected hours on 21st March, 21st June and 21st December – Base case of Hong Kong.

4.2 Parametric study

4.2.1 Copenhagen

4.2.1.1 Density variations

4.2.1.1.1 Sun hours

Both Density 1 and Density 2 were taller than the base case which meant that they had smaller floor area and courtyard area. Their sun hour acquiring conditions are shown in *Figure 47* and *Figure 48*.

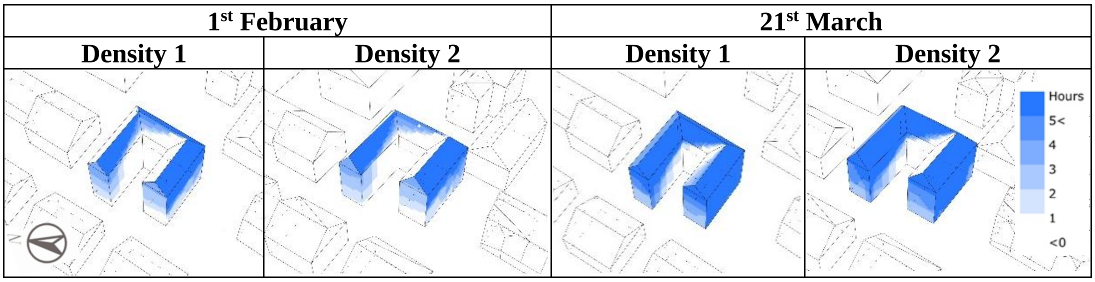


Figure 47 Sun hour distributions for entire building on 1st February and 21st March – density variations of Berlin.

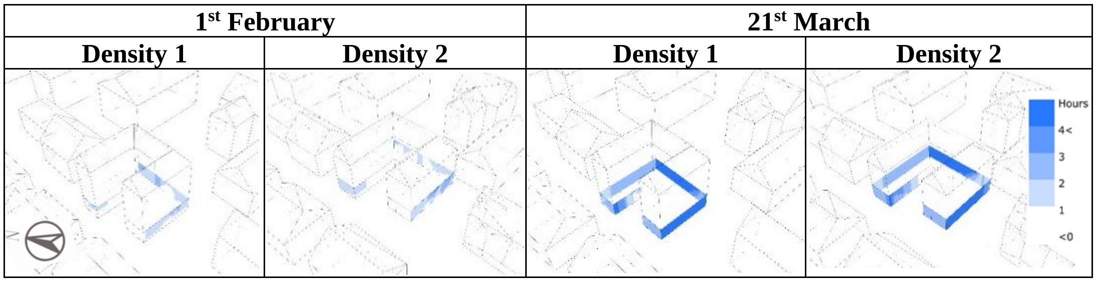


Figure 48 Sun hour distributions for building ground floor facades on 1st February and 21st March – density variations of Berlin.

Density 1 got significant improvement regarding the façade performance. For instance, 50% of the building surface got more than 1.5 sun hours on 1st February while its counterparts of base case and Density 2 was 20% and 29% respectively in *Figure 50*. However, from both *Figure 49* and *Figure 50*, it can be surprisingly observed that the overall performance rank was Density 2 < Base case < Density 1 rather than Base case < Density 2 < Density 1 which was expected initially. This indicated that the higher building height could balance the smaller inner courtyard size to some extent considering the building's sun hour potential.

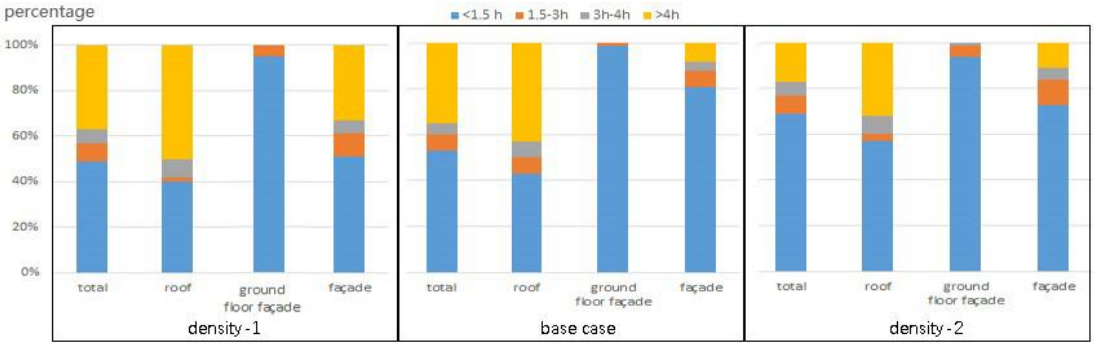


Figure 50 The accumulated figures of the percentage of building surfaces (density variations) that in the four sun hour range of EU sunlight guideline on 21st March.

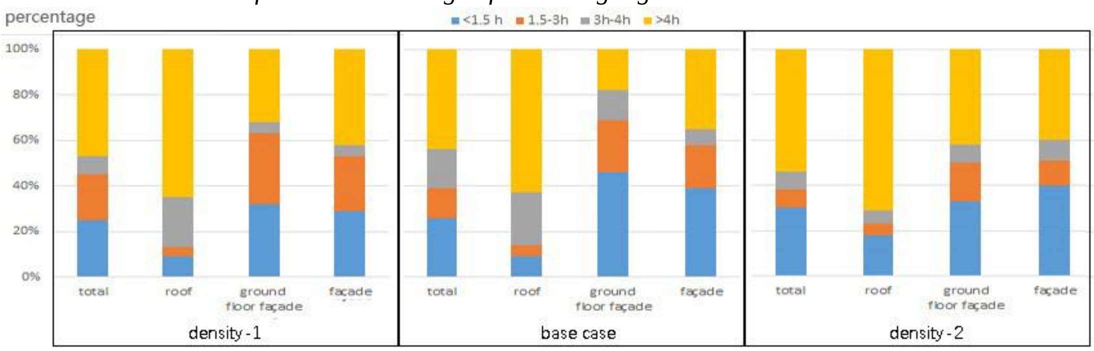


Figure 49 The accumulated figures of the percentage of building surfaces (density variations) that in the four sun hour range of EU sunlight guideline on 1st February.

4.2.1.1.2 Vertical daylight illuminance

In *Figure 51*, the Density 1 case performed bad particularly on 12.00 and 14.00 in regard to the inner facades. Besides the outer west facades, the south façade performed well as well during the whole day.

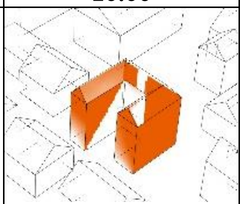
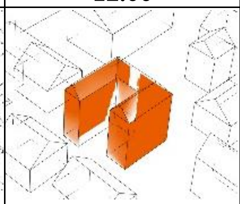
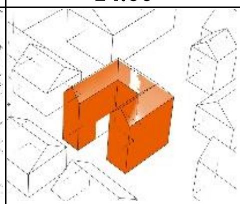
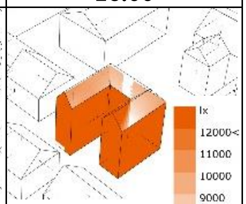
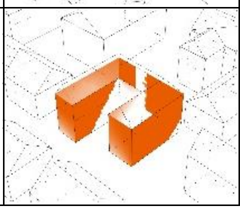
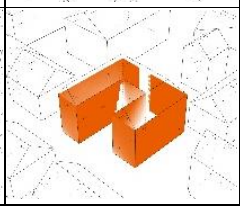
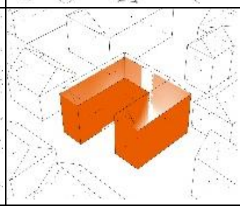
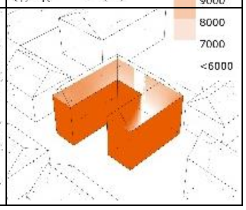
	10.00	12.00	14.00	16.00
21.06 (Density 1)				
21.06 (Density 2)				

Figure 51 The VDI distributions for four selected hours on 21st June – density cases of Copenhagen.

4.2.1.1.3 Vertical sky component

The height of the two study cases were all higher than the base case. And the east roof surface of these two cases can not meet the recommendation. The performance of the east façade was basically the same as the base case. The results are shown in *Figure 52* in two perspectives.

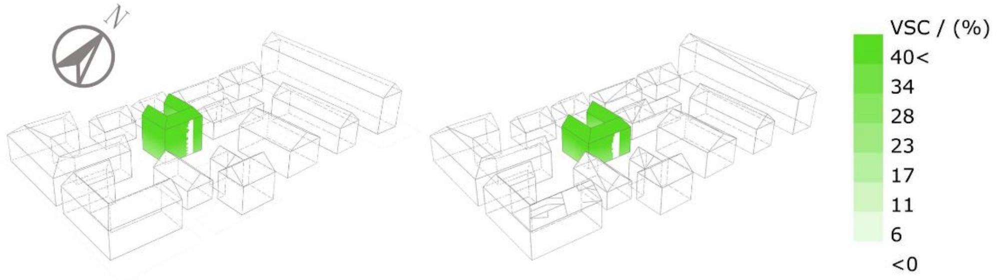


Figure 52 The VSC results of two density study cases in Copenhagen.

The VSC results of roof and east surface were basically the same in these two cases. For other surfaces, study case 2 was almost all better than study case 1 in all thresholds as shown in *Figure 53* below.

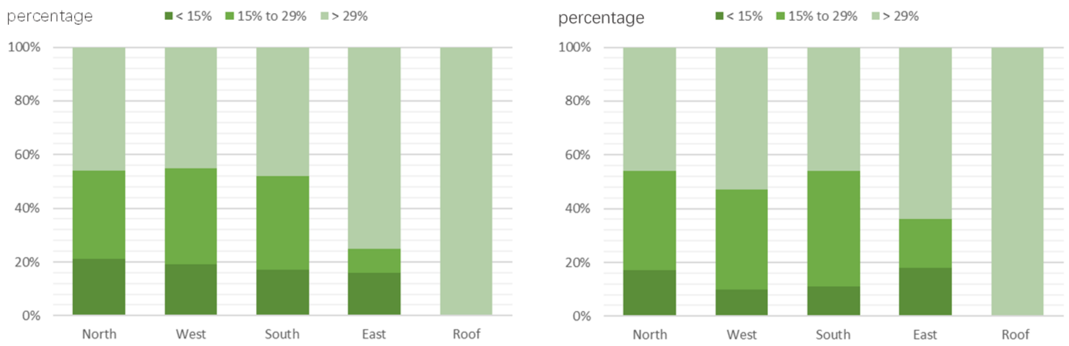


Figure 53 The ratio of density case 1 (left) and density case 2 that met the VSC recommendation in Copenhagen.

The ratio of two cases that had VSC results over 15% is shown in *Table 24*. Thus, the VSC performance of buildings with same density and floor area decreased as the number of building floors increased in this study.

Table 24 The ratio of two study cases that had the VSC over 15%.

	North	West	South	East	Roof
Study case1	79%	81%	83%	84%	69%
Study case2	83%	90%	89%	82%	68%

4.2.1.1.4 Heating season irradiation

It can be seen from *Figure 54* that the studied percentage saw a 2% decrement but a 4% increment when the building height was increased by 1/4 and 1/2. This was due to the wall exposure when the building was higher than surrounding buildings.

Density1	Density2
18%	14%

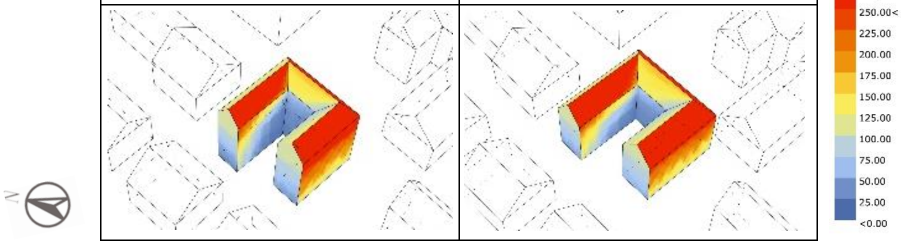


Figure 54 The heating season irradiation distributions – density variations of Copenhagen.

4.2.1.1.5 Shadow study

Density did not affect the shadow casting circumstance at all in such a small scale that this result was derived from *Figure 55* and *Figure 56*.

	10.00	12.00	14.00	16.00
21.03				
21.06				
21.12				

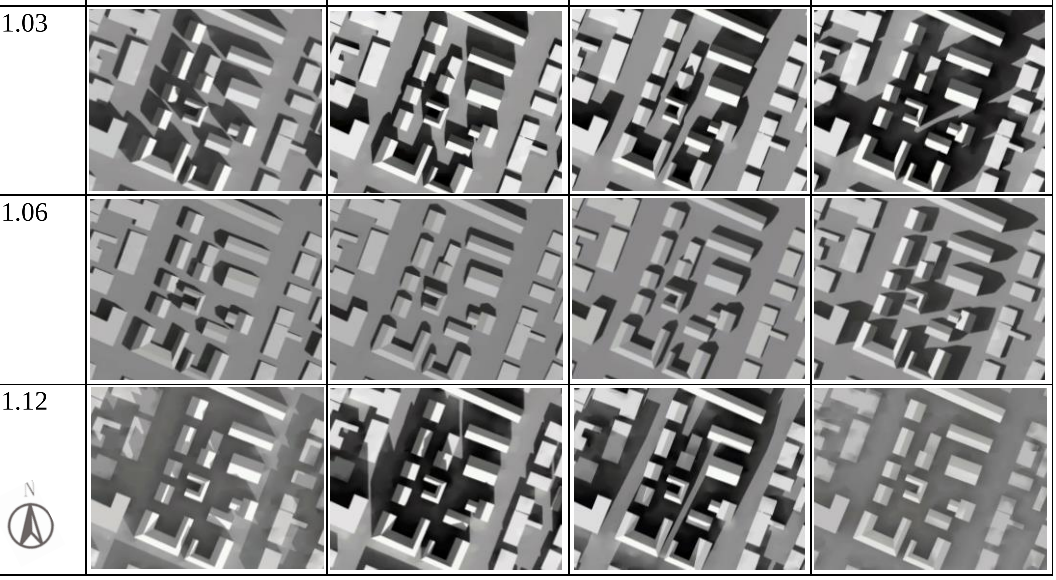


Figure 55 The building shadow cast for four selected hours on 21st March, 21st June and 21st December – Density 1 case of Copenhagen.

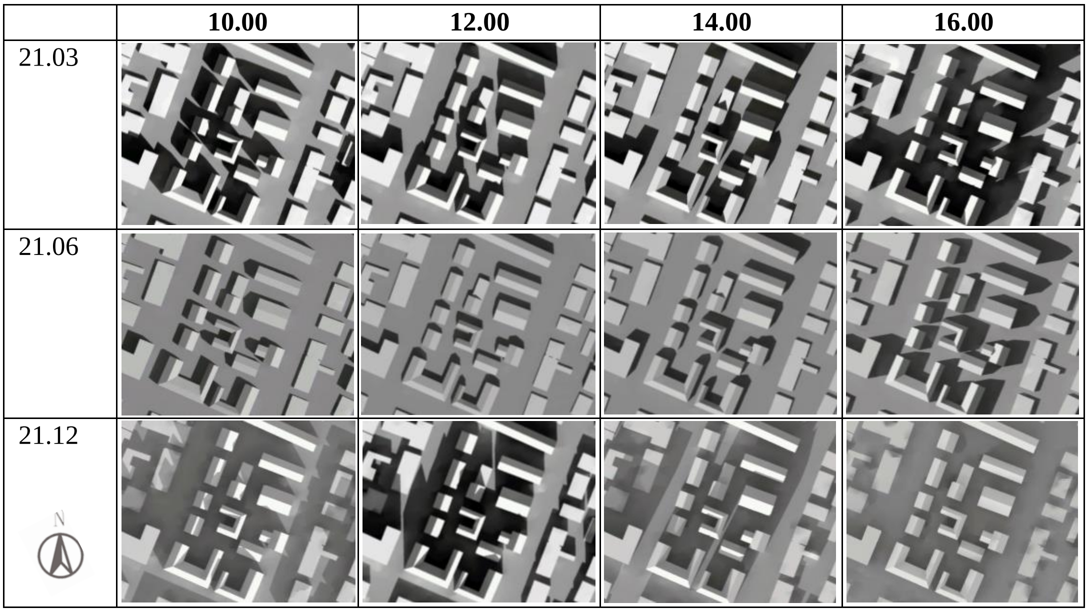


Figure 56 The building shadow cast for four selected hours on 21st March, 21st June and 21st December – Density 2 case of Copenhagen.

4.2.1.2 Shape variations

4.2.1.2.1 Sun hours

The sun hour results are shown in *Figure 57*. Shape 1 had simple metric but relatively the best sun hour gain. *Figure 58* also shows that the ground floor façade obtained more sunlight in Shape 1 case. This was because that the building Shape 1 was simple and without self-occlusion.

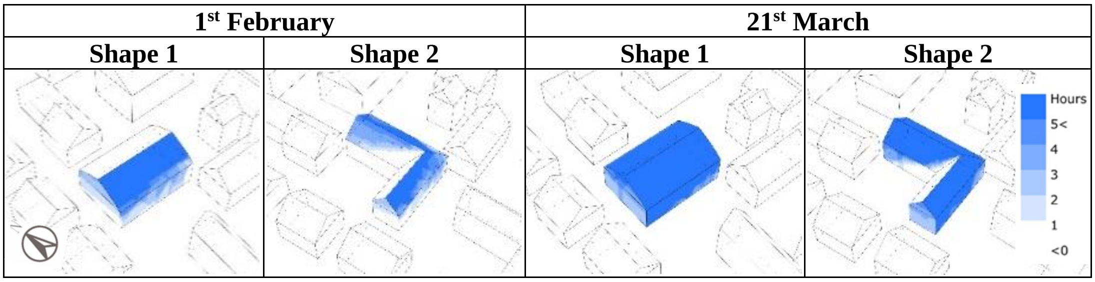


Figure 57 Sun hour distributions for entire building on 1st February and 21st March – shape variations of Berlin.

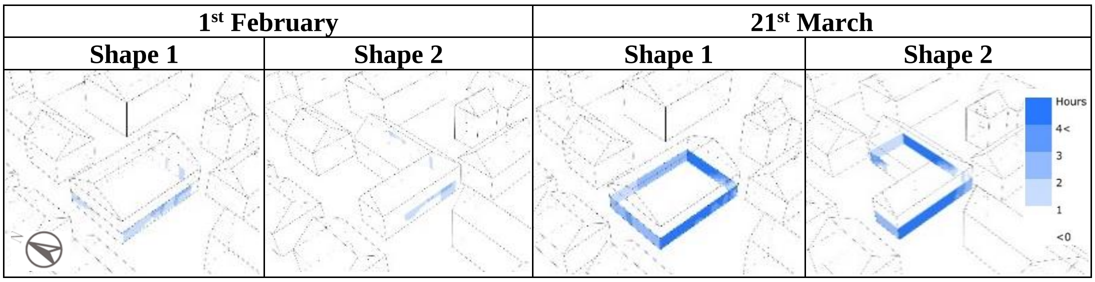


Figure 58 Sun hour distributions for building ground floor facades on 1st February and 21st March – shape variations of Berlin.

Figure 59 and *Figure 60* present that linear shape (Shape 1) helped raising the ground floor façade and building façade sun hour gain especially the area percentage lying in 1.5 – 3 h range. Even though all cases had the same roof slope, the L-shape case and base case had their roofs mutual-shaded that decreased the roof performance.

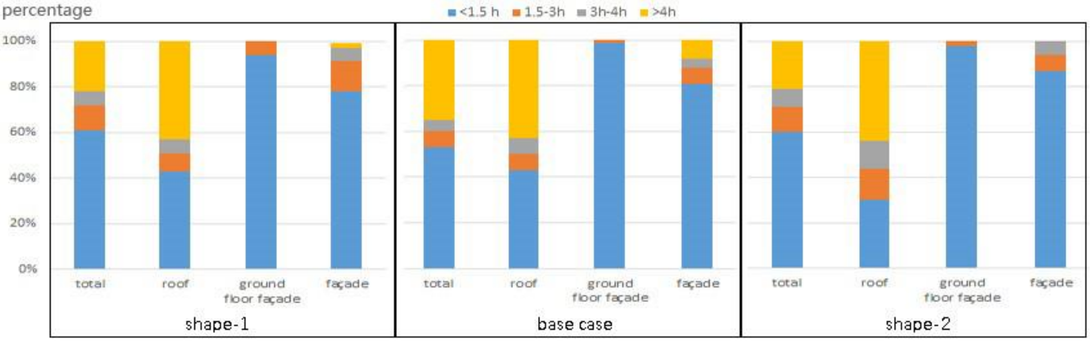


Figure 59 The accumulated figures of the percentage of building surfaces (shape variations) that in the four sun hour range of EU sunlight guideline on 1st February.

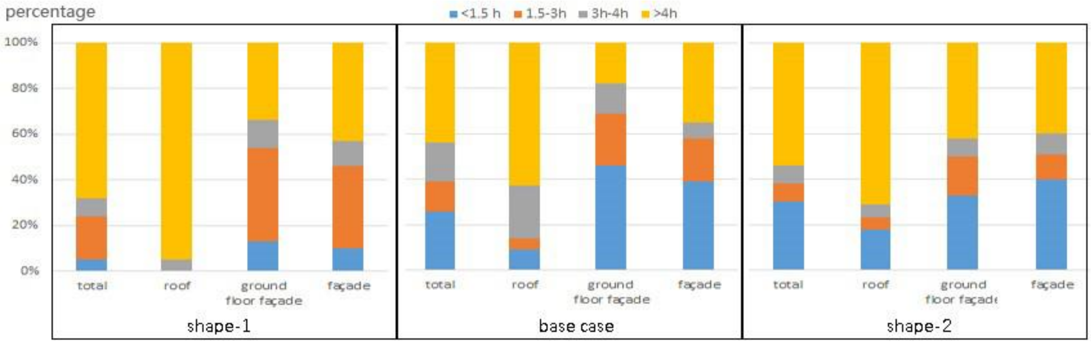


Figure 60 The accumulated figures of the percentage of building surfaces (shape variations) that in the four sun hour range of EU sunlight guideline on 21st March.

4.2.1.2.2 Vertical daylight illuminance

Figure 61 shows that the illuminance distribution was common as expected that the south façade always had the best illumination. However, it can be seen that the closed surrounding buildings provided the studied building with high reflection that increased the performance a lot seeing the north façade illuminance distribution of 'Shape 1 14.00'. For these two cases, the worst condition appeared on 16.00.

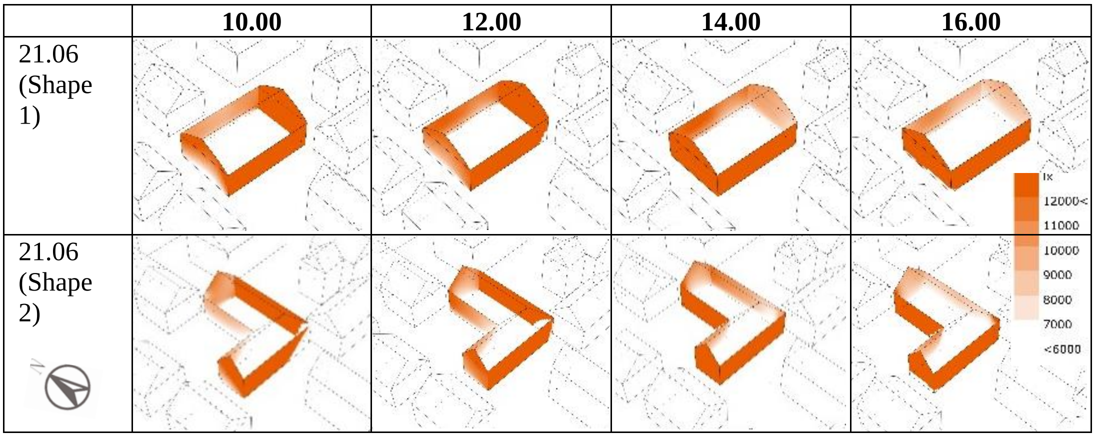


Figure 61 The VDI distribution for four selected hours on 21st June – shape variations of Copenhagen.

4.2.1.2.3 Vertical sky component

The shape of study case 1 and 2 were linear and L-shape respectively. The east and south roof surfaces in these two cases were all in bad conditions as shown in *Figure 62*.

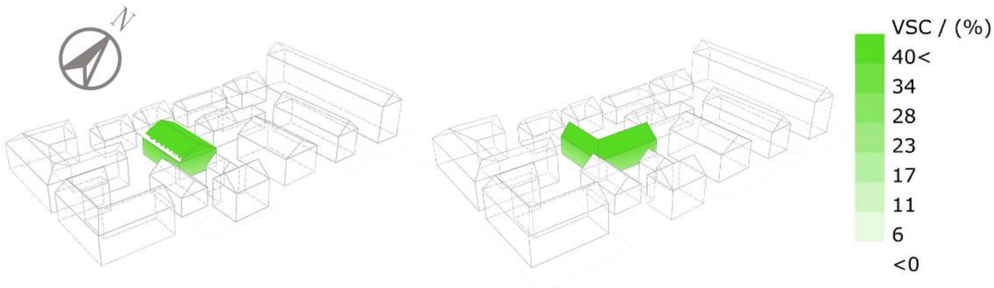


Figure 62 The VSC results of two shape study cases in Copenhagen.

In the threshold of over 29%, north, west and roof surface of study case 2 was better than case 1. And for other surfaces, they were exactly the opposite. In the threshold of between 15% to 29%, the performance of the envelope in four directions were the opposite of the first threshold while the roof was in same condition. These results are shown in *Figure 63*.

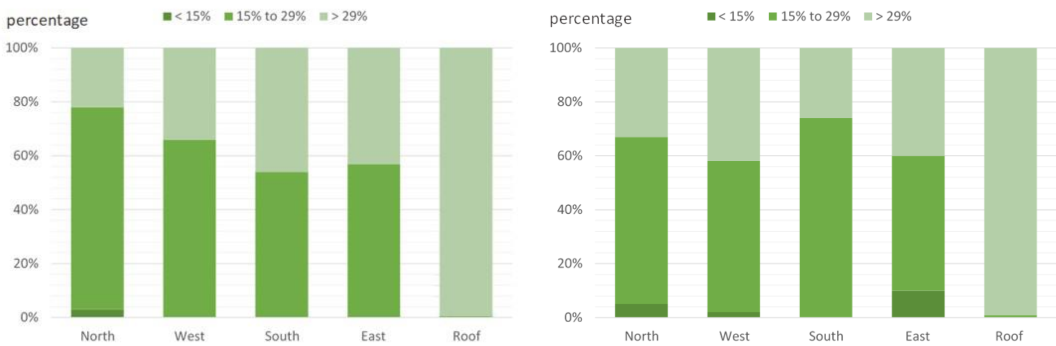


Figure 63 The ratio of shape case 1 (left) and shape case 2 (right) that met the VSC recommendation in Copenhagen.

If the sum of these two thresholds was considered in this study, study case 1 was always better than case 2 except roof surface as shown in *Table 25*.

Table 25 The ratio of two study cases that had the VSC over 15%.

	North	West	South	East	Roof
Study case 1	97%	100%	100%	100%	44%
Study case 2	95%	98%	100%	90%	54%

4.2.1.2.4 Heating season irradiation

The shape change helped to increase the potential slightly by opening the courtyard from 16% (base case) to 20% (both shape variations) looking at *Figure 64*. The west roof of Shape 2 saw the most noticeable improvement compared with the base case.

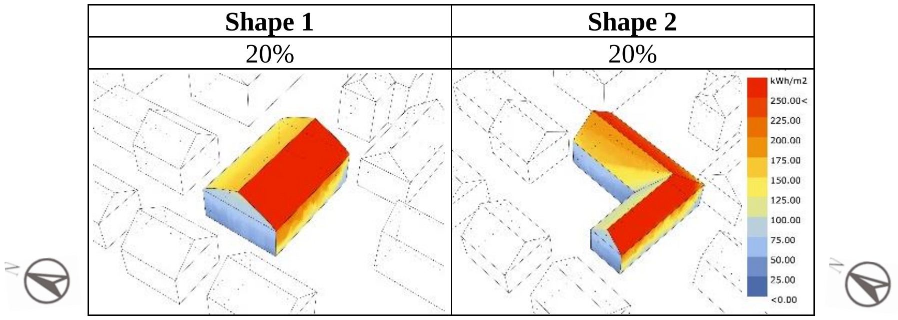


Figure 64 The heating season irradiation distributions – shape variations of Copenhagen.

4.2.1.2.5 Shadow study

There was no inner courtyard for this linear shape, but the building shadow covered smaller surrounding courtyard area as presented in *Figure 65*.

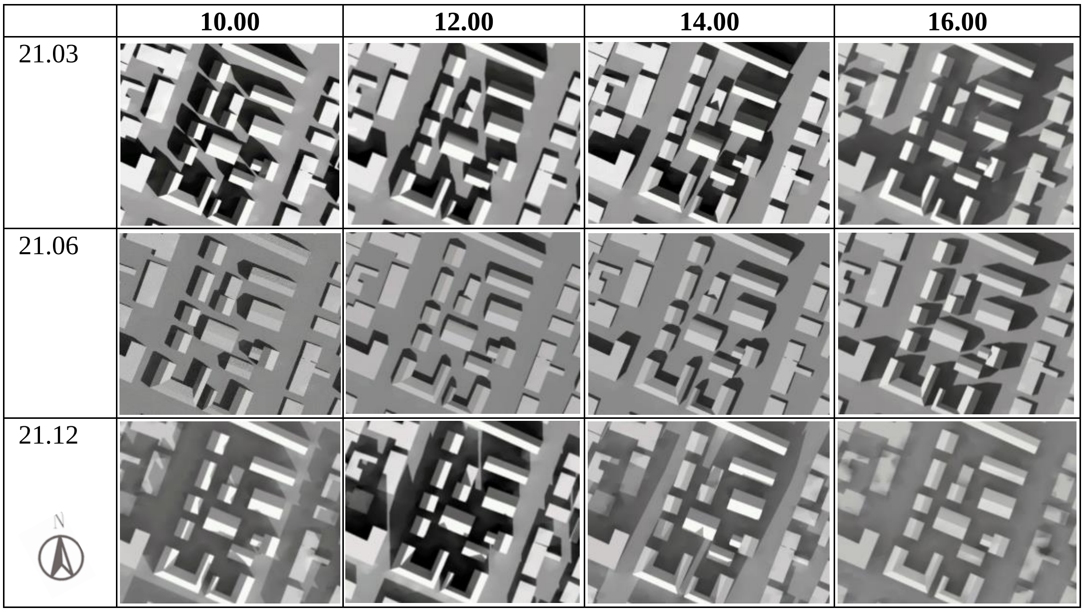


Figure 65 The building shadow cast for four selected hours on 21st March, 21st June and 21st December – Shape 1 case of Copenhagen.

This L-shape building had the best courtyard shadow performance among all three cases indicating that semi-enclosed courtyard was better than three-sides enclosure courtyard seen in *Figure 66*.

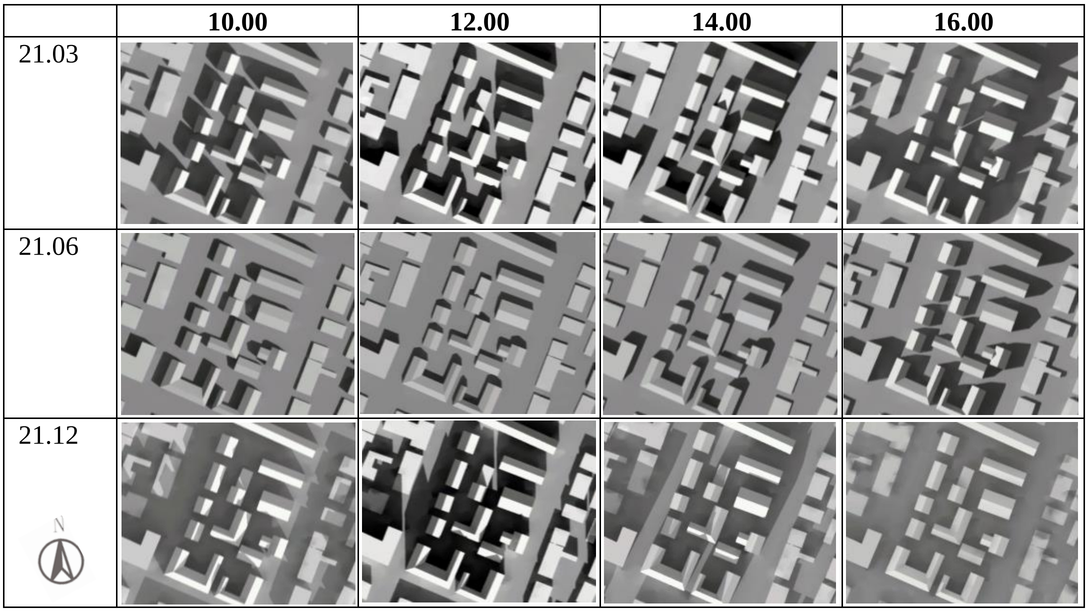


Figure 66 The building shadow cast for four selected hours on 21st March, 21st June and 21st December – Shape 2 case of Copenhagen.

4.2.1.3 Roof variations

4.2.1.3.1 Sun hours

Figure 67 shows that compared with slope roof, 100% area of the flat roof accomplished the regulation while the north façades: neither the roof nor the wall was exposed to the direct sun on both days.

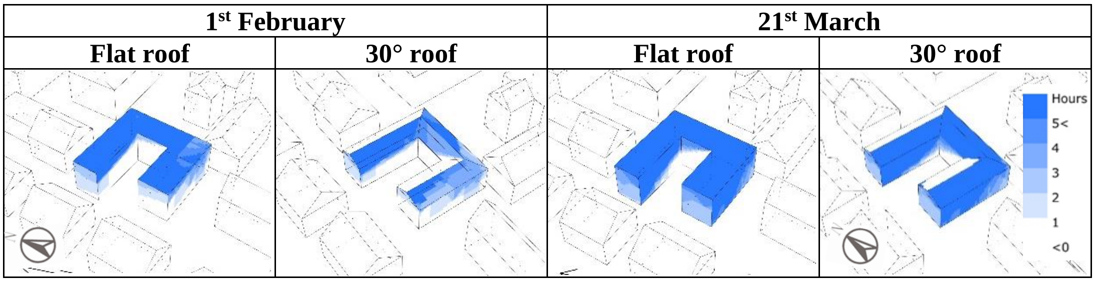


Figure 67 Sun hour distributions for building block on 1st February and 21st March – roof type variations of Copenhagen.

Combining *Figure 68* and *Figure 69*, flat roof performed the best considering the roof performance on both days that nearly 100% area obeying the sunlight recommendation. Also, the roof potential increased with the roof slope degree increasing if the roof was pitched.

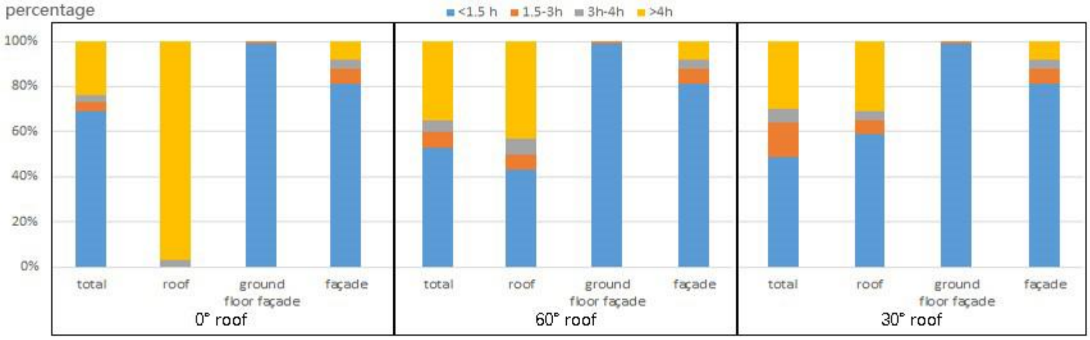


Figure 69 The accumulated figures of the percentage of building surfaces (roof variations) that in the four sun hour range of EU sunlight guideline on 1st February.

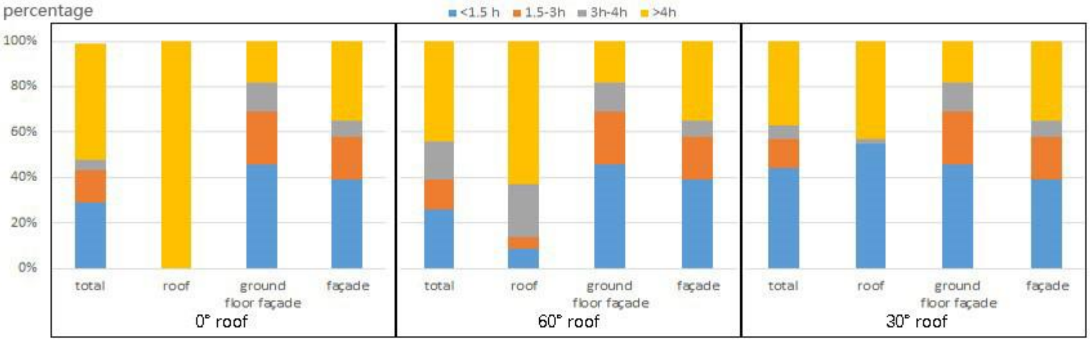


Figure 68 The accumulated figures of the percentage of building surfaces (roof variations) that in the four sun hour range of EU sunlight guideline on 21st March.

4.2.1.3.2 Vertical sky component

The roof inclination of study case 1 and 2 were 0 degree and 30 degrees, which were all lower than the base case. The VSC results of these two cases are shown in *Figure 70* below. The east façade was also the worst one as base case.

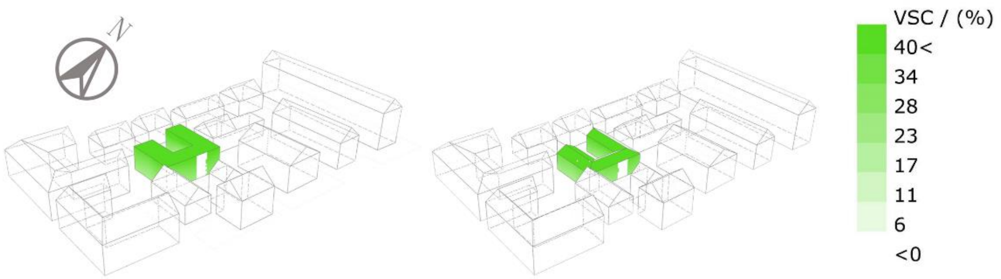


Figure 70 The VSC results of two roof study cases in Copenhagen.

In the threshold of over 29%, all the surfaces of study case 1 was better than case 2. In the threshold of between 15% to 29%, the performance of the envelope in four directions were the opposite of the first threshold while the roof was in the same condition. This is shown in *Figure 71* below.

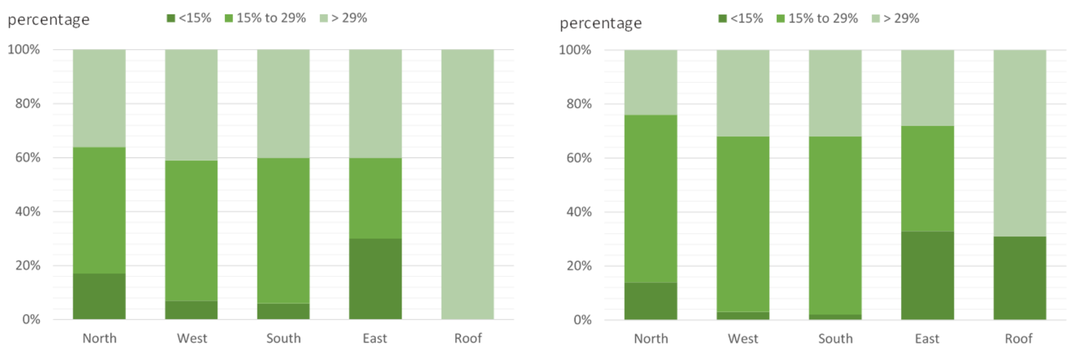


Figure 71 The ratio of roof case 1 (left) and roof case 2 that met the VSC recommendation in Copenhagen.

If the sum of these two thresholds was considered, study case 2 was better than case 1 except roof and east surface as shown in *Table 26*.

Table 26 The ratio of two study cases that had the VSC over 15%.

	North	**West**	**South**	**East**	**Roof**
Study case 1	83%	93%	94%	70%	100%
Study case 2	86%	97%	98%	67%	69%

4.2.1.3.3 Heating season irradiation

Flat roof gained the highest amount of heating season irradiation while the ratio remained the same as 16% whatever the roof degree varied shown in *Figure 72*.

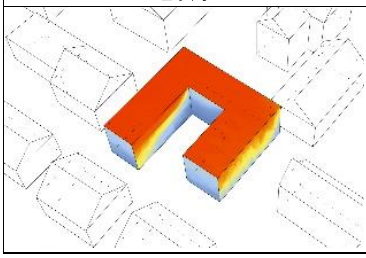
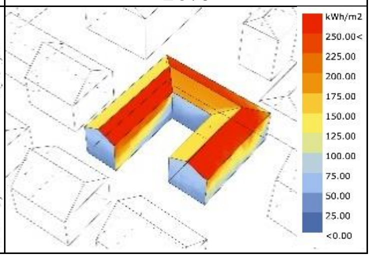
0° roof	**30° roof**
20%	16%
	

Figure 72 The heating season irradiation distributions– roof variations of Copenhagen.

4.2.1.4 Material variations

4.2.1.4.1 Vertical daylight illuminance

In Berlin, the biggest difference regarding the VDI between concrete and glass was that the north façade was unable to get any reflection from the surrounding glass buildings seen from *Figure 73*. It is worth mentioning that for glass curtain variation, the best illuminance condition appeared on 14.00 rather than 12.00.

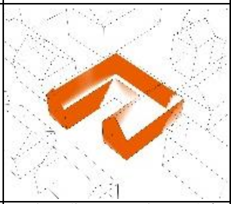
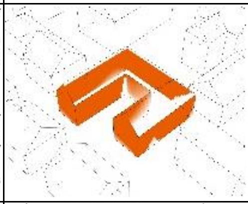
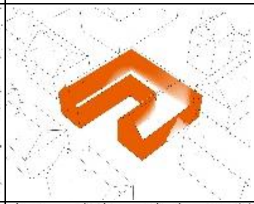
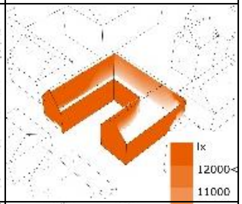
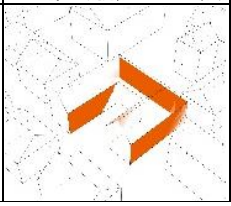
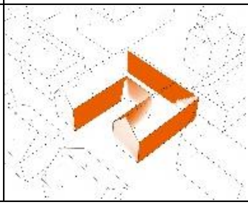
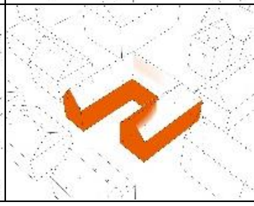
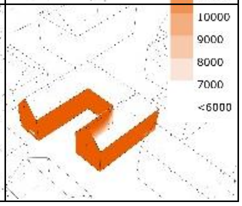
	10.00	12.00	14.00	16.00
21.06 (Material 1)				
21.06 (Material 2)				

Figure 73 The VDI distributions for four selected hours on 21st June – material variations of Copenhagen.

4.2.1.5 Combination for vertical daylight illuminance

Figure 74 presents that the percentage range for different case varied a lot. In particular, the Material 1 improved the performance significantly that its low bound: 77% was higher than the high bound: 73% of the base case whereas the worst variation was Shape 2. It was surprisingly that Density 2 case performed slightly better than the base case indicating that in Copenhagen, the VDI performance could be improved by finding an appropriate height-floor area integration.

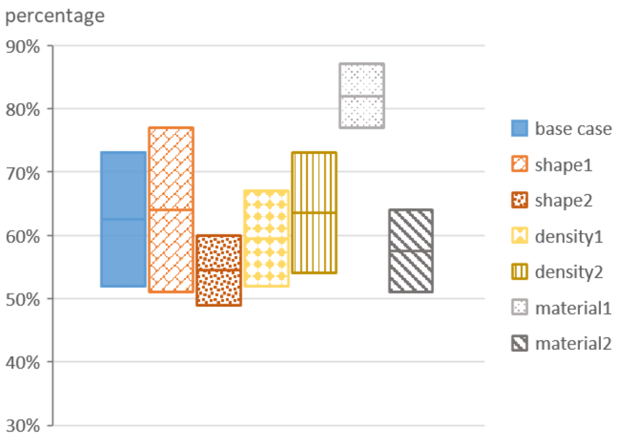


Figure 74 The range of percentage of surface area that received more than 10 000 lx for each case of Copenhagen on 21st June.

4.2.2 Berlin

4.2.2.1 Density variations

4.2.2.1.1 Sun hours

Density 2 case had a larger surrounding public space which contributed to a much better outer façade sunlight potential illustrated by *Figure 75* and *Figure 76*.

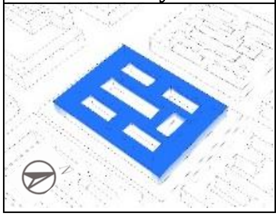
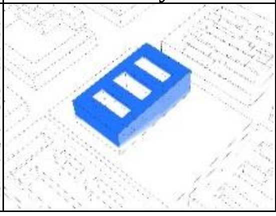
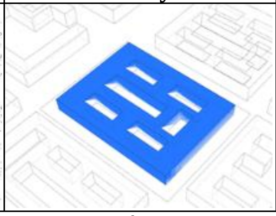
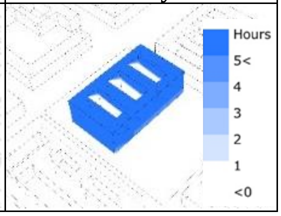
1st February		21st March	
Density 1	**Density 2**	**Density 1**	**Density 2**
			

Figure 75 Sun hour distributions for entire building on 17th January and 21st March – density variations of Berlin.

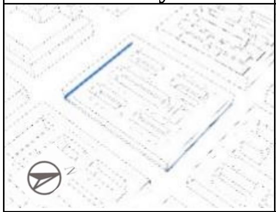
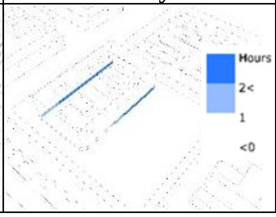
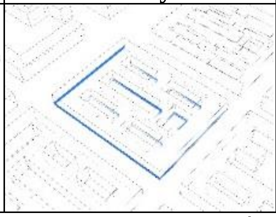
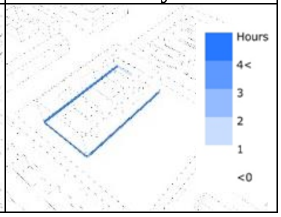
1st February		21st March	
Density 1	**Density 2**	**Density 1**	**Density 2**
			

Figure 76 Sun hour distributions for building ground floor facade on 17th January and 21st March – shape variations of Berlin.

Looking at the total percentage which achieved the standard, the ratio was similar shown in *Figure 77*. Inner facades received less sunlight when the building became taller. Density 2 was the best among the three cases considering only the outer facades while density 1 got the largest inner facades sun potential.

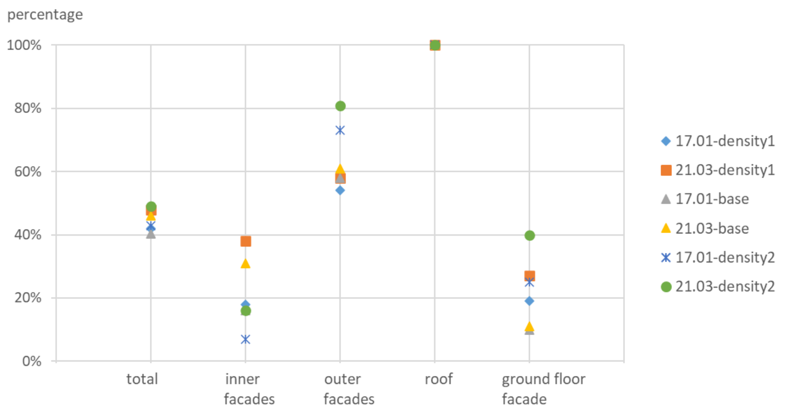


Figure 77 The exact percentage of the surface area that obeyed the sun hour regulation organised by different building elements and the overview consisting of the base case and density variations in Berlin.

4.2.2.1.2 Vertical daylight illuminance

Figure 78 illustrates that since the building of Density 2 case was twice as tall as the base case, its courtyard south facades' illumination dropped noticeably. But there was no clear difference between the results of base case and Density 1 case even if the building height was decreased in the latter case.

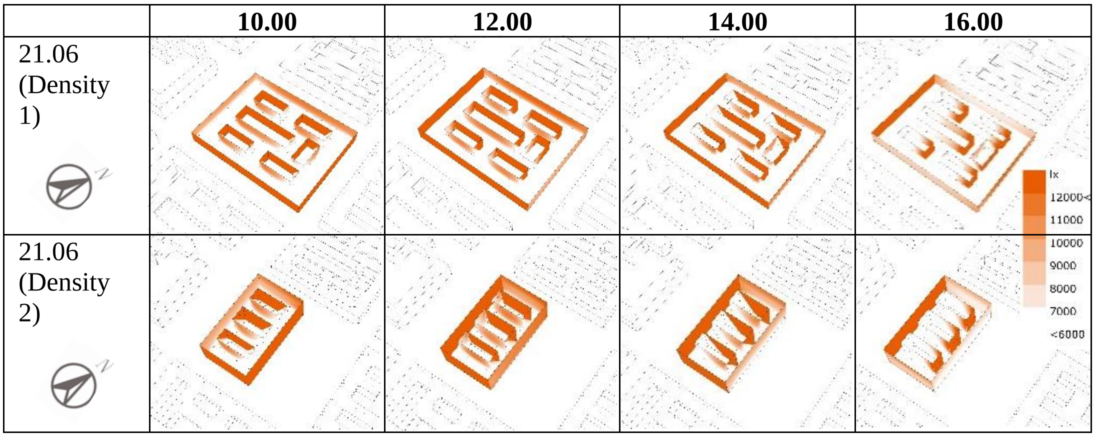


Figure 78 The VDI distribution for four selected hours on 21st June – density variations of Berlin.

4.2.2.1.3 Vertical sky component

The VSC results of two density study cases in Berlin are shown in *Figure 79*.

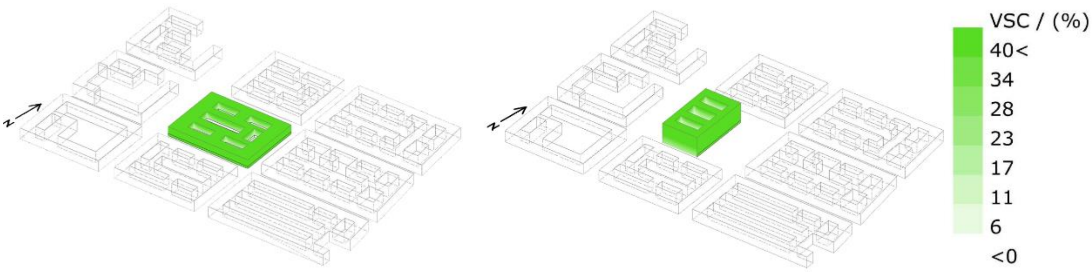


Figure 79 The VSC results of two density study cases in Berlin.

Study case 1 was better than case 2 except the west and south facades. While a sharp raise in regard to the south façade performance was seen from study case 2 which is shown in *Table 27*.

Table 27 The ratio of two study cases that met the VSC recommendation (> 27%) in Berlin.

Study case 1					Study case 2				
North	**West**	**East**	**South**	**Roof**	**North**	**West**	**East**	**South**	**Roof**
52%	67%	48%	50%	100%	41%	73%	40%	73%	100%

4.2.2.1.4 Heating season irradiation

Density 2 accumulated the least solar irradiation during the heating period. Its surface area that had full passive heating possibility decreased by 10% compared with the base case shown in *Figure 80*. This was resulted from the building footprint and height variation.

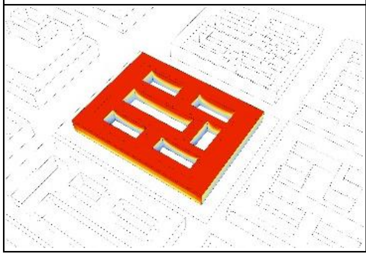
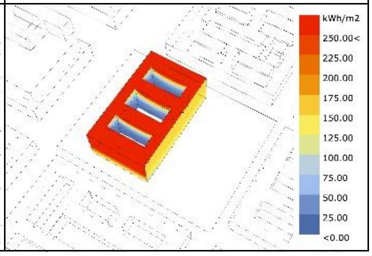
Density 1	**Density 2**
52%	37%
	

Figure 80 The heating season irradiation distributions – density variations of Berlin.

4.2.2.1.5 Shadow study

It was observed from *Figure 81* that when the building was shortened by 1/5, the shadow area on the streets was reduced by around 25% except 21st December.

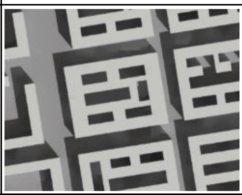
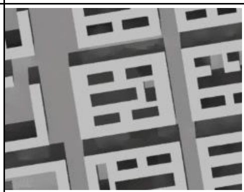
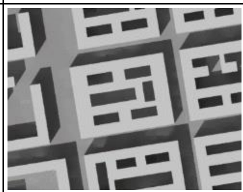
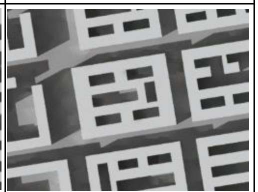
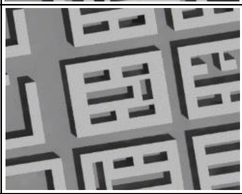
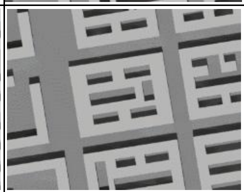
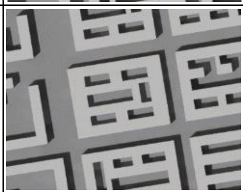
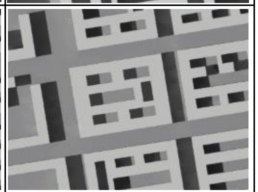
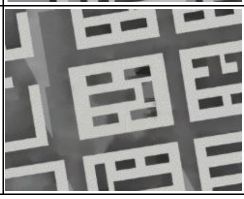
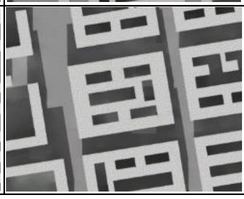
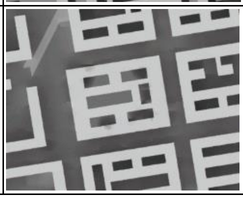
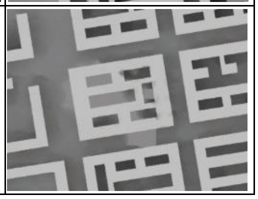
	10.00	**12.00**	**14.00**	**16.00**
21.03				
21.06				
21.12				

Figure 81 The building shadow cast for four selected hours on 21st March, 21st June and 21st December – Density 1 case of Berlin.

It was found that at dusk hours on 21st March, no matter how large the open space (eastern one seen in *Figure 82*) was, the shadow was always quite long.

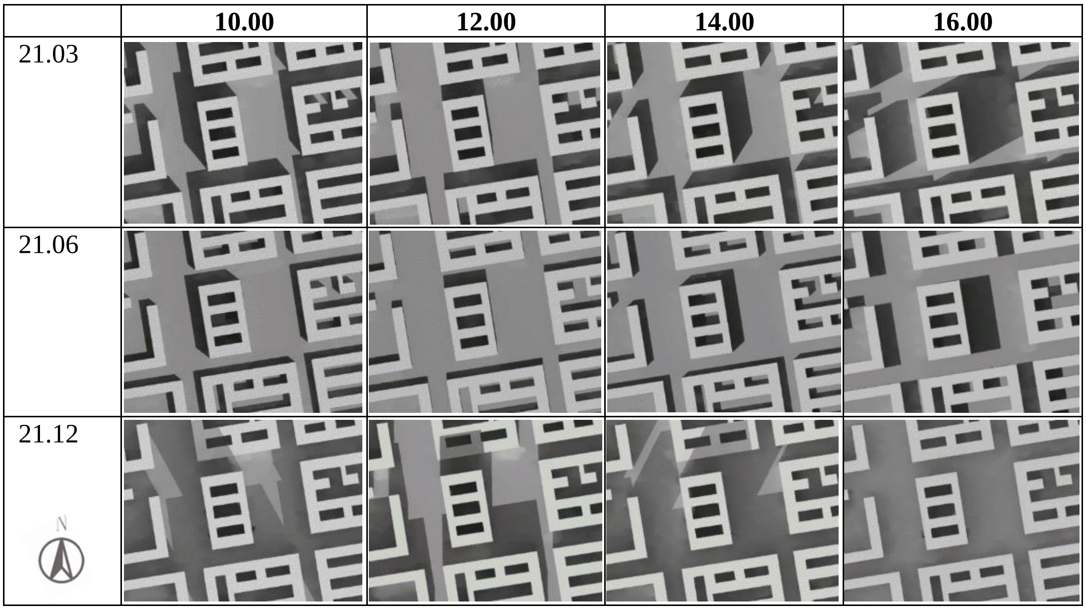


Figure 82 The building shadow cast for four selected hours on 21st March, 21st June and 21st December – Density 2 case of Berlin.

4.2.2.2 Shape variations

4.2.2.2.1 Sun hours

Shape 2 had larger central courtyard resulting in better inner facades sunlight performance than the other two cases especially the ground floor façades (*Figure 84*). In all, Shape 2 had a smaller building footprint that had a much better sun hour performance in total seen in *Figure 83*. Moreover, it also shows that the inner facades of Shape 1 case received 0 sun hour during 17th January.

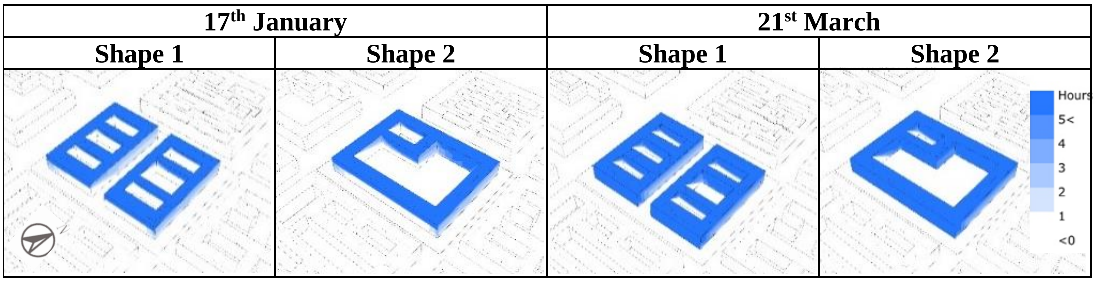


Figure 83 Sun hour distributions for entire building – shape variations of Berlin.

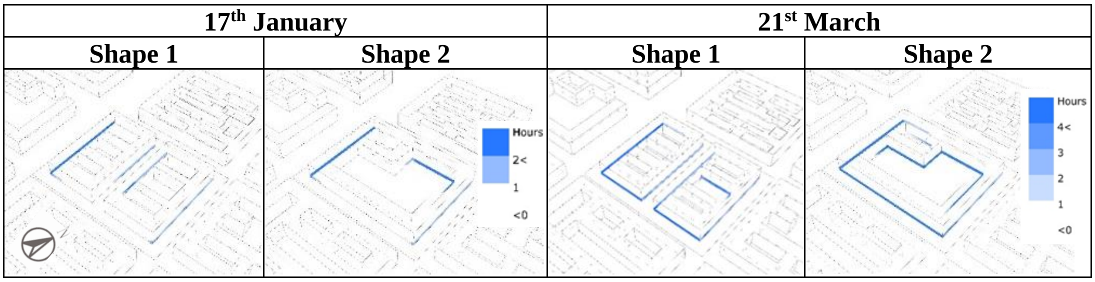


Figure 84 Sun hour distributions for building ground floor facade – shape variations of Berlin.

In *Figure 85*, Shape 1 had its outer surface potential increased significantly from 58% to 69% on 17th January which was caused by its separated building parts. Although both cases had enhancement compared with the base case, Shape 2 was more recommended.

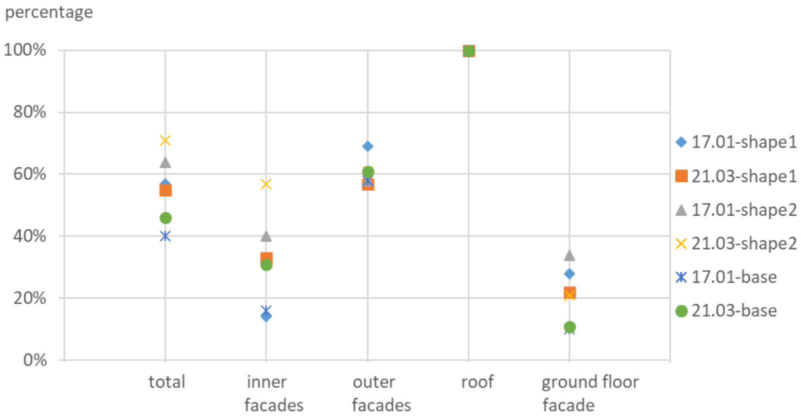


Figure 85 The exact percentage of the surface area that obeyed the sun hour regulation organised by different building elements and the overview consisting of the base case and shape variations in Berlin.

4.2.2.2.2 Vertical daylight illuminance

Figure 86 shows that the VDI for courtyard facades of Shape 2 experienced an obvious raise. It was worth noting that the west and east façades facing the added middle street had the quite similar vertical illuminance distribution with the original facades regardless of the relatively narrow street canyon.

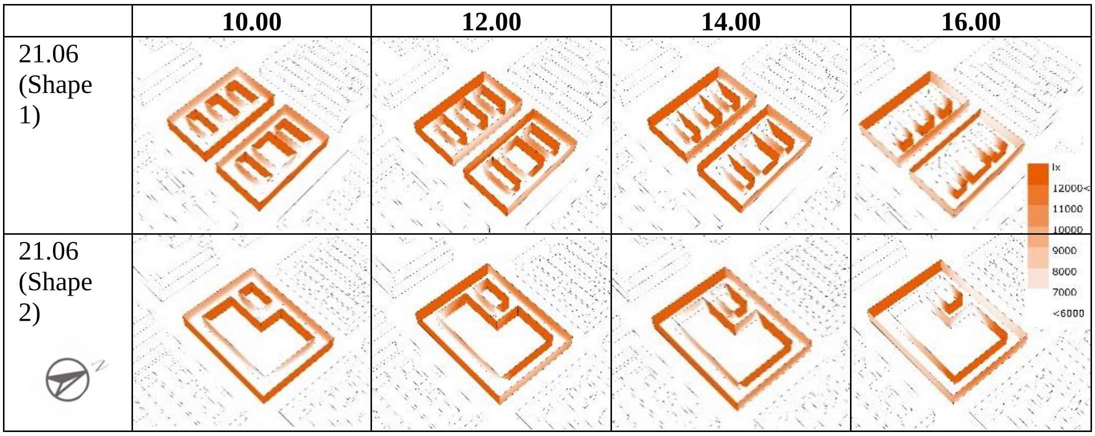


Figure 86 The VDI distributions for four selected hours on 21st June – shape variations of Berlin.

4.2.2.2.3 Vertical sky component

The VSC results of two shape study cases in Berlin are shown below in figure *Figure 87*.

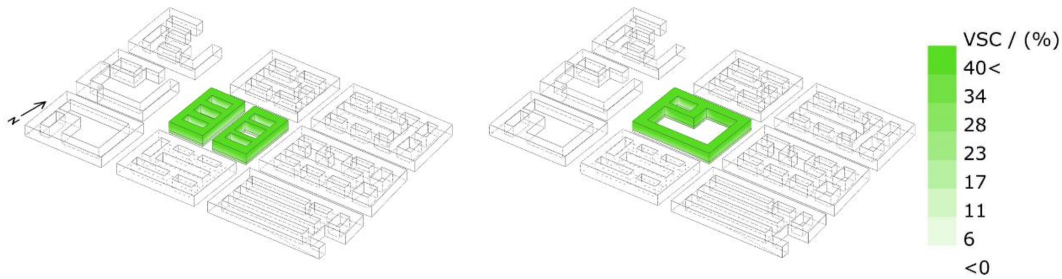


Figure 87 The VSC results of two shape study cases in Berlin.

The roof surface of these two studied cases all fully met the requirements. Other facades of study case 2 were all better than case 1 seen in *Table 28*. Obviously, the interior occlusion of case 2 was much less.

Table 28 The ratio of two study cases that met the VSC recommendation (> 27%) in Berlin.

Study case 1					**Study case 2**				
North	**West**	**East**	**South**	**Roof**	**North**	**West**	**South**	**East**	**Roof**
48%	60%	50%	47%	100%	75%	88%	71%	68%	100%

4.2.2.2.4 Heating season irradiation

In Berlin, building shape was a crucial parameter in terms of the passive heating potential as displayed in *Figure 88*. With longer distance between building parts, the façade irradiation increased significantly. The roof always had the highest potential as shown.

Shape 1	**Shape 2**
29%	44%

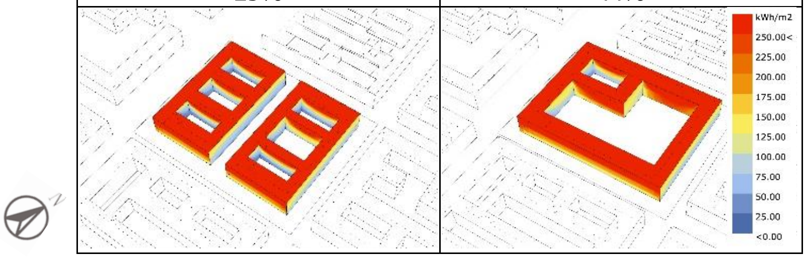


Figure 88 The heating season irradiation distributions – shape variations of Copenhagen.

4.2.2.2.5 Shadow study

On 21st June, the shadow coverage ratio for the courtyards was bigger in light of the short building width. And the western open space became smaller that was totally covered by shadow on 16.00 21st March displayed by *Figure 89*.

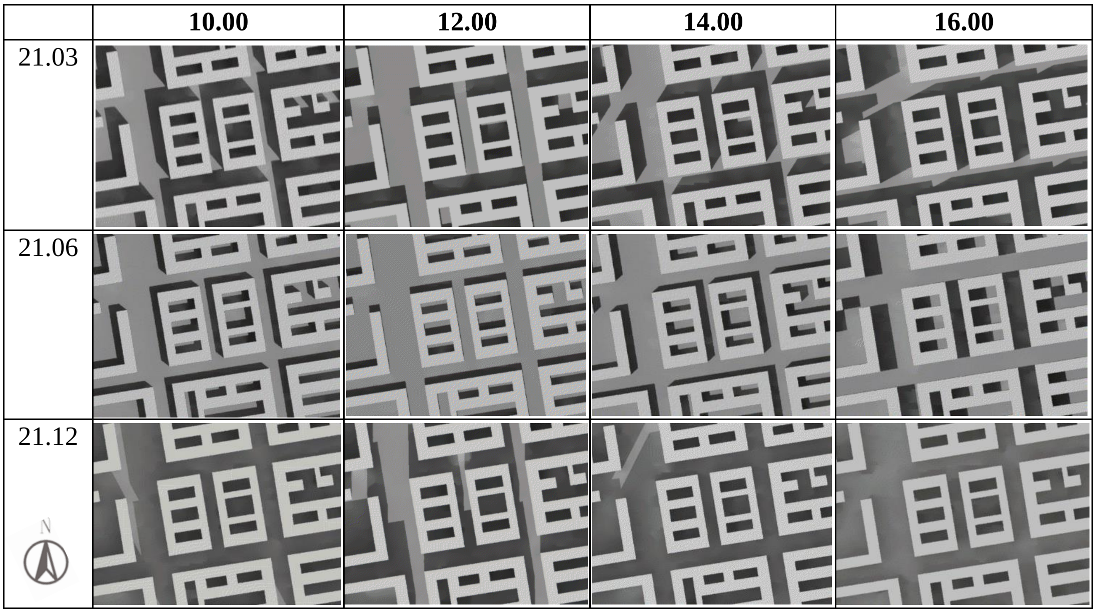


Figure 89 The building shadow cast for four selected hours on 21st March, 21st June and 21st December – Shape 1 case of Berlin.

For the results of this loose-shaped building in *Figure 90*, around 50% of the courtyard was shaded on 21st March. Even though the courtyard was large enough, it was shaded the whole day on 21st December.

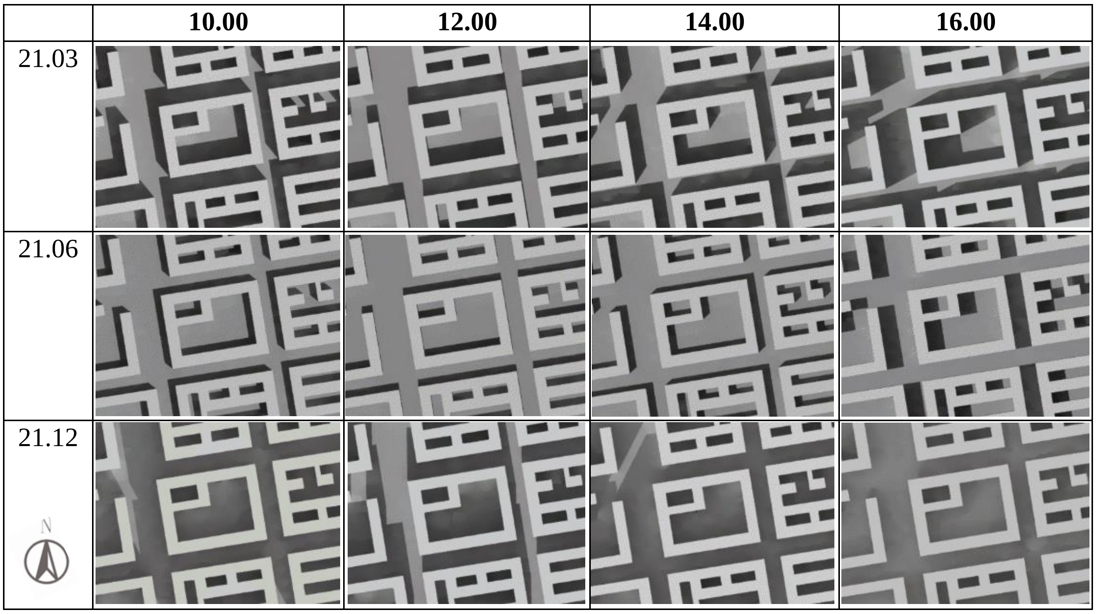


Figure 90 The building shadow cast for four selected hours on 21st March, 21st June and 21st December – Shape 2 case of Berlin.

4.2.2.3 Roof variations

4.2.2.3.1 Sun hours

30° roof and 60° roof were studied comparing with the 90° base case. It can be seen that slope roof was beneficial to the inner façade sunlight potential in *Figure 91*. Also, it is clear to see that 30° inclination performed much better than the 60° inclination in regard to the roof surface. However, the roof degree change did not affect ground floor façade sun hour performance so much shown in *Figure 92*.

17th January		21st March	
30° roof	60° roof	30° roof	60° roof

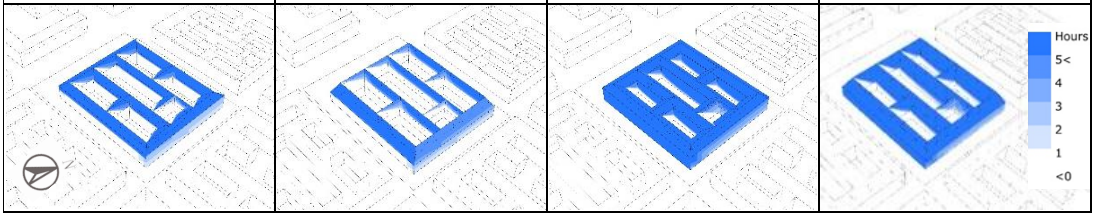


Figure 91 Sun hour distributions for entire building – roof type variations of Berlin.

17th January		21st March	
30° roof	60°roof	30° roof	60°roof

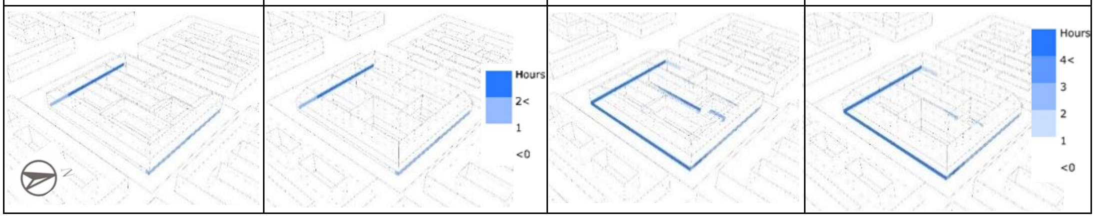


Figure 92 Sun hour distributions for building ground floor facade – roof type variations of Berlin.

It was found that a 30° inclined roof performed the best overall in all aspects except the ground floor façade and inner facades potential where 60° roof ranked the first. Roof performance fluctuated the most with the roof slope change while the qualified outer facades and ground floor façades area percentage did not change remarkably between cases and days seen in *Figure 93*.

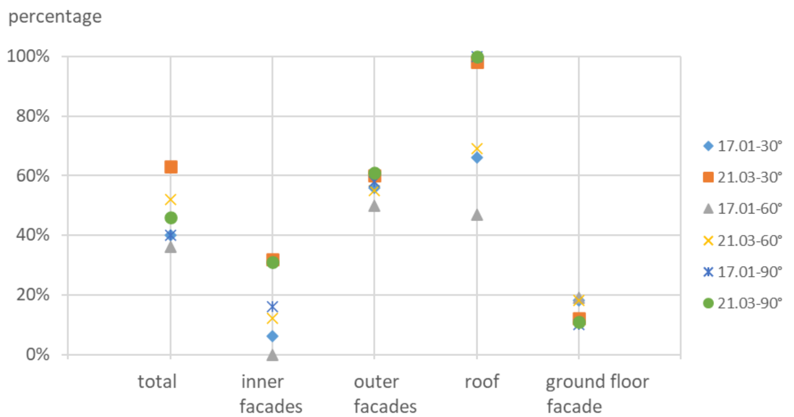


*Figure 93 The exact percentage of the surface area that obeyed the sun hour regulation organised by different building elements and the overview consisting of the base case and roof variatio*ns in Berlin.

4.2.2.3.2 Vertical daylight illuminance

It can be seen from *Figure 94* that compared with the base case, 60° roof contributed to a much better courtyard facades illuminance condition especially on 12.00 and 14.00 which was because that the inclined-roof was able to provide more reflectance.

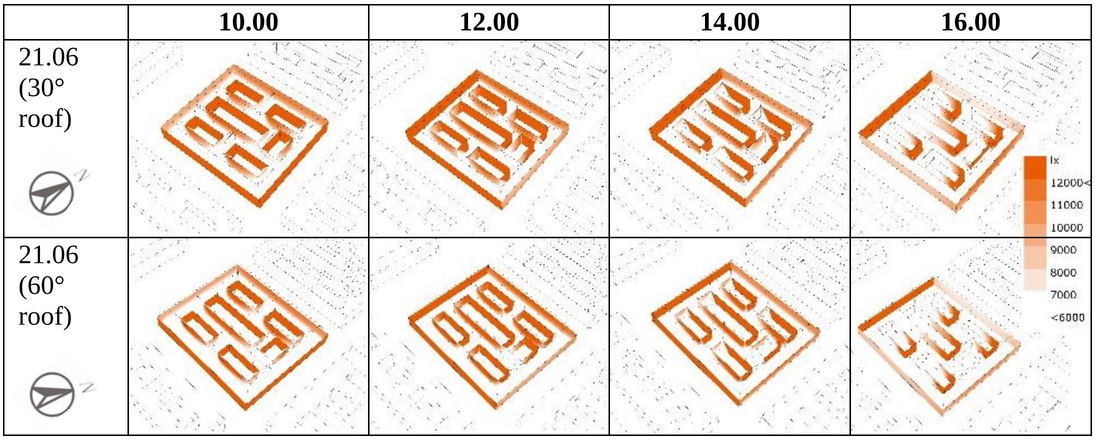


Figure 94 The VDI distributions for four selected hours on 21st June – roof variations of Berlin.

4.2.2.3.3 Vertical sky component

The VSC results of two study cases with different roof inclinations are shown in *Figure 95* below.

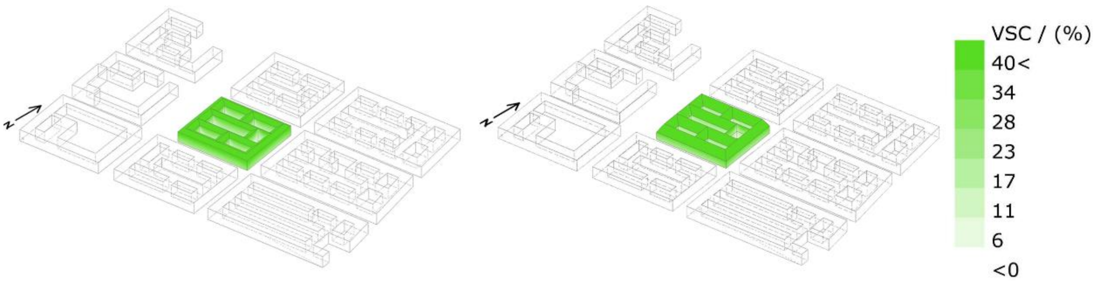


Figure 95 The VSC results of two roof study cases in Berlin.

The VSC values of all surfaces of study case 1 were better than case 2 as shown in *Table 29* below.

Table 29 The ratio of two study cases that met the VSC recommendation (> 27%) in Berlin.

Study case 1 (30°)					**Study case 2 (60°)**				
North	**West**	**East**	**South**	**Roof**	**North**	**West**	**South**	**East**	**Roof**
44%	60%	44%	42%	100%	19%	49%	17%	26%	98%

4.2.2.3.4 Heating season irradiation

It was observed that flat roof (base case) had the best irradiation performance and the potential saw a slight drop while the roof slope decreasing in *Figure 96*.

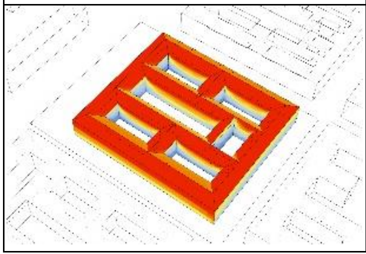
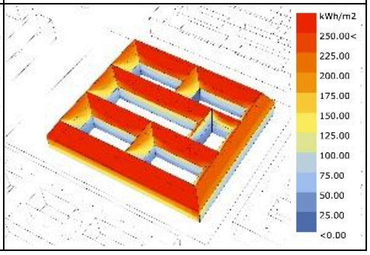
30° roof	**60° roof**
40%	42%
	

Figure 96 The heating season irradiation distributions – roof variations of Berlin.

4.2.2.3.5 Shadow study

Compared with the base case, 30° roof contributed to a bit smaller shadow casting area in the courtyard especially on 21st June seen in *Figure 97*.

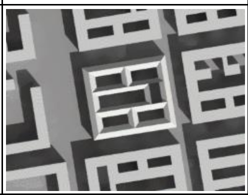
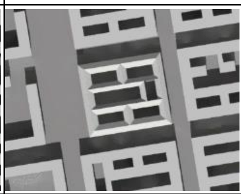
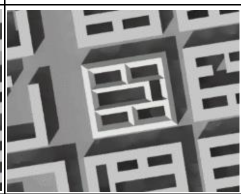
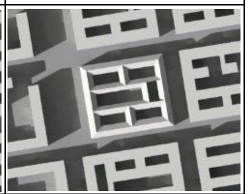
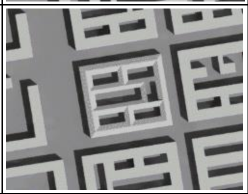
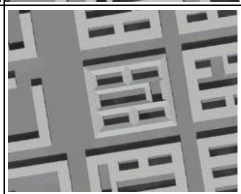
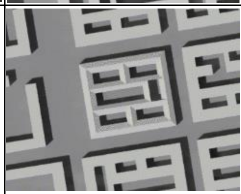
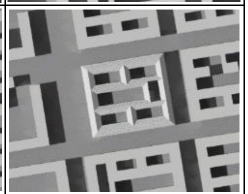
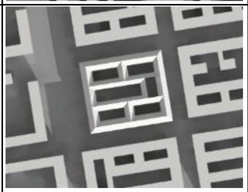
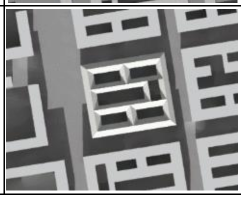
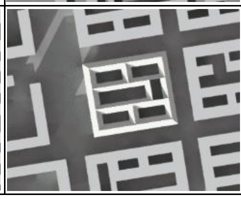
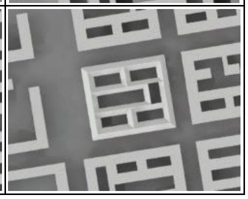
	10.00	**12.00**	**14.00**	**16.00**
21.03				
21.06				
21.12				

Figure 97 The building shadow cast for four selected hours on 21st March, 21st June and 21st December – 30° roof case of Berlin.

Figure 98 says that 60° roof made the building slightly higher which resulted in a worse shadow condition on 21st March for the east-west roads. The courtyards had the similar shadow range as the base case.

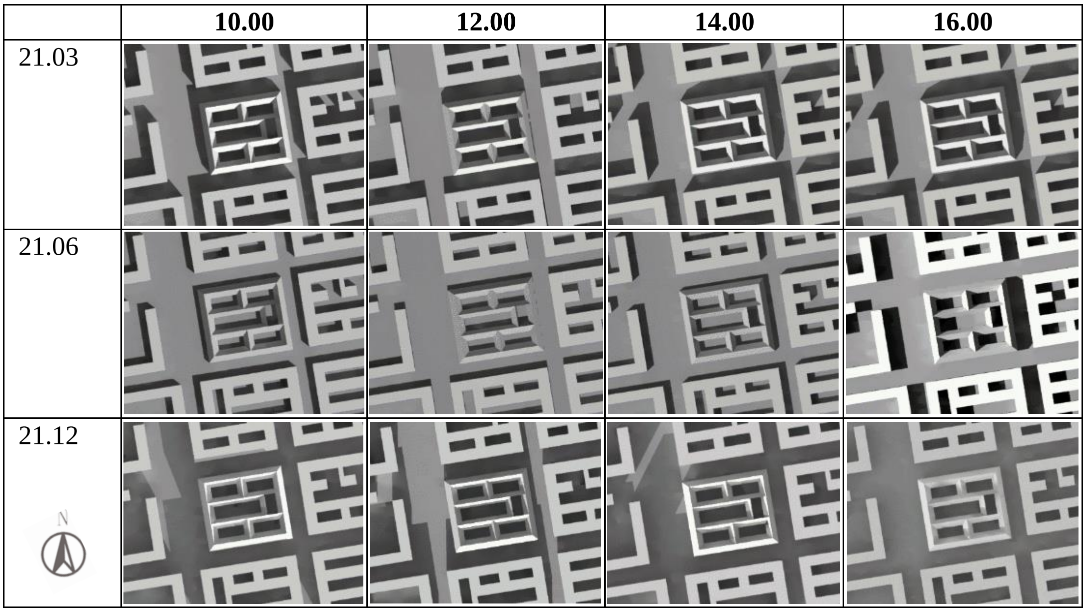


Figure 98 The building shadow cast for four selected hours on 21st March, 21st June and 21st December – 60° roof case of Berlin.

4.2.2.4 Material variations

4.2.2.4.1 Vertical daylight illuminance

As *Figure 99* displayed, light-coloured concrete building finish (Material 1) caused much higher VDI on all facades at each simulated hour. However, the glass curtain resulted in a remarkably different illuminance distribution with the concrete materials that the inner facades got uniform illumination and at least half of the outer facades had extremely bad condition.

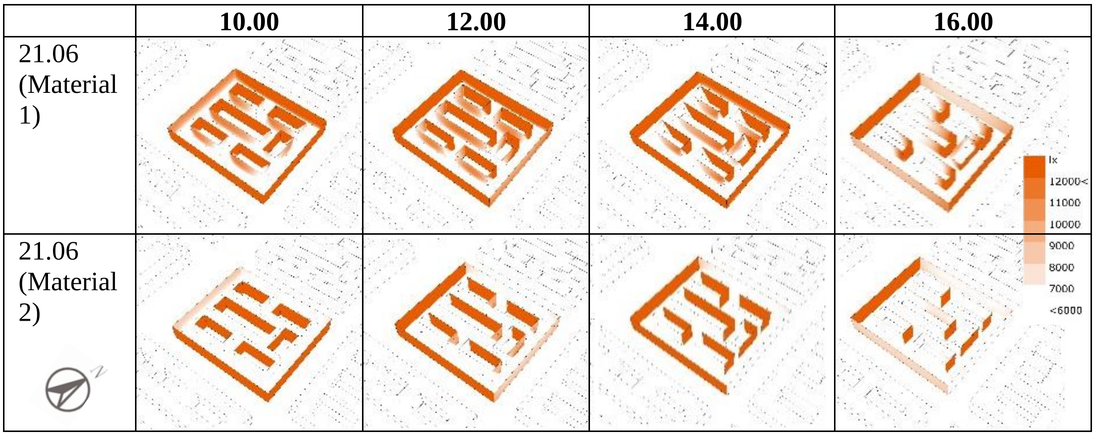


Figure 99 The VDI distribution for four selected hours on 21st June – material variations of Berlin.

4.2.2.5 Combination for vertical daylight illuminance

Looking at the comparison between all studied Berlin cases in *Figure 100*, it was concluded that nearly all variations helped to enhance the high bound of the qualified façade area except Shape 1 and Material 2 cases and among them 60° roof contributed the most by around 13%. Similarly, Density 2 and 60° roof decreased the percentage low bound slightly by no more than 5% while Material 2 was the most special case that it was half as the base case.

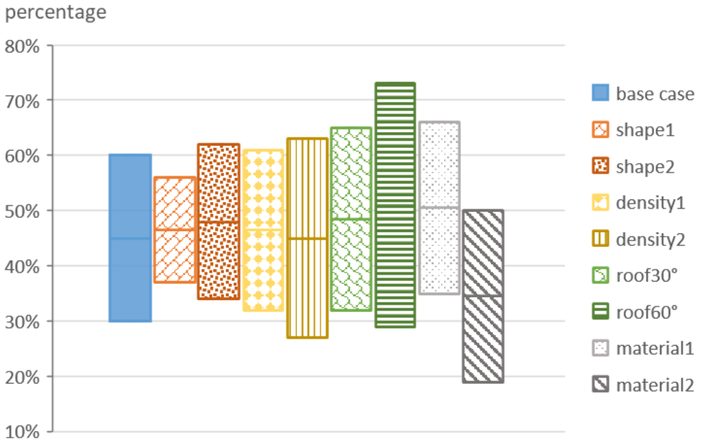


Figure 100 The range of percentage of surface area that received more than 10 000 lx for each case of Berlin on 21st June.

4.2.3 Hong Kong

4.2.3.1 Density variations

4.2.3.1.1 Sun hours

The tower had 50% façade getting more than 3 sun hours on the evaluated day for both cases seen in *Figure 101*. This was because that the tower building was too high to be influenced by the surrounding shading effect.

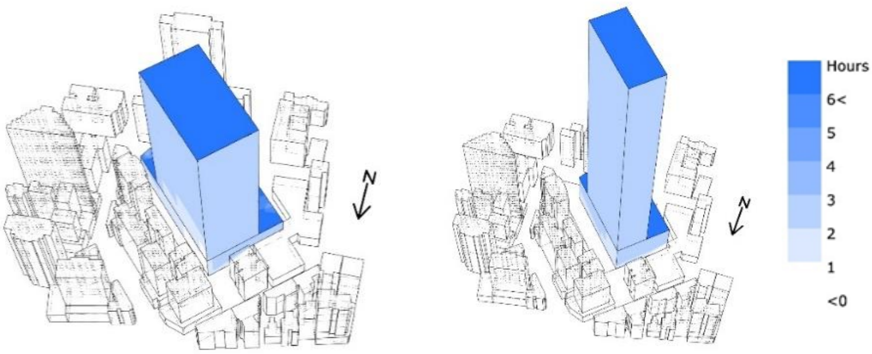


Figure 101 Sun hour distributions for building block on 20th January – density variations of Hong Kong.

The podium size of Density 2 case was reduced which resulted in an obvious improvement of the ground floor façade and podium facade performance by around 15%. In addition, Density 1 case had 62% surface area that complied with the regulation that ranked the best among the three cases displayed in *Figure 102*.

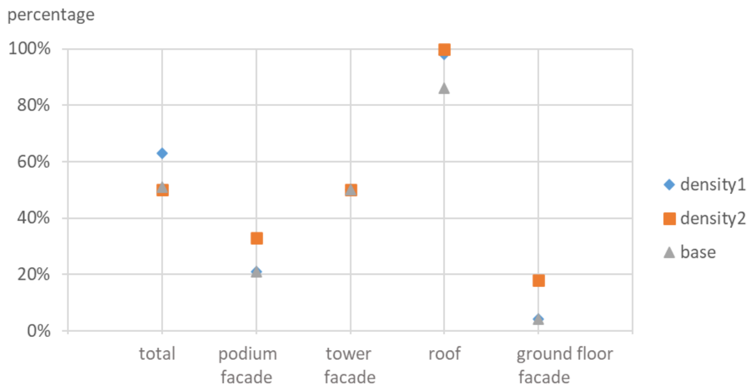


Figure 102 The exact percentage of the surface area that obeyed the sun hour regulation organised by different building elements and the overview consisting of the base case and density variations in Hong Kong.

4.2.3.1.2 Vertical daylight illuminance

The VDI on the tower was quite similar as the base case for all studied hours shown in *Figure 103* but for Density 2 case, the northeast podium façade saw a remarkable improvement particularly on 10.00.

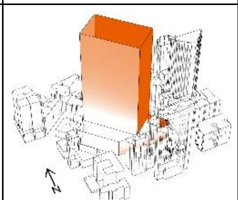
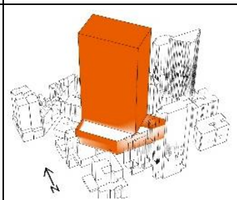
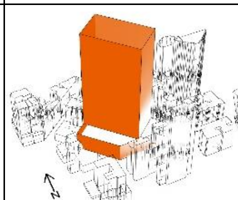
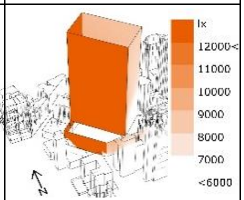
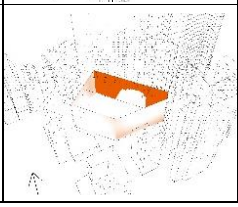
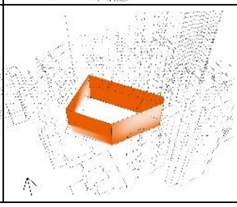
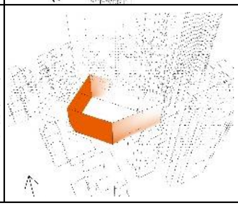
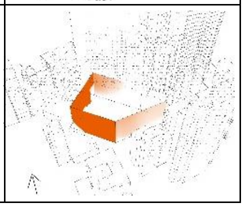
	10.00	**12.00**	**14.00**	**16.00**
21.06 (Density 1) 				
21.06 (Density 2) 				

Figure 103 The VDI distribution for four selected hours on 21st June – density variations of Hong Kong (considering the podium condition for case density2).

4.2.3.1.3 Vertical daylight factor

The VDF results of two density study cases in Hong Kong are shown in *Figure 104* below.

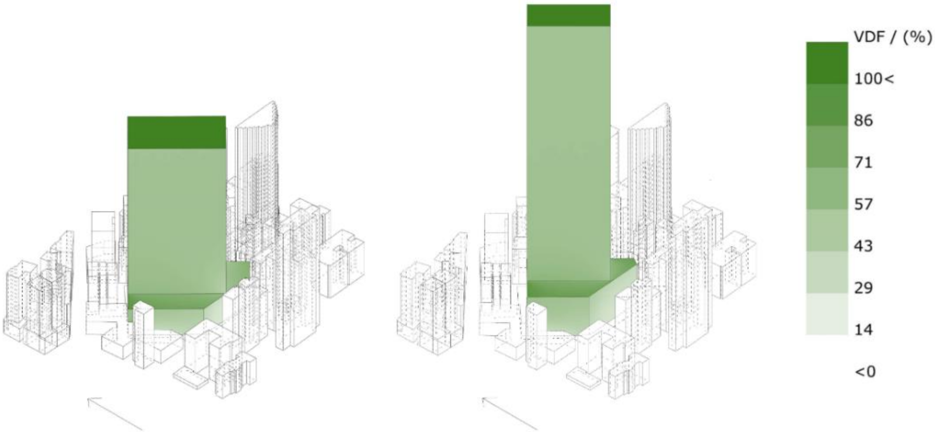


Figure 104 The VDF results of two density study cases in Hong Kong.

The ratio of each surfaces that could meet the VDF standard for kitchen and habitable room of two density cases in Hong Kong are shown in *Table 30*, *Table 31*, *Table 32* and *Table 33* below. All surfaces except north-west, north-east and south-west façade of the podium in study case 1 can meet the VDF standard requirements. However, facades in study case 2 all had higher VDF value than requirements.

Table 30 The ratio of each surface in density case 1 that met the VDF standard for kitchen in Hong Kong.

	Northeast	Northwest	Southwest	South	Southeast	Roof	Total
Podium	100%	84%	96%	100%	100%	100%	97 %
Tower	100%	100%	100%	-	100%	100%	100%
Total	-	-	-	-	-	-	99%

Table 31 The ratio of each surface in density case 1 that met the VDF standard for habitable room in Hong Kong.

	Northeast	Northwest	Southwest	South	Southeast	Roof	Total
Podium	99%	82%	96%	100%	100%	100%	96%
Tower	100%	100%	100%	-	100%	100%	100%
Total	-	-	-	-	-	-	99%

Table 32 The ratio of each surface in density case 2 that met the VDF standard for kitchen in Hong Kong.

	Northeast	Northwest	Southwest	South	Southeast	Roof	Total
Podium	100%	100%	100%	100%	100%	100%	100%
Tower	100%	100%	100%	-	100%	100%	100%
Total	-	-	-	-	-	-	100%

Table 33 The ratio of each surface in density case 2 that met the VDF standard for habitable room in Hong Kong.

	Northeast	Northwest	Southwest	South	Southeast	Roof	Total
Podium	100%	100%	100%	100%	100%	100%	100%
Tower	100%	100%	100%	-	100%	100%	100%
Total	-	-	-	-	-	-	100%

4.2.3.1.4 Heating season irradiation

Similarly, only a small part of the area on the podium that was unable to get 4 kWh/m^2 irradiation during the heating time in all cases. Case 1 had lower qualified surface area ratio because of the smaller building surface. While Case 2 nearly did not see any improvement even if the street width was broadened presented in *Figure 105*.

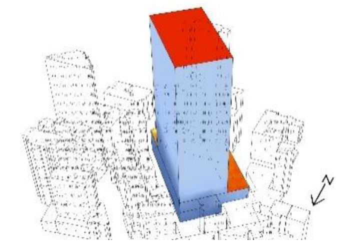
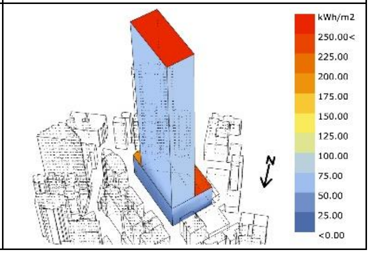
Density 1	**Density 2**
93%	99%
	

Figure 105 The heating season irradiation distributions – density variations of Hong Kong.

4.2.3.1.5 Shadow study

Even though the tower was shortened by around 1/2, the surrounding street kept the same shadow as the base case seen in *Figure 106*.

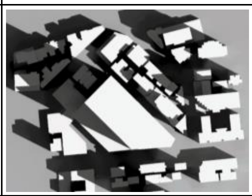
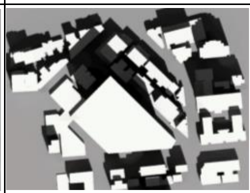
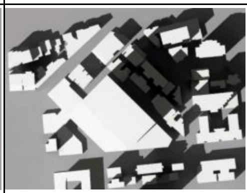
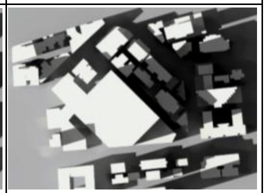
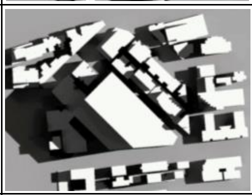
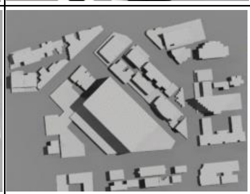
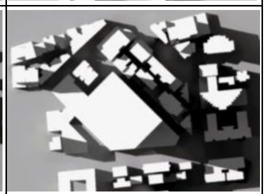
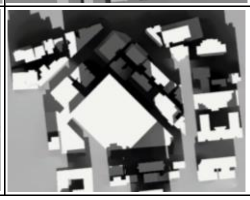
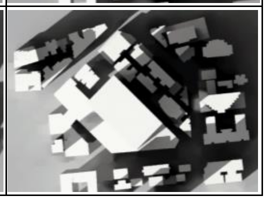
	10.00	**12.00**	**14.00**	**16.00**
21.03				
21.06				
21.12				

Figure 106 The building shadow cast for four selected hours on 21st March, 21st June and 21st December – Density 1 case of Berlin.

Figure 107 shows that the wider street provided the public with more shadow-free space at the studied hours particularly the morning hours on 21st March.

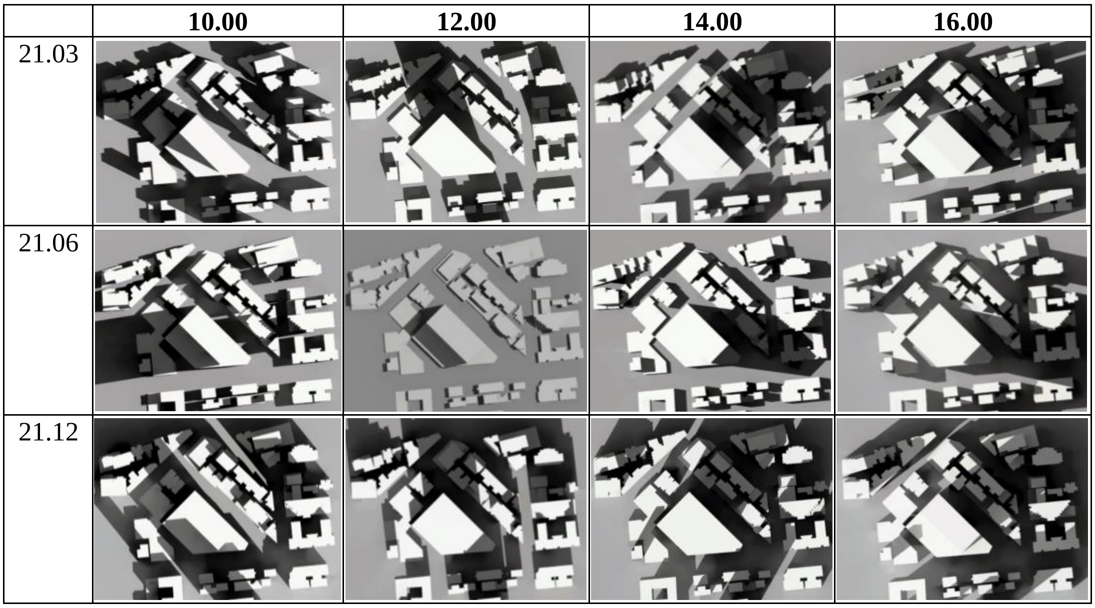


Figure 107 The building shadow cast for four selected hours on 21st March, 21st June and 21st December – Density 2 case of Berlin.

4.2.3.2 Shape variations

4.2.3.2.1 Sun hours

In Shape 1 case, parts of the podium roof were shaded by the tower branches and it can be seen that two tower branches even experienced mutual-shading. The condition of the podium façade remained the same since its shape was not manipulated. Comparing the sun hour distributions of the northeast and northwest facades between these two variations, it can be concluded that the building branch orientation was a crucial parameter in the Hong Kong case considering the sun hour performance presented in *Figure 108*.

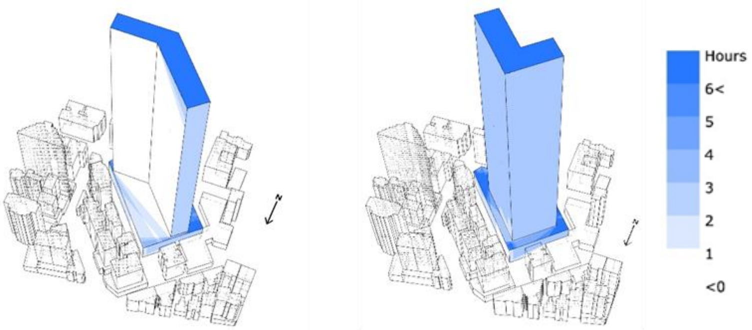


Figure 108 Sun hour distributions for building block of shape 1(left) and shape 2 (right) in Hong Kong on 20th January.

Tower facades always had around 50% area meting the sun hour regulation in Hong Kong no matter how the tower shape manipulated shown in *Figure 109*. The roof percentage reduced due to the shaded podium roof mentioned above.

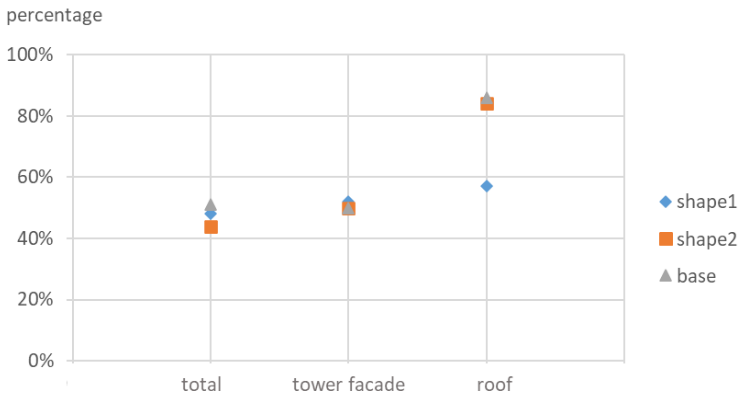


Figure 109 The exact percentage of the surface area that obeyed the sun hour regulation organised by different building elements and the overview consisting of the base case and shape variations in Hong Kong.

4.2.3.2.2 Vertical daylight illuminance

Shape 1 had a larger degree between the tower branches than the shape 2 case which contributing to a better tower illuminance performance looking at the southeast and southwest facades in *Figure 110*.

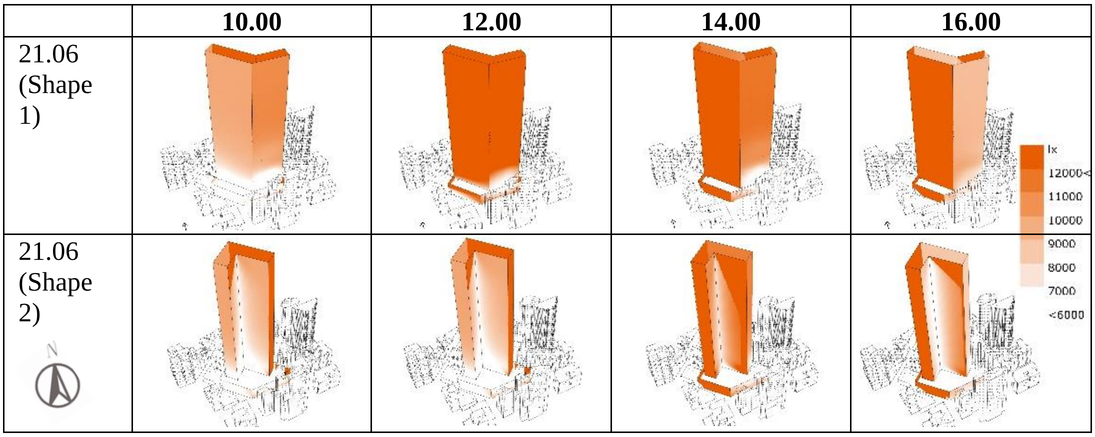


Figure 110 The VDI distributions for four selected hours on 21st June – shape variations of Hong Kong.

4.2.3.2.3 Vertical daylight factor

The VDF results of two shape study cases in Hong Kong are shown in *Figure 111*.

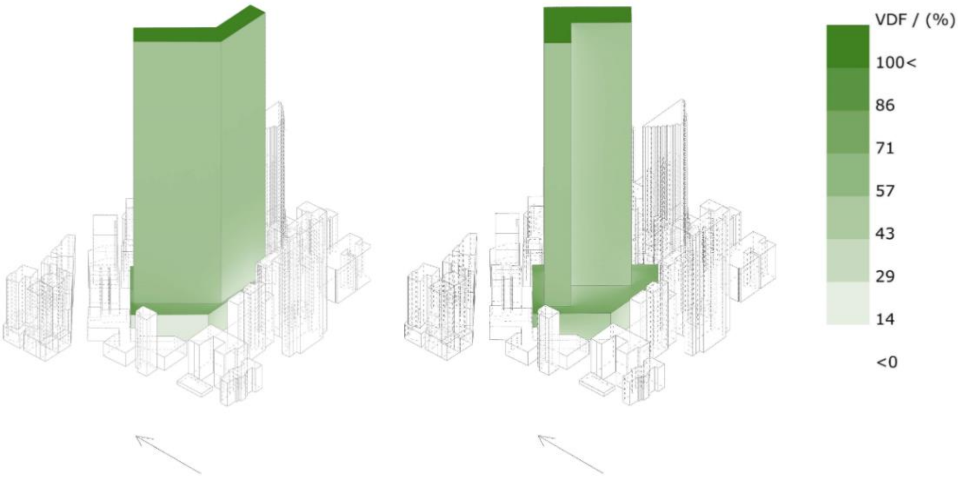


Figure 111 The VDF results of two shape study cases in Hong Kong.

The ratio of each surfaces that can meet the VDF standard for kitchen and habitable room of two shape cases in Hong Kong are shown in *Table 34*, *Table 35*, *Table 36* and *Table 37* below. All surfaces except north-west and south-west façade of podium in these two cases can meet the VDF standard requirements. Considering the comprehensive level of the whole building, study case 2 was better.

Table 34 The ratio of each surface in shape case 1 that met the VSC standard for kitchen in Hong Kong.

	Northeast	Northwest	Southwest	South	Southeast	Roof	Total
Podium	100%	84%	96%	100%	100%	100%	97%
Tower	100%	100%	100%	-	100%	100%	100%
Total	-	-	-	-	-	-	99%

Table 35 The ratio of each surface in shape case 1 that met the VSC standard for habitable room in Hong Kong.

	Northeast	Northwest	Southwest	South	Southeast	Roof	Total
Podium	100%	82%	96%	100%	100%	100%	97%
Tower	100%	100%	100%	-	100%	100%	100%
Total	-	-	-	-	-	-	99%

Table 36 The ratio of each surface in shape case 2 that met the VSC standard for kitchen in Hong Kong.

	Northeast	Northwest	Southwest	South	Southeast	Roof	Total
Podium	100%	84%	96%	100%	100%	100%	97%
Tower	100%	100%	100%	-	100%	100%	100%
Total	-	-	-	-	-	-	97%

Table 37 The ratio of each surface in shape case 2 that met the VSC standard for habitable room in Hong Kong.

	Northeast	Northwest	Southwest	South	Southeast	Roof	Total
Podium	100%	82%	96%	100%	100%	100%	97%
Tower	100%	100%	100%	-	100%	100%	100%
Total	-	-	-	-	-	-	97%

4.2.3.2.4 Heating season irradiation

Figure 112 conveys the message that in Hong Kong, no matter how the shape changed, almost the entire building could meet the solar irradiation suggestion in the winter time which meant that no active heating strategy was needed as estimated.

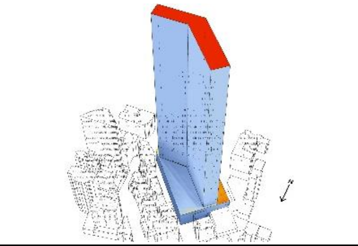
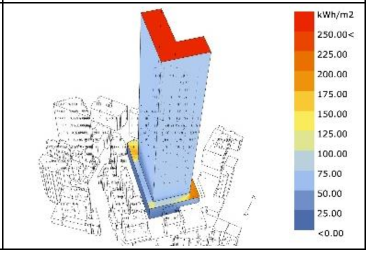
Shape 1	**Shape 2**
99%	95%
	

Figure 112 The heating season irradiation distributions – shape variations of Hong Kong.

4.2.3.2.5 Shadow study

This sort of shape and the tower position made the majority part of the podium roof shaded. It was interesting to find that on 21st June, the shadow shape of 14.00 and 16.00 was similar seen in *Figure 113*.

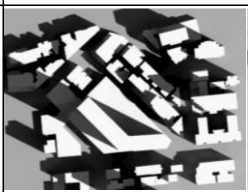
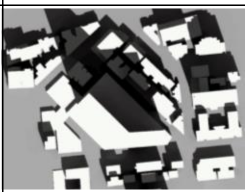
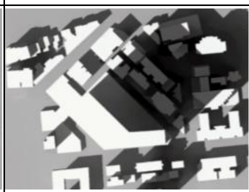
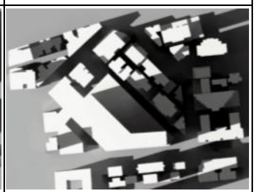
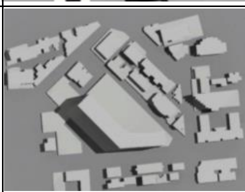
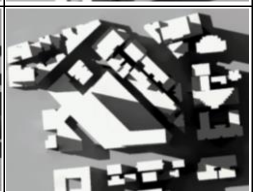
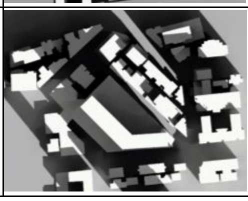
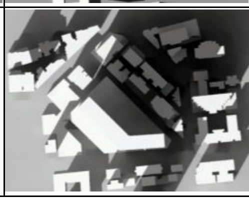
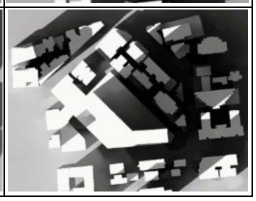
	10.00	**12.00**	**14.00**	**16.00**
21.03				
21.06				
21.12 				

Figure 113 The building shadow cast for four selected hours on 21st March, 21st June and 21st December – Shape 1 case of Berlin.

Compared with Shape 1, the podium roof was exposed more to the environment and the street shadow condition changed due to the L-shape in Shape 2 case presented in *Figure 114*.

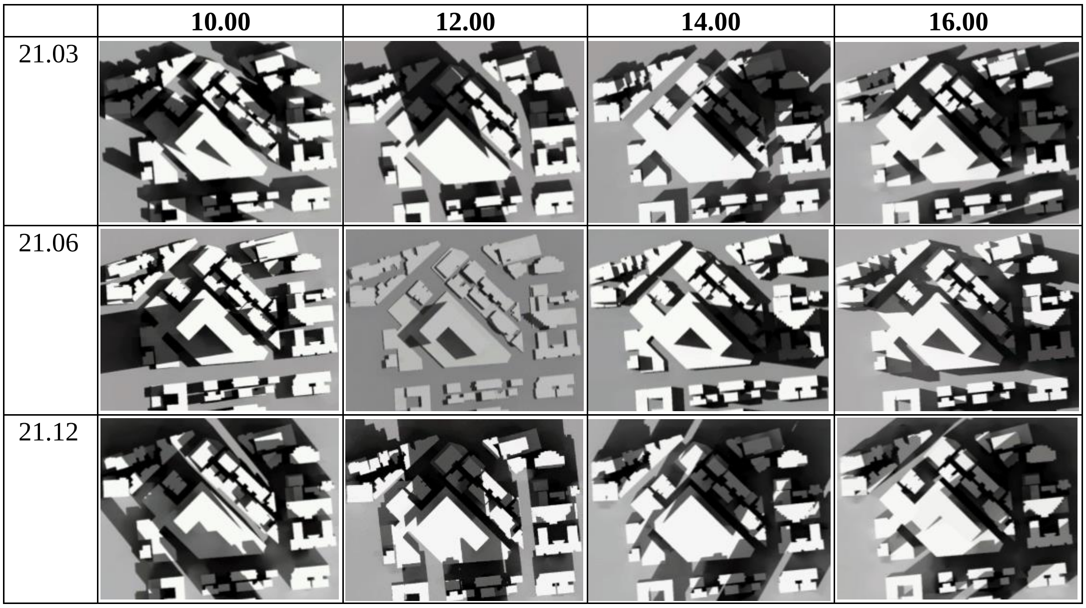


Figure 114 The building shadow cast for four selected hours on 21st March, 21st June and 21st December – Shape 2 case of Berlin.

4.2.3.3 Material variations

4.2.3.3.1 Vertical daylight illuminance

For all cases, the VDI at 10.00 was the lowest and it was surprisingly to see that the condition of 14.00 and 16.00 showed almost no difference. Additionally, the light-coloured concrete improved the south façade performance on all hours presented in *Figure 115*.

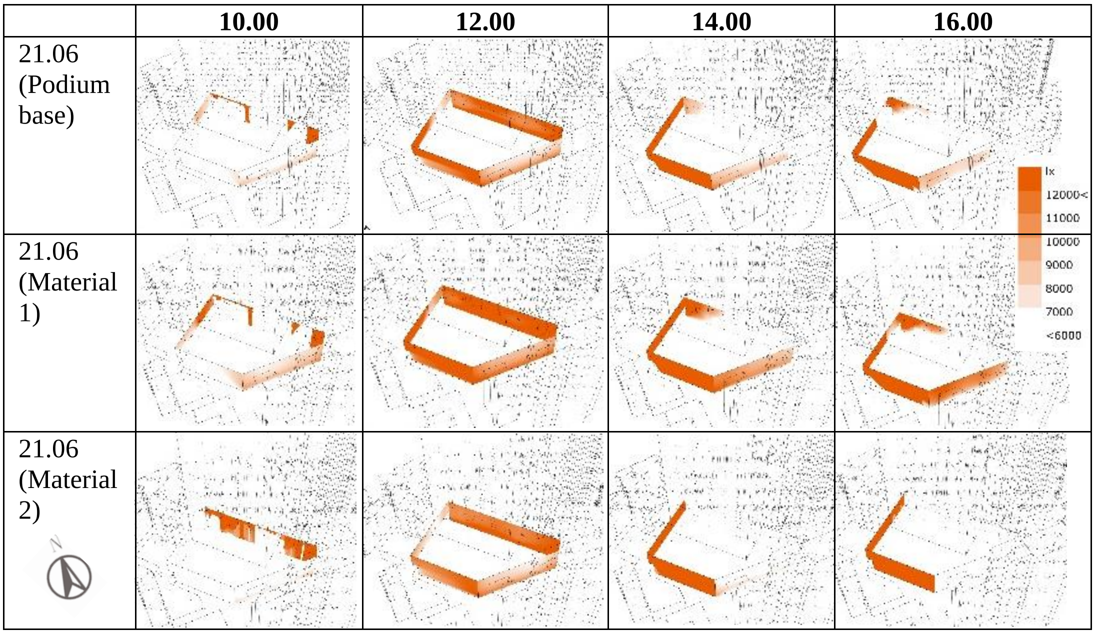


Figure 115 The VDI distributions for four selected hours on 21st June – material variations of Hong Kong (only considering the podium condition).

4.2.3.4 Combination for vertical daylight illuminance

It can be found from *Figure 116* that the qualified surface percentage of all podium cases was around 1/2 of the whole building vertical surfaces which was because of the surrounding buildings. Density 1 case had almost the same result as the base case. Both shape variations performed worse than the base case. For the podium potential evaluation, wider street (Density 2 case) raised the high bound and low bound by 6% and 13% respectively which was considerable. Glass curtain was the worst material among the three materials.

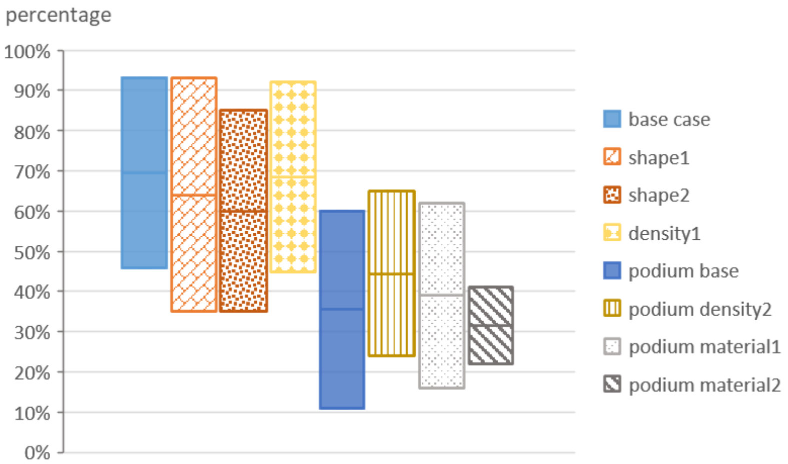


Figure 116 The range of percentage of surface area that received more than 10 000 lx for each case of Berlin on 21st June.

4.2.4 Combined comparison between three cities

The sun hours results of the density study cases in three cities were compared together, as shown in *Figure 117*. The FAR of Hong Kong was the highest in these cities, while Copenhagen was the lowest one. Due to this, the results of sun hours in Hong Kong were not as good as the overall situation in Copenhagen, even though it has the lowest latitude among the three cities.

Surprisingly, the result of sun hours in Berlin was the worst, although the latitude of Berlin and the FAR of the building are all located at the middle level of the three cities. One reason for this result may be that the latitude of Berlin is not much lower than Copenhagen, but the FAR of the building in Berlin was twice of that in Copenhagen.

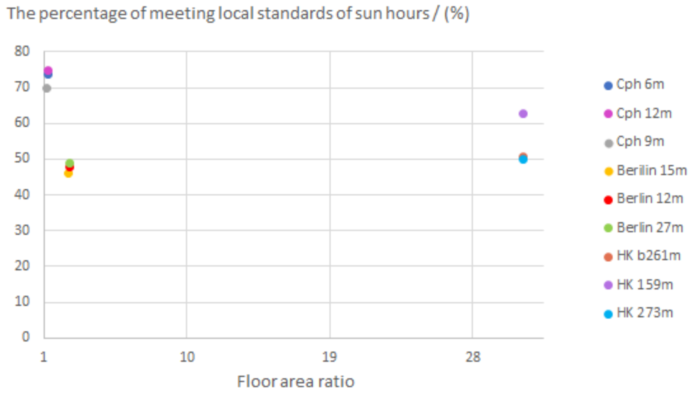


Figure 117 The percentage of base cases and density study cases in three cities that met the local standards of sun hours.

In the density parametric study, the FAR of the study cases in three cities were kept the same with base case separately. The footprint and building height were all different. In order to further analyse the impact of building height on sun hours results in each city clearly, the relationship between the percentage of meeting local regulations and building height are shown in *Figure 118* and *Figure 119*.

In Copenhagen and Berlin, the percentage of meeting the local regulation respectively reached the low peak when the building height was 8 m and 15 m. The reason for the worse sun hour result in the early stage of increasing the building height may be that in Copenhagen and Berlin, the distance between the buildings was relatively large. So, when the height of the study case was lower than the surrounding buildings, the sunlight can fall onto the building facades through the gap around. But when the building height was almost the same as surrounding buildings, higher percentage of building surfaces were blocked.

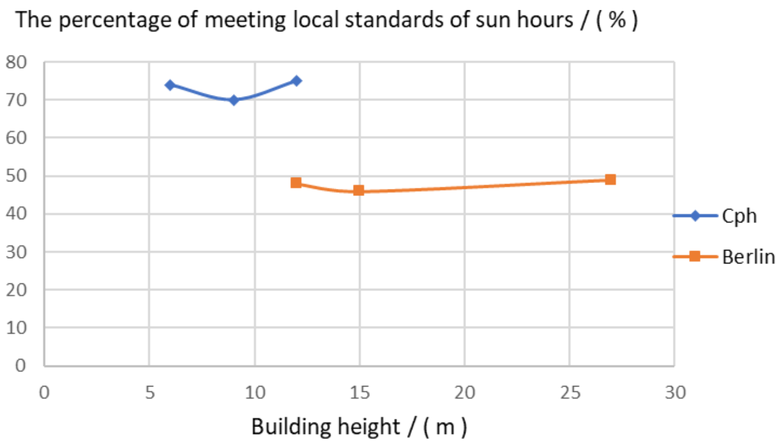


Figure 118 The percentage that met the local sun hour standards of study cases in Copenhagen and Berlin.

Based on this discovery, urban planners and architects can choose a more appropriate building height based on a fixed FAR value, which was also an effective way to improve the daylight performance of the building.

For the cities with high FAR value like Hong Kong, the situation was totally different. The sun hours always increase as the reduction of building height. Due to the high density of these cities, there were still a lot of occlusion even if the height was properly reduced. However, the appropriate reduction in height can still improve the daylight performance.

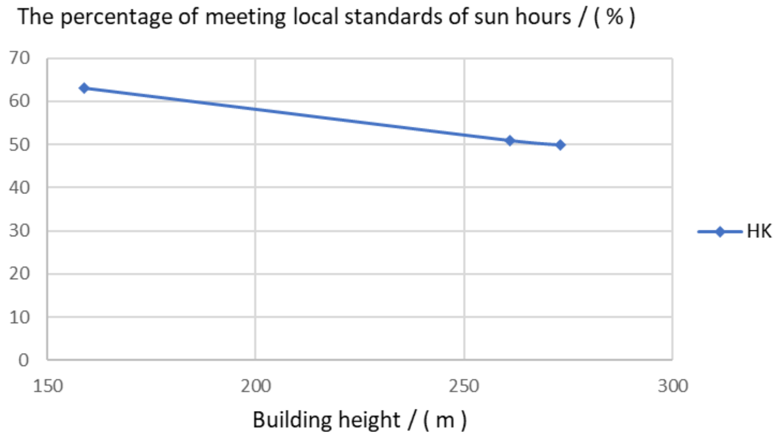


Figure 119 The percentage that met the local sun hour standards of study cases in Hong Kong.

In fact, most of the buildings in Hong Kong have flat roofs. Thus, based on this reality, only Copenhagen and Berlin had roof inclination parametric study. The results are shown in *Figure 120*. For Copenhagen, the roof inclination at the time of low peak was similar to the inclination of the surrounding buildings. And this also applies to Berlin. In addition, when the roof inclination of the building in Berlin was similar to the latitude, the result reached a peak.

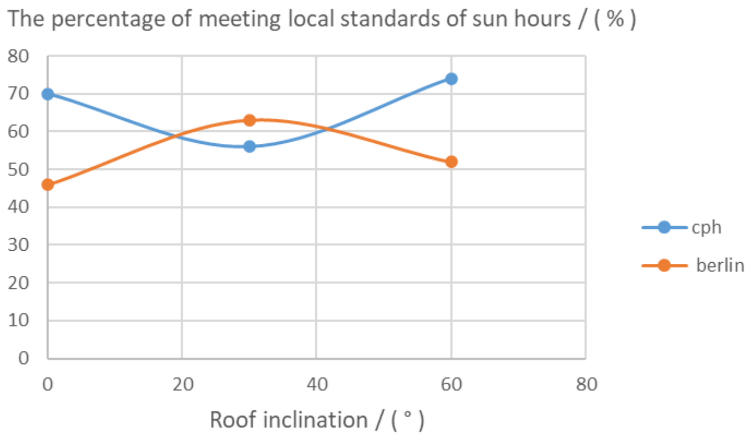


Figure 120 The percentage of roof study cases in Copenhagen and Berlin that met the local standards of sun hours.

5 Conclusions

In this project, the information of the local daylight building codes of Berlin, Copenhagen and Hong Kong were collected firstly. The solar potential of the selected base case of each city was simulated then compared with its corresponding building code in order to assess the code's adaptability.

Three research questions were investigated. The first one was: 'Does the building daylight standard fit its corresponding urban status quo?' It is found that there can be a big improvement in regard to each studied cities' daylight building regulation since only around 50% surface area of the studied cases in this project were able to reach their thresholds. The following paragraphs explain more specific.

Daylight standard

- Almost no studied cases obey their corresponding legislations considering the sun hours for the building surface. This indicates that the current legislations are a bit harsh and need to be modified. For example, it can be more appropriate if the sun hour threshold is different for different-oriented façades. In addition, the sun hour regulation applied in Copenhagen in this project is a cross-European standard and its adaptability of each European country is expected to be an interesting topic in the future studies.

- In all cities, the investigated open areas easily meet the BRE guideline 3.3.17 section which is about sun hours for open space. More specifically, Hong Kong site performs the best, then comes the Copenhagen site while Berlin open space ranked the last. However, there is no domestic regulation for each city (country), which should be improved.

- The shadow casting aerial images are difficult to analyse to get any clear conclusion and should only be shown for visual purpose. Additionally, in this study the shadow range for all cases are compared with the BRE regulation. It would be better to develop regional requirements as well. For example, there is no sunlight at 16.00 on the 21st December in Berlin and Copenhagen, revealing that BRE is not applicable in neither city.

- The BRE shadow range study was not well-matched with the sun hour analysis taking Berlin base case for instance. In particular, around 15% discrepancy occurred between the results of these two studies on the 21st June and the 21st December. If the shadow domain is checked hourly instead of every two hours as stated in the current BRE then this problem is expected to be solved. Therefore, the BRE shadow standard provides the urban planners with a rough visual concept of the buildings' shading influence on the surrounding open space but the sun hour analysis is more accurate.

After that, a comprehensive parametric study was carried out with the independent variables of building density, roof inclination degrees, building material and building shape. This study answered the other two research questions: 'How does the building geometry and urban layout affect the passive and active solar energy potential?' and 'Which parameter contributes the most to the solar potential?'

It was found that the courtyard's size, roof inclination and building FAR affect the Berlin building solar potential most significantly. For the buildings in Copenhagen, building shape should be considered the most. For the Hong Kong buildings, wider street is the most contributory parameter, however, it is also the hardest urban formation to be achieved there since the current high city dense. The more detailed suggestions for each city are proposed as follows.

Berlin

- In Berlin, the current typical building has several small inner courtyards. For the urban planners there, perhaps a 4 or 5 storey building with 30° sloped roof and relatively larger inner courtyard is suggested as it improves the passive and active solar potential the most significantly for buildings in Berlin. If the building density is constrained, then the type of building which has shorter height and larger footprint is recommended.

- Comparing the results of Berlin and Copenhagen, it is found that for a city with a high latitude, urban planners and architects can effectively improve the sun hours situation of the building envelope by reducing the FAR value.

- For cities with relatively low FAR values, even if the FAR value remains unchanged, architects and urban planners can seek better sun hours results by changing the building height and footprint.

Copenhagen

- The sunlight during winter period in Copenhagen is the most insufficient among the three cities.

- For Copenhagen variations, building shape is the most contributory factor. Simple geometry is highly recommended. The linear-shaped construction not only performs better in terms of sun hours and VSC, but also has the least impact on the shading of the open spaces. Moreover, the roof has the worst potential if the building height (or roof inclination degree) is similar to its surrounding buildings.

-

Hong Kong

- In Hong Kong, the heating season irradiation performance is extraordinary indicating that active heating measurements are even unnecessary if the winter condition is not extremely bad.

- Since the buildings in Hong Kong are normally thin and tall that the building podium design is more important. If possible, a relatively wider street is the most recommended urban layout pattern there. Also, box-shaped building tower performed the best there.

Finally, some general conclusions about the assessed daylight and solar metrics are drawn from the parametric studies.

- The shape, density, and roof inclination of the building may have a greater influence on the solar irradiation of the facade than the geographical location of the city.

- When designing a PV system, overproduction should be analysed according to the specific city situation. The greatest potential month for a PV system differs between cities.

- When the building is much taller than the surrounding buildings, the shape and density of the building have little effect on the VDF of its facade.

- When the height of the building is about the same as that of the surrounding buildings, the simpler shape of the building means the less self-occlusion and the higher the VSC values.

- Roughly, building material influences the vertical illuminance performance the most if the building shape is not manipulated a lot. Glass curtain is not recommended.

- Wider street (larger surrounding area) helps to enhance all daylight and solar potential for building facades though to different extent.

- Flat roof always gains the most solar irradiation if not shaded by other buildings.

- Shadow coverage area is larger during afternoon hours than the morning hours in this study which is caused by the solar altitude change regularity during the day in the northern hemisphere.

6 Summary

As the urban population continues to grow at a high speed, the situation of urban space use is becoming increasingly tense. However, many urban planners only consider to satisfy the living demand of large population at the early urban planning stage, which means that they often ignore the personal feelings and the sense of use in the later operational stage of buildings.

The daylight condition of the building and of the streets or urban gardens is a very important part in this circumstance. The daylight penetrating the building cannot only delight the inhabitants in it, but also provide the building systems with energy. This energy section consists of saving electricity for artificial lighting and adjusting indoor temperature. It can also provide energy through active methods such as solar thermal (ST) and PV panels.

However, in the early stage of urban planning, many details of a building have not yet been determined, including the orientation, size, shape, etc. which have a great impact on the daylight performance. Therefore, how to use the outdoor daylight metrics to initially analyse the building's future daylight and solar potential is an important step before the architectural design phase. This study was mainly focused on the impact of more compact neighbourhoods on the daylight performance of the building and its surroundings, and provide a reference or theoretical support for the initial stage of the building industry through outdoor daylight parameters assessment.

Based on the main contradictions in the city planning status mentioned above, the studied cases are three representative cities, Copenhagen of Denmark, Berlin of Germany, and Hong Kong of China. The geographical location, urban planning form and architectural style of the three cities are distinctive. Thus, a residential building block in each city was considered as the base case which was compared with the local building daylight standard to analyse whether they comply with the current regulation. The impact of different building forms on the daylight situation was evaluated, which can finally provide urban planners and architects with effective information and a general concept about how to maintain acceptable solar potential when they make decisions during the early urban planning stage.

The entire research was accomplished by the online map tool: CADMAPPER, simulation tools: Honeybee and Ladybug via Grasshopper plug-in of Rhino and data processing tool: Excel. Because of the necessity of reducing computational time, the building models were simplified and the simulation parameters were set to error-acceptable level which might have a slight adverse impact on the accuracy of the simulation.

The first step was to analyse the buildings' solar potential through outdoor daylight and solar metrics assessments which were then compared with the local building codes. These metrics include annual solar irradiation, heating season irradiation, vertical daylight illuminance, sun hours, vertical daylight factor, vertical sky component and shadow cast aerial view.

Next, in order to investigate the impact of different building forms on building solar potential, a comprehensive parametric study was carried out. The independent variables of the parametric study cases are urban / building-related parameters which have influence on solar potential, including the roof inclination degrees, the building density, the building shape and the building material (which is only applied in illuminance-related studies).

Through this project, it was found that the current daylight building regulations of the three studied cities are so harsh that almost none of the studied buildings achieve them. Moreover, the current daylight codes pay too much attention to sun hours assessment while ignoring the other metrics, for example, the vertical daylight illuminance in this project, which is studied by several scholars but is not mentioned in any legislation. A possible solution is to develop more detailed domestic regulations.

Also, the research results provide some suggestions to urban planners and architects to help them make decisions considering passive and active solar potential of the building and its surroundings in the early urban design stage based on the location of the city. For Berlin, the size of the courtyard influenced the building solar potential the most. For Copenhagen, where the buildings are relatively short and scattered, a simple building shape should be adopted and a more reflective surface material is also an ideal design strategy. For Hong Kong, the street width is the most contributory factor.

This project mainly focuses on the passive solar potential evaluation and a more in-depth investigation on the active solar potential including the availability of PV and ST systems can be carried out in future studies.

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