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The Hong Kong Polytechnic University
Department of Building and Real Estate

BRE466 Capstone Project

**A Study on the Sustainable Building in Hong Kong:
Appropriate Window to Wall Ratio (WWR) to
minimize energy consumption of high-rise
buildings**

Chong Mung

1406

Dissertation Submitted in Partial Fulfillment of the Requirement for
Degree of Bachelor of Science (Honours) in
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Student's Statement

I declare that the completed Dissertation represents my own work, except where due acknowledgement is made, and that to the best of my knowledge it has not been previously included in a thesis, dissertation, or report submitted to this University or to any other institution for a degree, diploma or other qualification.

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Mr. Au, Sub-Agent, Gammon Construction Limited

Mr. Mak, Building Engineer, Gammon Construction Limited

Mr. Tsui, Agent of Subcontractor, Million Hope Industries Limited

Ms. Cheng, Resident of Public Housing

Ms. Li, Resident of Public Housing

Abstract

Title of Dissertation : A Study on the Sustainable Building in Hong Kong:
Appropriate Window to Wall Ratio (WWR) to minimize
energy consumption of high-rise buildings

Name of the Student : Chong Mung

Year of Submission : 2017

Energy consumption in building sector has been already increased since many years. However, the element of window to wall ratio of the building is slightly neglected for energy saving in Hong Kong. Heat gain through the window is different to the heat gain from concrete wall. The research focus on investigating the proper area of window to reduce the cooling load of the building.

Numerous case studies and the experimental study reveal that the conditions of indoor environment and the thermal comfort are generally affected under different window to wall ratio of building. More importantly, several case studies indicate that better thermal comfort is produced with larger area of window that leads to decrease the demand of cooling system. Moreover, questionnaire survey and interviews are evaluated that it is feasible and flexible to adjust the window to wall ratio in the design stage of the construction project by adopting advanced simulation software.

Element of window to wall ratio of public housing should be improved or increased so as to reduce the cooling load and the energy consumption of the building. It is proved that it is essential to conduct the comprehensive study for designing appropriate window to wall ratio.

Abbreviations

BIM	Building Information Modelling
CLO	Clothing Level
GFA	Gross Floor Area
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
SHGC	Solar Heat Gain Coefficient
SHGF	Solar Heat Gain Factor
SC	Shading Coefficient
WWR	Window to Wall Ratio
VT	Visible Transmission

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Chapter 1 Introduction

1.1 Problem Statement

Building energy consumption has been significantly enhanced since many years. Heating, Ventilation, Air-Conditioning (HVAC) system in residential and commercial buildings occupies around half of total energy consumption (Environment Bureau, 2015). Although numerous measures have been launched by the government such as the financial supports and technical supports to develop the green and intelligent buildings for minimizing the energy consumption in buildings, the effect of these methods are not remarkable. However, the term of window to wall ratio of the building is slightly neglected for energy saving in Hong Kong.

Nevertheless, appropriate window to wall ratio of the building which is one of the building design improvements can be another effective method for reducing the building energy consumption. Abundant researches in other countries reveal that different window to wall ratios of the building can clearly influence the demand of HVAC system so as to control the energy consumption.

1.2 Aim and Objectives

This research aims to investigate the appropriate window to wall ratio of the high-rise buildings for minimizing the demand of HVAC systems. In order to achieve this aim, there are several objectives of the research:

- (i) To investigate the thermal comfort under different window to wall ratio in current high-rise buildings
- (ii) To explore the effects of the relationship between the different window to wall ratio and the demand of HVAC systems in Hong Kong and other countries
- (iii) To examine the appropriate window to wall ratio for high-rise buildings in Hong Kong
- (iv) To make recommendations for future implementation of the design of window to wall ratio

Chapter 2 Literature Review

2.1 Heat Transfer Mechanisms Through Windows

2.1.1 Energy Performance Ratings

There are three major elements to indicate the energy performance of the windows that the demand of Heating, Ventilation, Air-Conditioning (HVAC) system is influenced as different values of these elements fluctuates the rate of heat transfer through the windows.

2.1.2 Heat Transmission Coefficient (U-value)

According to National Fenestration Rating Council (2017), the rate of heat loss or gain through the windows is nationally recognized in the term of U-value or U-factor. The U-value is normally calculated in two different ways. One of the U-value is calculated for the whole window which includes the components of frame, glazing and sash while another is called “Center-of-glass U-value” which is only calculated the heat transfer perpendicular to the window plane. The greater the U-value, the lower resistance of heat flow. For instance, the “Center-of-glass U-value” of double pane, low-e and argon gas fin windows is around 0.33 while high-performance double-pane windows can reach the value of 0.3 or lower (Efficient Windows Collaborative, 2017). Therefore, the high-performance double pane windows have better performance of insulation properties that it has lower rate of heat flow through the windows. This value affects the rate of total heat transfer through the windows that the demand of HVAC is adjusted by different U-value of the windows.

2.1.3 Solar Heat Gain Coefficient (SHGC)

Solar Heat Gain Coefficient (SHGC) is the percentage of the available heat gain by solar energy that is passed through the window. The total heat gain through the windows is mainly dominated by the solar radiation that it is a vital value to reduce the undesirable heat gain especially during the summer season in Hong Kong. Low-emissivity window, which is also named low-e glass, is widely adopted for lowering the SHGC in other countries. Pilkington (2017) claims that the 43% of SHGC can be minimized by using the double glazing with low-solar-gain coatings because the solar reflectance of low-solar-gain coating is around 96% which only emits 4% through the windows. Therefore, huge amount of infra-red radiation which is the major heat source of solar radiation is reflected by using different low-e coatings in double glazing.

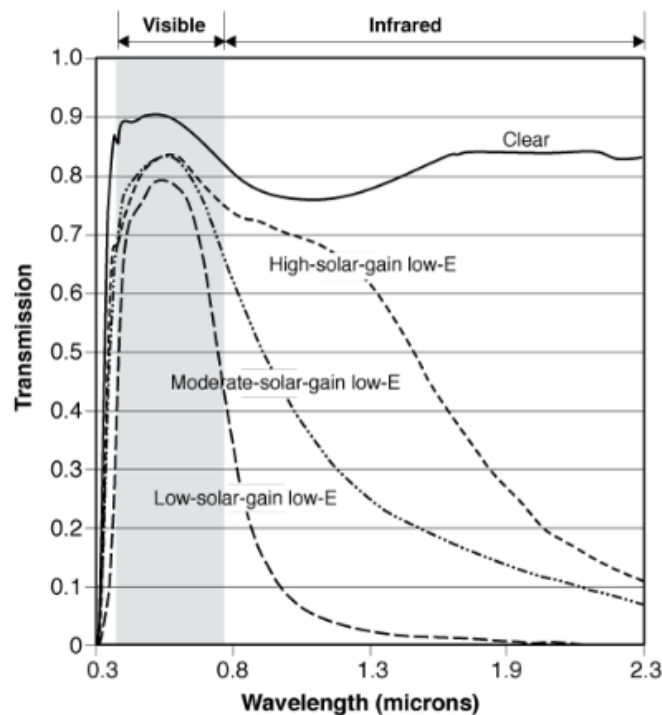


Figure 1 Percentage of visible light and infra-red radiation transmission with four low-e coatings
(Efficient Windows Collaborative, 2017)

Shading Coefficient (SC) is the older term which have been replaced by the SHGC. It is the ratio of the solar heat gain through the selected type of glass of window and glazing to the solar heat gain through the double glass of the window and glazing (Building Department, 2014). It is the measurement of the thermal performance of the glass which is factored by the color and reflectivity of the glass.

2.1.4 Solar Heat Gain Factor (SHGF)

Solar Heat Gain Factor (SHGF) is one of the elements encountered in the estimation of cooling load from solar heat gain through window and glazing. This factor is significantly influenced by the latitude of the location and orientation of the window that it considers the angle of incidence of the sun path to the surface of the windows (Building Department, 2014). For instance, the SHGF has been calculated according to different latitude of locations the by the ASHRAE clear sky approach.

Latitude	32°N							
	N	NE	E	SE	S	SW	W	NW
half-day total	79	107	570	1015	853	264	80	79
January	158	186	650	1279	1706	1279	650	186
half-day total	100	201	735	1080	780	228	100	100
February	200	301	835	1308	1560	1308	835	301
half-day total	124	359	875	1041	589	193	125	124
March	248	483	1000	1234	1178	1234	1000	483
half-day total	161	550	952	889	360	177	153	152
April	322	702	1105	1066	720	1066	1105	702
half-day total	222	702	985	747	250	183	175	174
May	444	876	1160	930	500	930	1160	876
half-day total	261	762	985	678	225	189	184	183
June	522	945	1169	867	450	867	1169	945
half-day total	231	701	967	726	248	187	180	179
July	462	880	1147	913	496	913	1147	880
half-day total	171	546	922	854	352	184	162	160
August	342	706	1084	1038	704	1038	1084	706
half-day total	130	345	831	993	574	197	130	129
September	260	474	961	1190	1148	1190	961	474
half-day total	103	200	708	1038	753	226	104	103
October	206	303	812	1264	1506	1264	812	303
half-day total	80	108	561	996	838	261	81	80
November	160	188	642	1257	1676	1257	642	188
half-day total	71	84	500	965	852	275	71	71
December	142	155	571	1240	1704	1240	571	155

Solar Heat Gain Factors - Daily Totals

$$\frac{\text{Btu}}{\text{ft}^2 \cdot \text{day}}$$

Latitude 40°N									
	N	NE	E	SE	S	SW	W	NW	
half-day total	61	73	452	904	813	273	62	61	
January	122	134	514	1177	1626	1177	514	134	
half-day total	84	152	648	1049	821	250	85	84	
February	168	236	733	1299	1642	1299	733	236	
half-day total	114	302	832	1087	694	220	114	113	
March	228	415	946	1307	1388	1307	946	415	
half-day total	154	501	957	994	488	199	148	147	
April	308	648	1105	1193	976	1193	1105	648	
half-day total	215	666	1024	881	358	200	176	174	
May	430	840	1200	1081	716	1081	1200	840	
half-day total	253	734	1038	818	315	204	188	186	
June	506	920	1226	1022	630	1022	1226	920	
half-day total	223	666	1008	858	352	204	181	180	
July	446	846	1189	1062	704	1062	1189	846	
half-day total	164	498	928	956	474	205	157	156	
August	328	654	1085	1161	948	1161	1085	654	
half-day total	119	291	787	1003	672	222	119	118	
September	238	409	906	1225	1344	1225	906	409	
half-day total	88	152	623	1006	791	247	89	88	
October	176	240	712	1253	1582	1253	712	240	
half-day total	63	75	445	887	798	269	63	63	
November	126	138	508	1156	1596	1156	508	138	
half-day total	52	56	374	822	775	276	53	52	
December	104	108	427	1098	1550	1098	427	108	

Solar Heat Gain Factors - Daily Totals

$$\frac{\text{Btu}}{\text{ft}^2 \cdot \text{day}}$$

Table 1 Solar Heat Gain Factor (SHGF) for different latitude of locations (ASHRAE, 2009)

Highlighted in yellow represents the daily total (SHGF) by btus per day and per square foot. For example, SHGF for exposure to the north, east, south and west in January at 40°N is 122 Btu/(day.ft²), 514 Btu/(day.ft²), 1626 Btu/(day.ft²) and 514 Btu/(day.ft²) respectively. Therefore, heat gain from radiation which exposures to south direction is largest in January at 40°N because of the greatest SHGF.

Li and Lam (2000) revealed that the data of SHGF is essential information for determine the average and peak cooling load of the buildings in Hong Kong that this factor partially affects the demand and the sizing of HVAC systems in summer season. Average SHGF for Hong Kong in different orientation of windows per month is pointed out in below Table 2.

Average SHGFs for Hong Kong

Period	Average SHGF (W/m ²)				
	Horizontal	N	E	S	W
January	242	73	124	222	128
February	211	65	97	147	111
March	226	69	97	119	119
April	285	98	132	124	156
May	325	99	126	103	153
June	335	103	127	96	146
July	390	117	158	114	192
August	359	102	160	121	185
September	340	137	201	212	242
October	352	85	159	226	164
November	307	82	167	306	178
December	242	72	142	278	138
Annual	301	89	138	167	154
9-month cooling season	332	98	146	146	166
6-month cooling season	350	100	148	136	168
4-month hot summer	354	111	169	125	176

Table 2 Average Solar Heat Gain Factor (SHGF) for Hong Kong (Li, D. H. and Lam, J. C., 2000)

It reveals that SHGF is largest where is exposure to south direction while the SHGF is lowest where is exposure to north. It is an important data to identify the suitable orientation of the windows faced for absorption less heat gain from the radiation per year. Moreover, it can be observed that the average SHGF in summer season (From June to September) is vast where faces to west direction. Demand of HVAC systems obviously is relatively enormous in summer season that the orientation of windows should not be installed in west direction for reducing the heat gain from solar energy.

2.1.5 Visible Transmission (VT)

Visible Transmission (VT) reveals the amount of visible light that can be penetrated through the windows. The amount of daylight is enhanced with increasing the value of VT that the sufficient daylighting can directly lower the demand of artificial lighting. For example, the amount of visible lighting is slightly reduced and reflected with low-e coating about 10% in Figure 1. There is an additional heat gain from the artificial lighting since it is absolutely required when the luminaires of visible light is not enough. Therefore, the value of VT is also included in the energy performance ratings of windows.

2.2 Heating, Ventilation, Air-Conditioning (HVAC) System

Heating, Ventilation, Air-Conditioning (HVAC) system involves the operation of numerous equipment such as air-conditioners, chillers and air handling units so as to achieve the appropriate requirement of heating and cooling for residential, commercial or industrial buildings. Therefore, building consumption in building life cycle is mostly produced by the operation of HVAC systems. Indoor air quality (IAQ), internal temperature and indoor humidity are generally regulated and controlled from the HVAC system in order to satisfy the thermal comfort. The mechanism and operation of the HVAC system is introduced in Figure 2. More importantly, internal humidity and temperature can be adjusted by the operable windows. Therefore, the demand of the mechanical HVAC system can be decreased for energy saving.

Humidity can be controlled by the natural ventilation through the operable windows. Natural ventilation occurs when there is a difference between the air pressure of indoor and outdoor that the direction of air flow is from the positive pressure to the negative pressure through the operable windows. Dehumidification and humidification are also driven when the ventilation is naturally happened that the process of dehumidification is more desirable as the relative humidity is normally high in Hong Kong. Moreover, the indoor temperature

can also be slightly reduced because of dehumidification. Accumulation of air moisture is extracted by the dehumidification from ventilation process. Therefore, there is a heat loss by releasing the heat inside the air moisture.

Indoor temperature is significantly influenced by the operable windows. The U-value of the windows and concrete wall with insulation layer are clearly distinct that the heat transfer through the windows is greater than the heat transfer through the concrete wall. According to GeorgiaState University (2017), the material of window frame commonly is the aluminum which has thermal conductivity of 205 (W/mK) while the thermal conductivity of concrete is 0.8 (W/mK). Furthermore, large amount of heat gain is absorbed from the radiation through the glazing of windows. Therefore, the rate of heat gain or loss of operable windows is greater than the concrete wall.

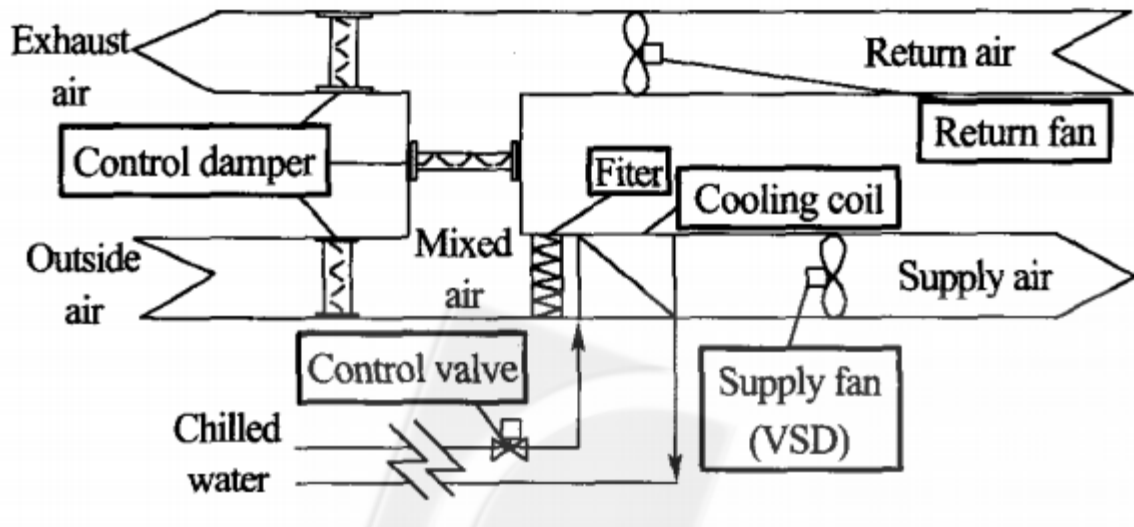


Figure 2 Typical HVAC system (Kibaya, A. R., 2013)

2.2.1 Thermal Comfort

Thermal comfort is the standard to identify the thermal environmental conditions for human occupancy. Health and Safety Executive has reported that the indoor thermal comfort is generally determined by six basic factors which are dry and wet bulb temperature, relative humidity, clothing levels and air velocity. The aim of identifying the thermal comfort is to investigate whether the indoor environment is acceptable to a majority of occupants in the space (ASHRAE, 2014).

Leung (2008) pointed out that it has been proved to control the thermal comfort, which is closely related to the temperature and humidity, for achieving the requirements of comfort zone. When the indoor environment conforms to the “comfort zone”, the occupants would feel comfortable within the space that it can decrease the frequency of operation of HVAC system and the consumption of HVAC system (Javad, 2014). In Figure 3, two blacken area reveals the area of comfort zone in winter and summer that the thermal comfort of occupants should lie on these two areas according to the seasons. In Figure 4, the two blacken area also show the area of comfort zone but that is affected by the clothing level (clo) of occupants. Therefore, it is important to adopt the appropriate standard of comfort zone. For instance, the comfort zone in Figure 4 should be more suitable and flexible for the identification of thermal comfort in residential buildings as the clothing level of occupants always be informal which is kept in 0.5 clo. Therefore, it can be more feasible and convenient to plot the data in the graph.

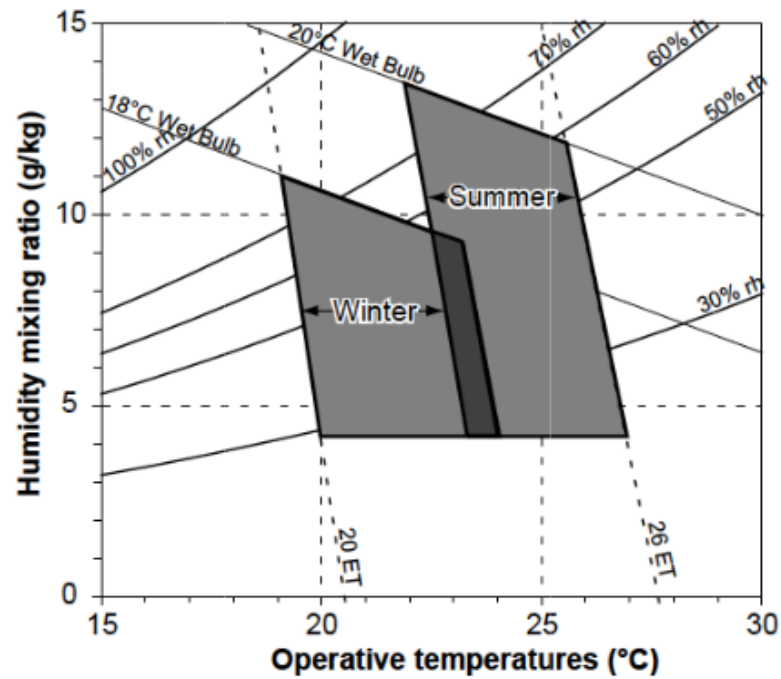


Figure 3 Comfort zone in summer and winter (Building Department, 2014)

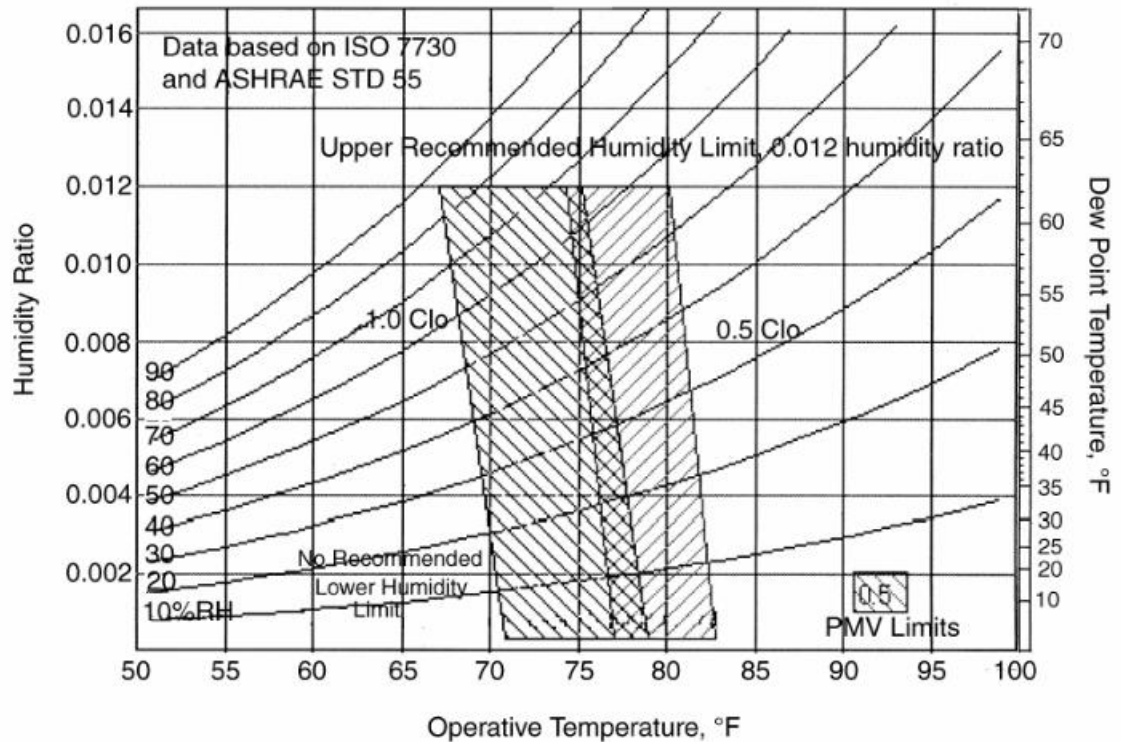


Figure 4 Comfort zone due to the clothing level of occupants (Ashrae, 2014)

Controlling the thermal comfort within the space, the designer and the professionals of building science frequently utilize the psychrometric chart to plot the collected data from the indoor. In Figure 5, it explores the data what should be examined and plot the points into the chart in order to investigate whether the space is laid on the comfort zone.

It is essential to control and improve the thermal comfort inside the space that it should be within the area of “comfort zone”. Different window to wall ratio of the building can contribute to different conditions of thermal comfort due to the dehumidification effect by natural ventilation of window and the heat loss or heat gain by the U-value of windows and walls. More importantly, the psychrometric chart should be persistently adopted in the design stage of the construction projects because the demand of HVAC could be minimized in a long term when the indoor environment lies on the area of comfort zone.

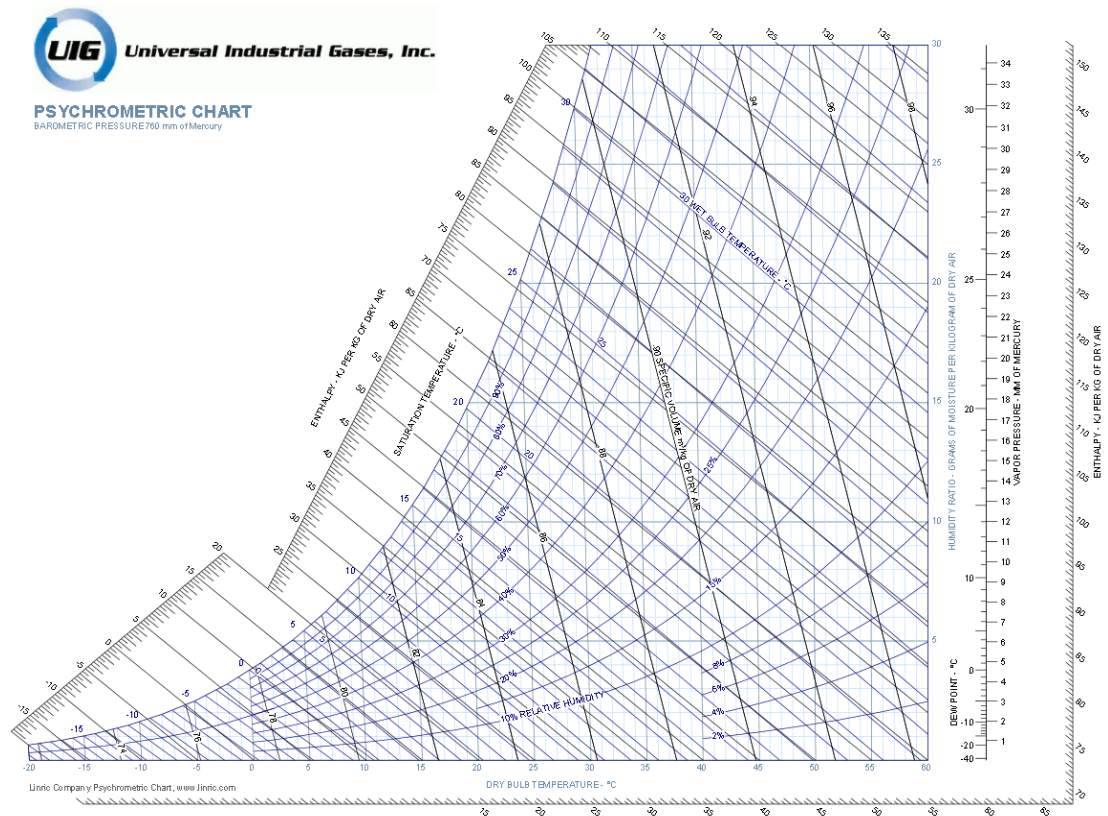


Figure 5 Psychrometric chart (Ashrae, 2009)

2.2.2 Cooling load estimation

Mechanical and electrical system which include air conditioning may be required in the buildings which have a large heat gain from the outdoor environment that leads to a high internal temperature. According to Ashrae (2009), conduction through roofs and walls, conduction and solar heat through glazing, infiltration and heat gain from outside air by convection are the typical heat gains for the buildings. Therefore, these factors need to be taken into account for the calculation of cooling load in the buildings.

Cooling Load of the buildings is mainly affected by the area of the windows. Heat gain from the radiation through windows and glazing is determined by SHGF and SC. Furthermore, both sensible and latent heat of infiltration and ventilation from outside air should be considered in cooling load estimation as there is the difference of moisture between outdoor and indoor environment (Ashrae, 2009). Therefore, it explores that the area of fenestration for windows definitely fluctuate the cooling load estimation as it changes the rate of infiltration and ventilation of the unit.

2.2.3 Cooling load of utilizing windows with low-e coatings

Auliciems and Szokolay (2007) point out that cooling load is the amount of heat gain from the outdoor environment and the equipment inside the building at design conditions which should be addressed by the HVAC system in order to satisfy the thermal comfort. Cooling load is accumulated by numerous components of the buildings such as sensible and latent infiltration gain at all windows, doors and cracks and the heat gain from the walls in Figure 6. For instance, heat gained from solar radiation is greatly absorbed for the orientation of buildings in north and south facade because the Hong Kong is located at the northern hemisphere (Electrical and Mechanical Services Department, 2011). More importantly, Hui and Cheung (1998) indicate that cooling load in building envelope is more advisable to be

removed than the heating load since the annual temperature and the humidity in Hong Kong is beyond the average value in other countries.

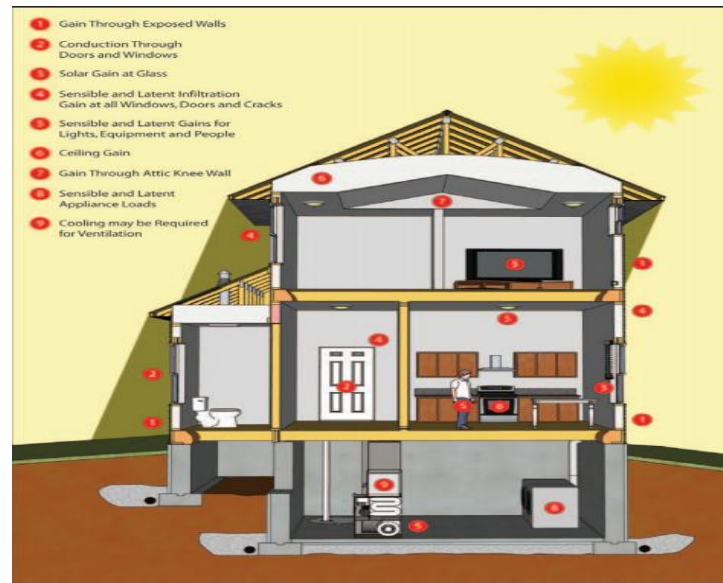


Figure 6 Cooling load from heat gain of numerous components (Burdick, A., 2011)

According to Burdick (2011), the peak cooling load in summer can be distinctly lowered by installing different types of windows. The requirement of HVAC systems such as the size of air conditioners and heat pump is clearly determined by the demand of cooling load. Efficient Windows Collaborative (2017) claims that the demand of operating air conditioners for the building which contains many windows with low-e coatings is two tons smaller than simple single or double-pane windows in Phoenix and Minneapolis. It also reveals that the cost of cooling energy can be reduced by 43% when the windows with low-e coatings are adopted in the buildings in Phoenix. Therefore, the size of cooling system in HVAC and the cooling load can be simply lessened by using the low-e coating windows.

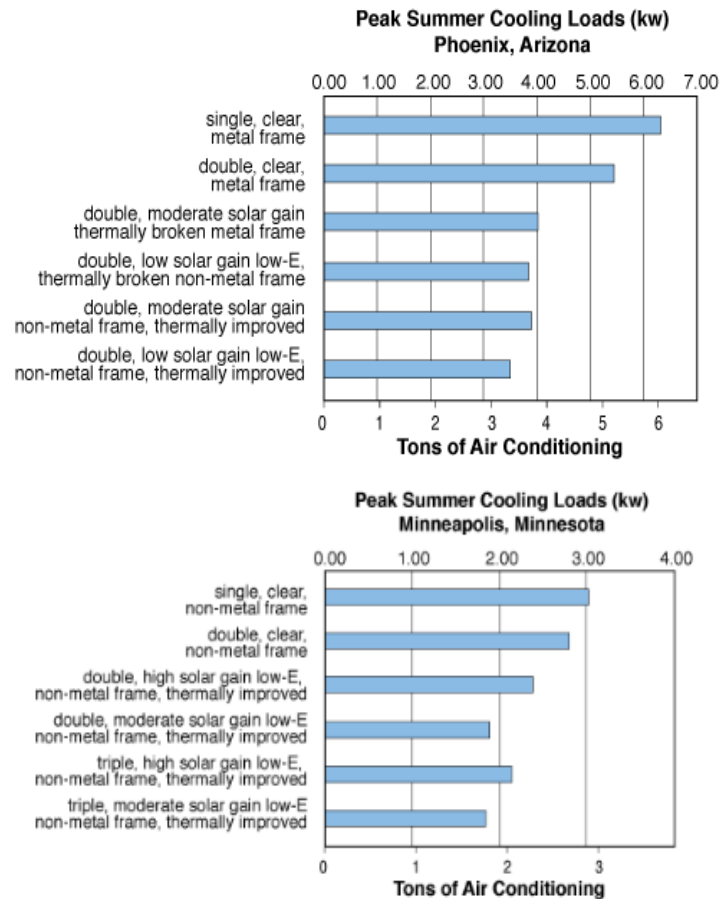


Figure 7 & 8 Peak cooling loads in Phoenix and Minneapolis by the windows with and without low-e coatings (Efficient Windows Collaborative, 2017)

2.2.4 Stereographic Sun path Diagram

Burdick (2011) indicated that the sun path diagram for each building should be considered for energy saving in early design stage. Period and location of the sun path directly affect the heat gain from the solar energy and the cooling load of the building envelope during the process of daylighting. Stereographic sun path diagram is one of the polar representations for expressing the azimuthal angle and the altitude angle of the sun path in a year. In Figure 9, it shows the example of Autodesk's sun path diagram which expresses the azimuthal line around the edge and altitude line around the concentric circular dotted lines.

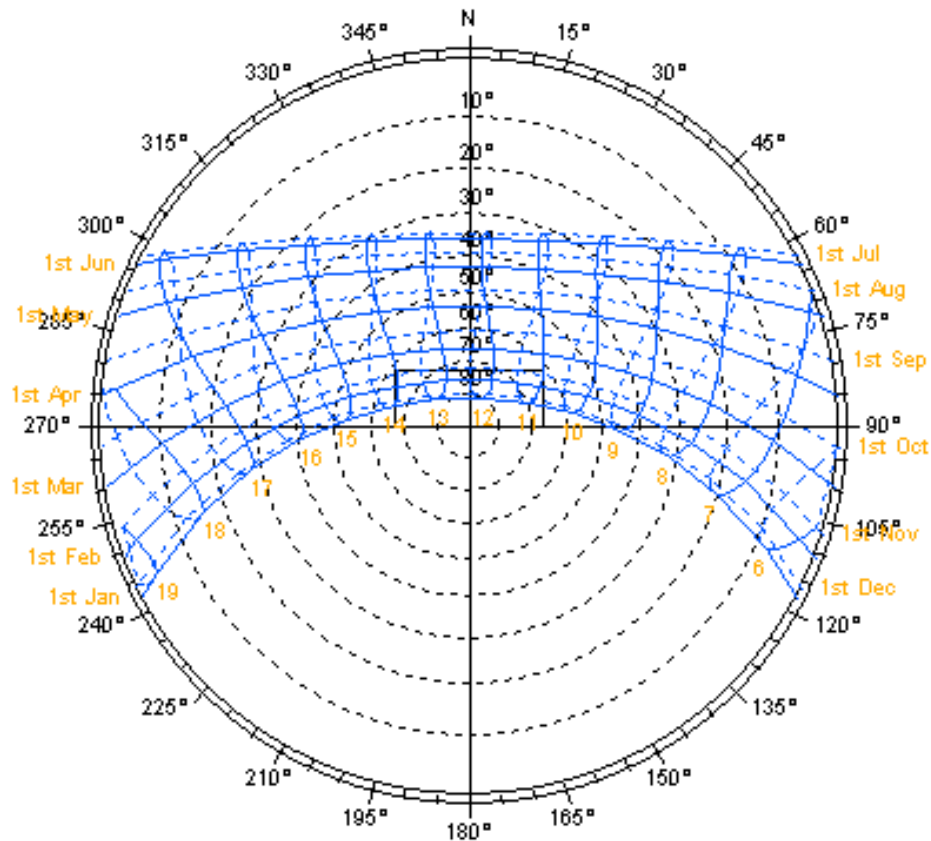


Figure 9 Autodesk's stereographic sun path diagram (Javad, K., 2014)

Numerous software simulation models of stereographic sun path diagram have been used for calculation of the annual and peak cooling load of the several residential buildings in North-east China (Du and Lu, 2013). The result of cooling load of these residential buildings is significantly regarded to the sun path diagram of those buildings and the orientation of the windows which directly absorb the heat from radiation. Therefore, the design of the orientation of windows should be preciously analyzed for reducing the period of gaining heat from the sunlight.

2.2.5 Orientation of the building and window

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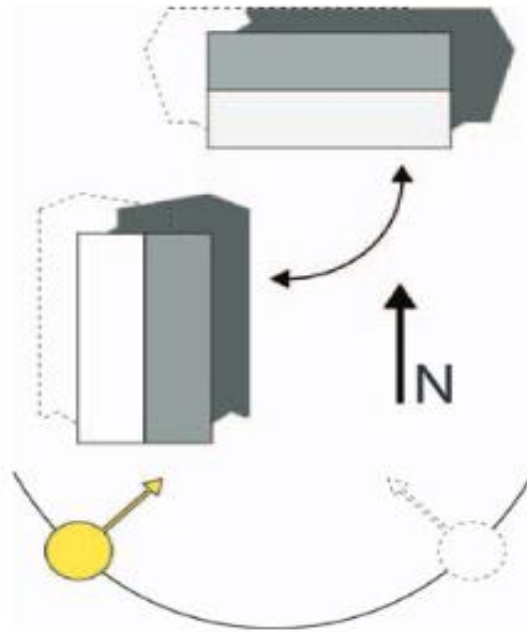


Figure 11 Sensible heat gain on different orientation of the buildings and windows
(Electrical and Mechanical Services Department, 2011)

2.3 Windows to Wall Ratio (WWR)

Windows to Wall Ratio (WWR) is the ratio of total area of window to the total area of wall (Building Energy Data Exchange Specification, 2017). This ratio is an essential term for balancing the demand of HVAC system as the indoor temperature, natural ventilation and indoor humidity are indirectly regulated by the area of windows in exterior wall that has been expressed in Chapter 2.2.

Chapter 3 Research Methodology

3.1 Literature review

Numerous literature reviews are conducted so as to provide a comprehensive understanding of the term of window to wall ratio, the mechanism of heat transfer through different types of operable windows and the relationship between the window to wall ratio and HVAC systems. Academic articles and books, research reports and the relevant online materials are included in the literature review.

3.2 Case Studies

Several case studies in other countries explore the building energy consumption from HVAC systems under different window to wall ratio. Different types of windows are also examined for determining accurately the effects of different window to wall ratio. The objective of these case studies is to provide practical information for finding out the appropriate window to wall ratio of the buildings.

Another case study is conducted for investigating the thermal comfort in high-rise residential buildings in Tin Shui Wai due to the window to wall ratio condition. Indoor and outdoor air temperature, internal relative humidity and air speed are examined in order to investigate the effect of area of window and the orientation of windows on the energy consumption of HVAC system. Windows and concrete wall have distinct heat transfer abilities that it significantly influences the demand of HVAC systems to satisfy the thermal comfort.

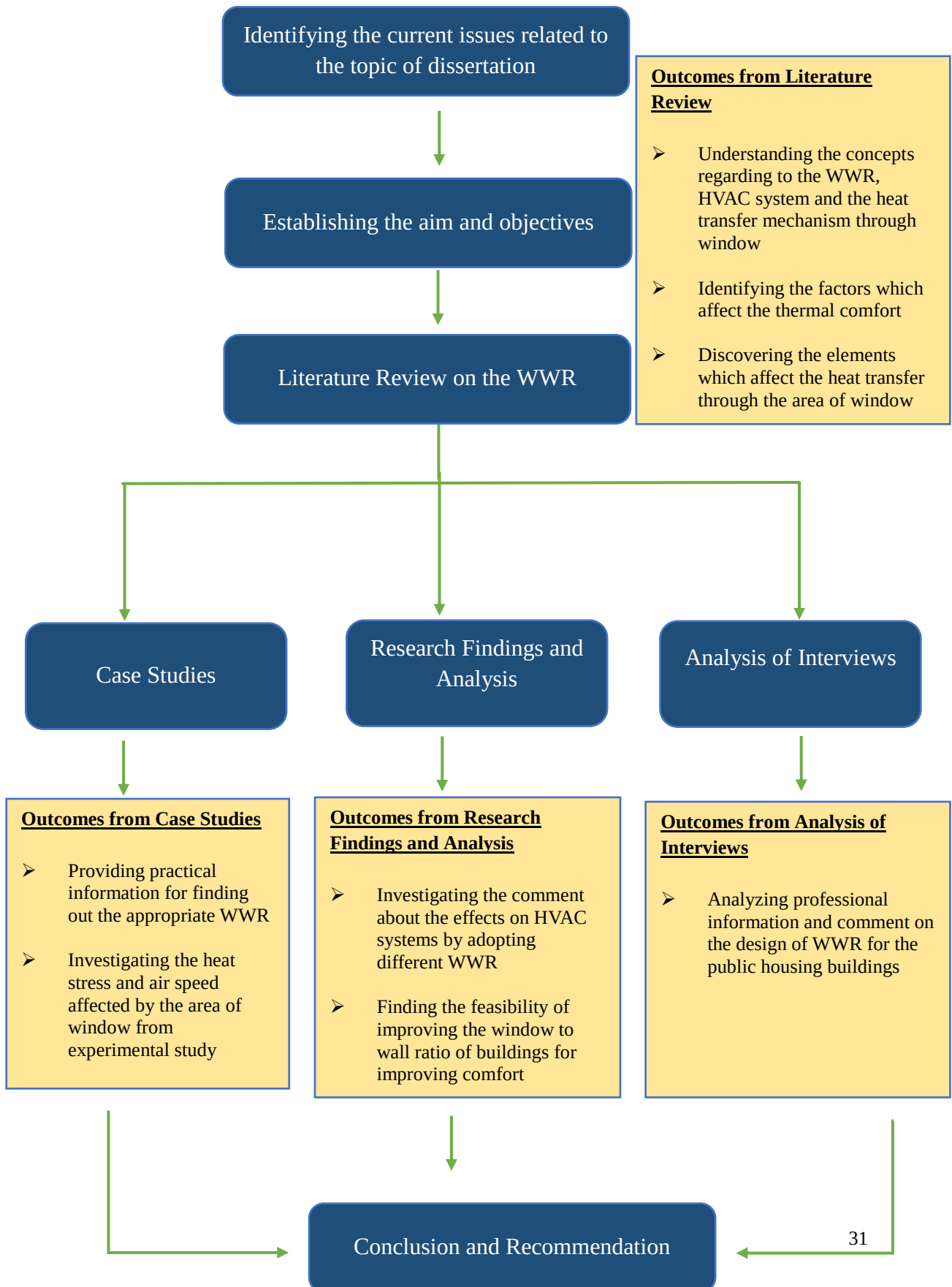
3.3 Interviews

Numerous interviews are conducted with representatives from main contractors and the experienced construction professionals. The aim of the interviews is to investigate the concept of designing the window to wall ratio and discuss the advantages and drawbacks of different window to wall ratio conditions.

3.4 Questionnaire Survey

Online and printed questionnaire survey are delivered to the construction professionals from main contractors, architectural consultants, sub-contractor and the developers through the email. The objective of the questionnaire survey is to investigate the comments about the effect of adoption different window to wall ratio on the HVAC systems and the feasibility of improving the window to wall ratio of the building for improving comfort of occupants. Residents are one of the target respondents to provide their opinions on the area of the window of the building.

3.5 Research Framework



Chapter 4 Case Studies

4.1 Introduction

Case studies from other countries and experimental case study of public housing building in Hong Kong are conducted and evaluated in this chapter. Each of case study was examined to investigate the correlation of the energy consumption under different window to wall ratio conditions. Four case studies from other countries were conducted by utilizing different simulation software to conduct a comprehensive result and analysis.

4.2 Typical residential building in Guangzhou (DeST-h model)

The study of the residential building is generated by using the simulation software of DeST-h that it aims to investigate the effect of different window to wall ratio in south orientation on the energy consumption due to HVAC system of the building (Li and Gao, 2013). Numerous researches have revealed that the building energy consumption in China is directly associated to the window to wall ratio of the building. More importantly, Jian and Jiang (2006) indicated that the energy consumption due to air-conditioning in summer in Shanghai is enhanced gradually with increased window to wall ratio on the orientation of north, east and west but the demand of air-conditioning is decreased with increased window to wall ratio on the south orientation of the building because of the natural shading effect. Therefore, the case study of the window to wall ratio of the south orientation of the residential building is conducted.

Air-conditioning system is operated by two modes which are mechanical mode and nature priority mode. Natural ventilation from the operate window on the south orientation is produced into the building in the nature priority mode that it is assumed to have 8 times per hour and 3 time per hour in 0.4 and 0.2 window to wall ratio respectively in Table 3. The

natural ventilation by opening the windows can reduce the frequency of the operation of air-conditioning system.

Mode	Ventilation mode	Tolerate Temperature range	Air-conditioning temperature	The time spatial distribution of air conditioning
All mechanical mode	Window closed ventilation rates at 0.5 times/h	18°C-26°C	26 °C in summer 18°C in winter	Running-continuously throughout the day; all rooms air conditioning;
Nature priority mode	8 times/h if window open when window-wall ratio is 0.4 ; 3 times/h if window open when window-wall ratio is 0.2; 0.5 times/h if window closed	16°C-29°C	26°C in summer 18°C in winter	Running-intermittent; air conditioning operation schedule as Table 2, kitchen & bathroom no air-conditioning

Table 3 Operation mode of air-conditioning system (Li and Gao, 2013)

In Figure 12, it shows the floor plan of each storey of the residential building which is total 12 stories and 119 square meters of residential unit area. The highlighted line represents the location of the operate windows that the heat transfer coefficient and shading coefficient of the window is $5.7\text{W}/(\text{m}^2\cdot\text{K})$ and 0.4 respectively.

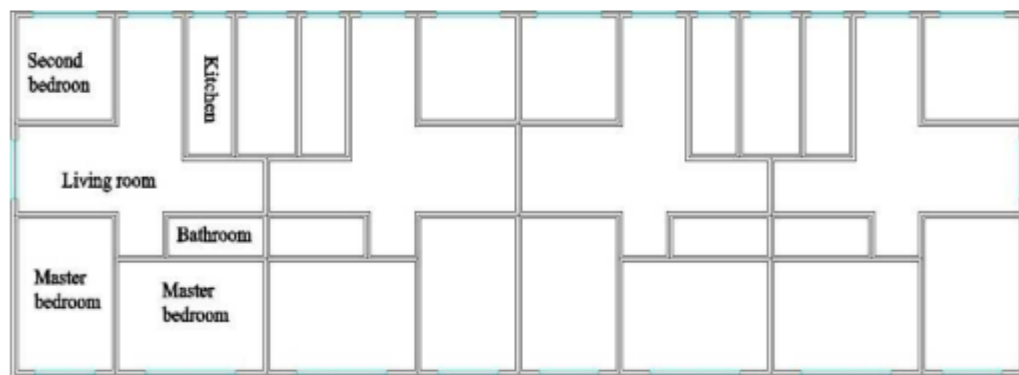


Figure 12 Floor Plan of the typical residential building in Guangzhou (Li and Gao, 2013)

According to the data collected in Figure 13 and 14 by Li and Gao, it is obvious that the cooling load of the building per month except July is minimized with the increased window to wall ratio on south orientation from 0.2 to 0.4. Natural ventilation is the major factor to decrease the cooling load of the building as the sufficient air flow inside the unit can reduce slightly the relative humidity and indoor temperature so as to enhance the thermal comfort

of the occupants. Therefore, the frequency of operating the air-conditioning system can be minimized when the ventilation rate through the window into the unit is adequate. Energy saving of 0.38 kWh/(m²·year) from the air-conditioning is generated by increasing to the 0.4 of window to wall ratio on south orientation.

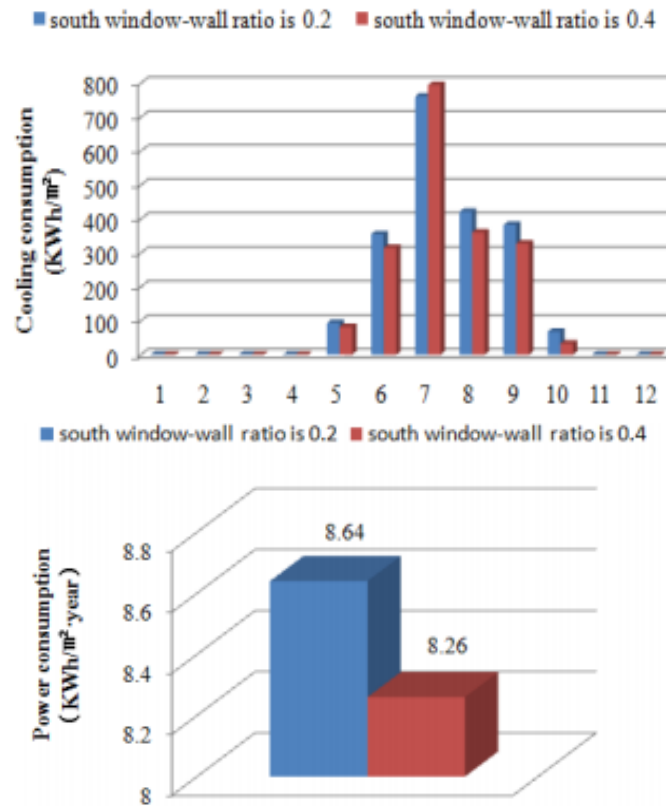


Figure 13 & 14 Cooling load and power consumption of the building based on 0.2 & 0.4 of window to wall ratio

(Li and Gao, 2013)

In conclusion, the research conducted by Li and Gao reveals the effect of window to wall ratio on the demand of HVAC system of the building in Guangzhou. This research also points out that it is necessary to consider the sun path diagram of the building as the heat gain from solar energy only on south orientation in Guangzhou is smallest and it could be negligible. Therefore, the better ventilation rate by increased window to wall ratio can be obtained for the building without increasing the heat transfer through the larger area of windows.

4.3 High-Rise Office Buildings in Tehran (eQUEST Software)

Impact of different window to wall ratio of the high-rise office buildings in Tehran on the energy consumption is conducted by the eQuest software model (Ghiai et al., 2014). The envelope of typical office buildings is generated by utilizing the base-case model in their research which is shown in Figure 14. 20%, 40%, 60%, 80% and 100% of the window to wall ratio on northern, eastern, southern and eastern fronts are simulated and examined for calculating the energy consumption due to HVAC system. Sun path diagram in Tehran also has been produced for the calculation of the heat gain from sunlight.

General Specifications	Architectural-Structural Characteristics
Plan Geometry: Rectangle Plan Proportions: 1: 1/35 Plan Dimensions: 35m x 26m Plan Spatial Arrangement: Open Space Storeys: 15 storeys + 3 storeys underground Storey height: 4m (floor to floor) (floor height up to the false ceiling = 3m; False ceiling height = 60 cm) Storey Area: 745m ² (net) (82% of total storey area); Core and Service Areas for each Storey: 165m ² Direction of Rotation: 30 degrees south east (in Tabriz) and 15 degrees south east in Yazd Building Skeleton Type: Concrete Skeleton and Central Core (total area: 165 m ² equal to 18% of storey area)	
Exterior wall Structure: Cement Plaster (2.5 cm), Concrete Wall (15 cm), Finished Plaster Cover as well as Paint (2.5 cm) Roof Structure: Mosaic Flooring (2.5 cm), Sand-Cement Mortar (2.5 cm), Roofing, light-Weight Concrete (5 cm), Structural Floor (25 cm) Storey Floor Structure: Stone Flooring (2.5 cm), Sand-Cement Mortar (2.5 cm), light-Weight Concrete (5 cm), Structural Floor (25 cm) Underground (Basement) Wall Structure: Concrete Wall (30 cm), Roofing Outer Wall Paint: Medium (Absorption Coefficient = 0.6) Opening Type and Material: 6 mm Double Glass (Double Clr/Tint) with the following Specifications: U: 0.54, SHGC: 0.7, VT: 0.79	Elements/Mythe Specifications

Figure 14 Base-case model specifications (Ghiai et al., 2014)

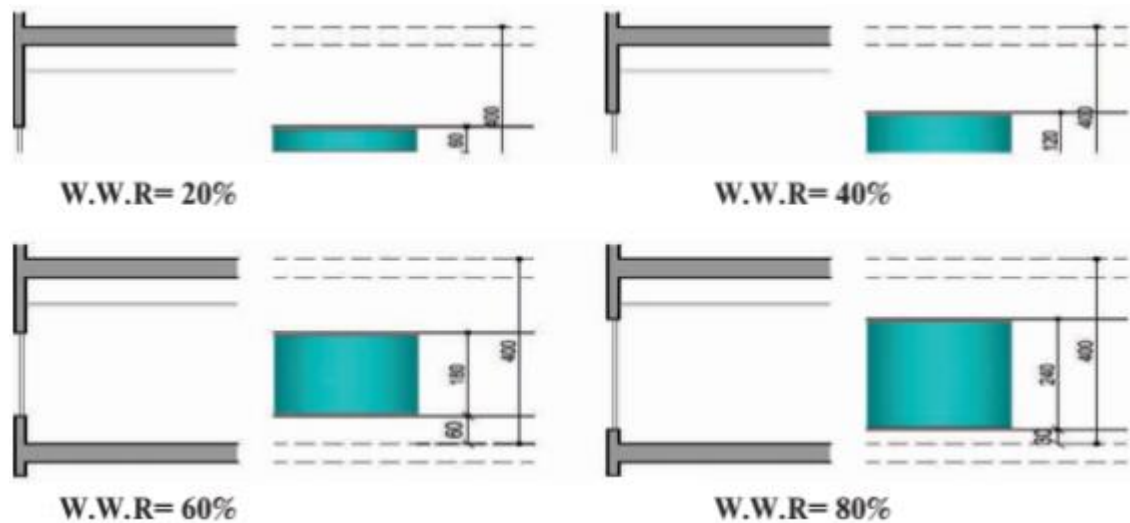


Figure 15 Different window to wall ratio of the office buildings (Ghiai et al., 2014)

The research discovered that the thermal load of the building is enhanced when the window to wall ratio is increased in the simulation model. In Figure 16, it expresses the cooling energy required for different window to wall ratio that the variation of window to wall ratio in Tehran can minimize the cooling energy by maximum of 58%. Moreover, the correlation coefficient between the WWR and energy consumption is near to 1 that these two elements are directly related at high level. Therefore, it consumes more energy for cooling in Tehran when it contains greater area of windows.

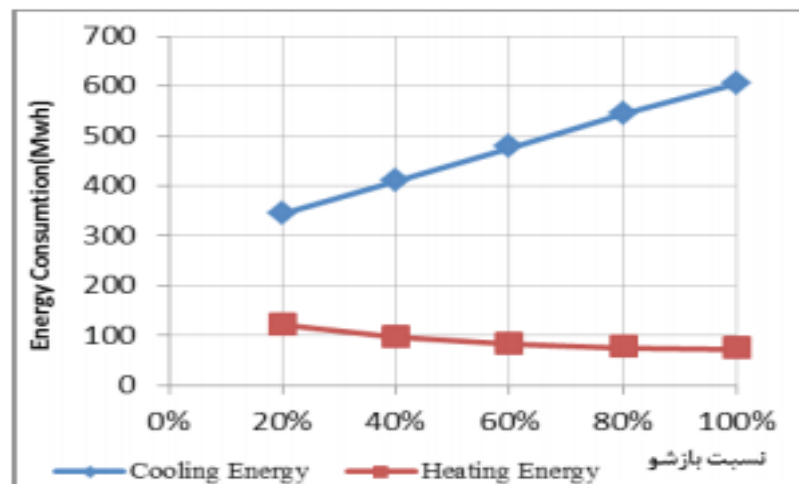


Figure 16 Cooling energy and Heating energy corresponding to different window to wall ratio
(Ghiai et al., 2014)

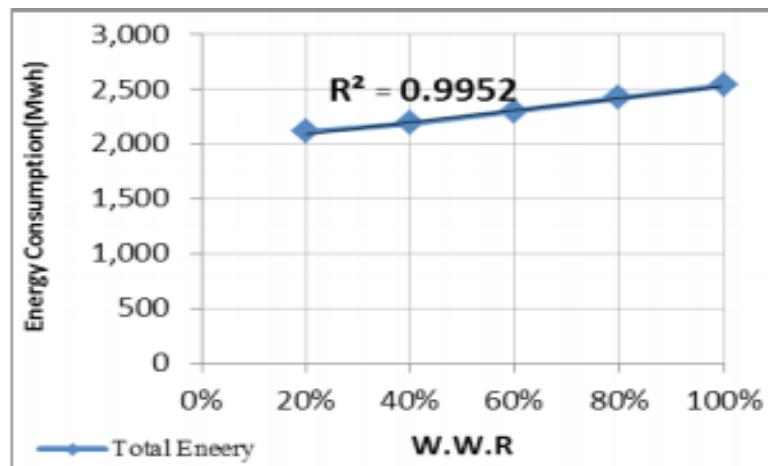


Figure 17 Correlation coefficient between the WWR and energy consumption (Ghiai et al., 2014)

Item	Window to Wall Ratio	Thermal Energy Variation	Total Energy Consumption Variation
1	W.W.R 80%	4%	9%
2	W.W.R 60%	9%	17%
3	W.W.R 40%	14%	25%
4	W.W.R 20%	17%	32%

Table 4 Thermal energy and Total energy consumption variation (Ghiai et al., 2014)

Furthermore, it can be observed in Figure 17 that the minimum energy consumption occurs at the lowest window to wall ratio which is 20%. Northern front of the buildings gains relatively greater heat gain than another three fronts. For the relationship between northern front and WWR, the energy consumption is enhanced significantly when the WWR beyond the 40% while the energy consumption is increased but negligible from 20% to 40%. Similarly, the increase of energy consumption is lowest when the WWR is increased from 20% to 40% but it should not be negligible.

The research also reveals that the WWR corresponding to the north, south, east, and west decrease around the energy consumption by 2%, 7%, 5%, and 4% respectively. Meanwhile, the slope of southern front is largest in Figure 18 that the mostly period of sunlight shines on this side of the building. In the result, the findings in the research recommend the buildings in Tehran that the appropriate WWR for the northern and southern fronts should be up to 40% while the eastern and western fronts should be between 20% and 40%.

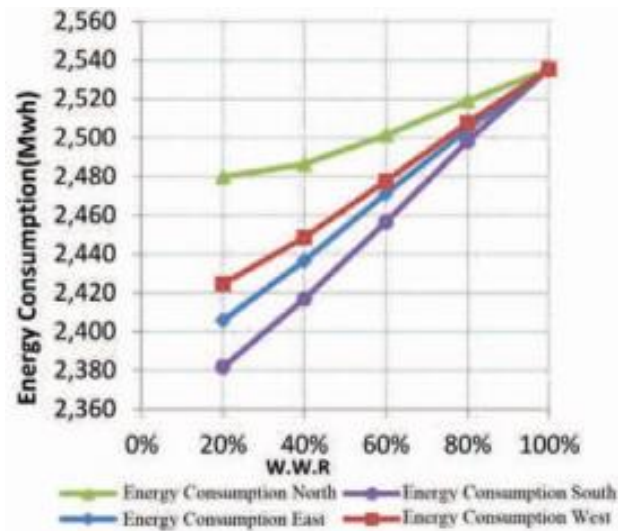


Figure 18 Relationship between four orientations of WWR and energy consumption (Ghai et al., 2014)

To conclude, the study discovers that the energy consumption is increased with increasing area of window for the building in Tehran. Simulation of the sun path diagram for the building was conducted for calculating the proper window to wall ratio of each orientation of the building. Four orientations of wall should have distinct window to wall ratio regarding the radiation through the window.

4.4 Office Buildings in Korea (COMFEN 4.0 Simulation Tool)

Variation of energy consumption in the office buildings due to the area and type of windows in Korea is conducted (Kim et al., 2014). The aim of the study is to investigate the relationship between the window to wall ratio and the energy consumption in the buildings. COMFEN 4.0 had been adopted for the simulation of the energy analysis. Cooling loads from different elements in the building is shown in the Table 5. It is essential to assume plainly the number of occupants and the equipment used vary with the period. Number of officers and equipment used is significantly enhanced as it is at the working period from 9.00 a.m to 6.00 p.m which is shown in the Figure 19.

Section	Contents
Building type	Office
Floor area	27 m ² (6 × 4.5 m)
Facade height	2.7 m
HVAC	Packaged single zone (PsZ)
Setpoint	Cooling: 24 °C Heating: 21 °C
Lighting load	16 W/m ²
Equipment load	10 W/m ²
People	3 People
Simulation period	Annual

Table 5 Simulation of the cooling load in the office building (Kim et al., 2014)

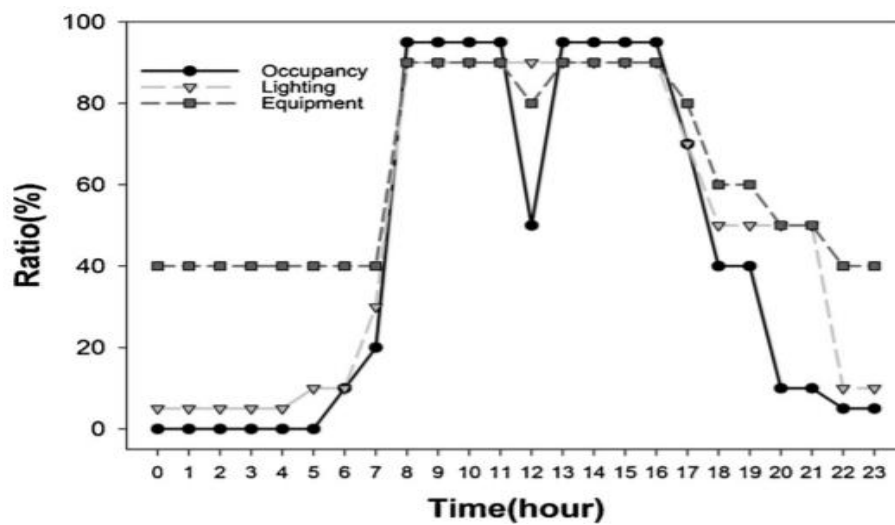


Figure 19 Variation of the officers and equipment in a day (Kim et al., 2014)

Moreover, different types of glazing for the window are examined for the simulation of the energy consumption in different orientation. SHGC and U-value of the glazing are the major factors to fluctuate the heat transfer through the window that significantly alters the cooling load of the building and the thermal comfort for the occupants. Therefore, total 16 types of glazing are examined for the energy study to discover the most appropriate type of glazing in Korea.

Type of glazing.				
U-Value	SHGC			
	0.2	0.4	0.65	0.75
1.0	Type 1	Type 6	–	–
1.4	Type 2	Type 7	–	–
2.1	Type 3	Type 8	Type 11	Type 14
2.8	Type 4	Type 9	Type 12	Type 15
3.4	Type 5	Type 10	Type 13	Type 16

Table 6 16 types of glazing according to different SHGC and U-value (Kim et al., 2014)

Simulation of replacing different types of glazing in east and south direction is mainly investigated as eastern and southern front of the building consumes most of the energy from the solar energy in Seoul. More importantly, 20%, 40%, 60% and 80% of window to wall ratio for each type of glazing are particularly examined for the energy consumption of the HVAC system within the building.

Energy consumption by HVAC system is increased gradually with increasing the ratio of window to wall area in east direction. For instance, energy consumption is totally enhanced by 300 MJ per year when 20% of window to wall ratio is increased to 80% that contains glazing with 3.4 of u-value and 0.75 SHGC. It is apparent that the difference of energy consumption becomes relatively significant when the SHGC of glazing is more or equal to 0.4 in east direction. It can be found that only 1.0 and 1.4 u-value in 0.2 to 0.4 SHGC of glazing should adopt more than 40% of window to wall ratio due to the lower energy consumption in east direction (Kim et al., 2014). Therefore, appropriate characteristics of glazing should be installed for increasing the area of window of the building in east orientation.

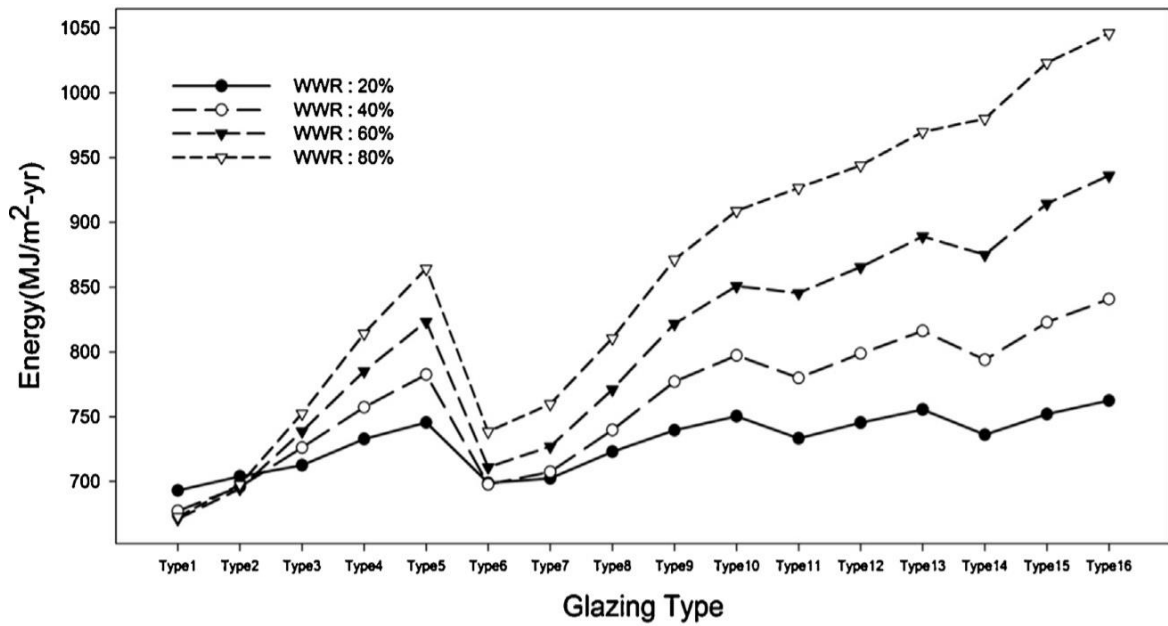


Figure 20 Energy consumption according to different WWR and types of glazing in east direction
(Kim et al., 2014)

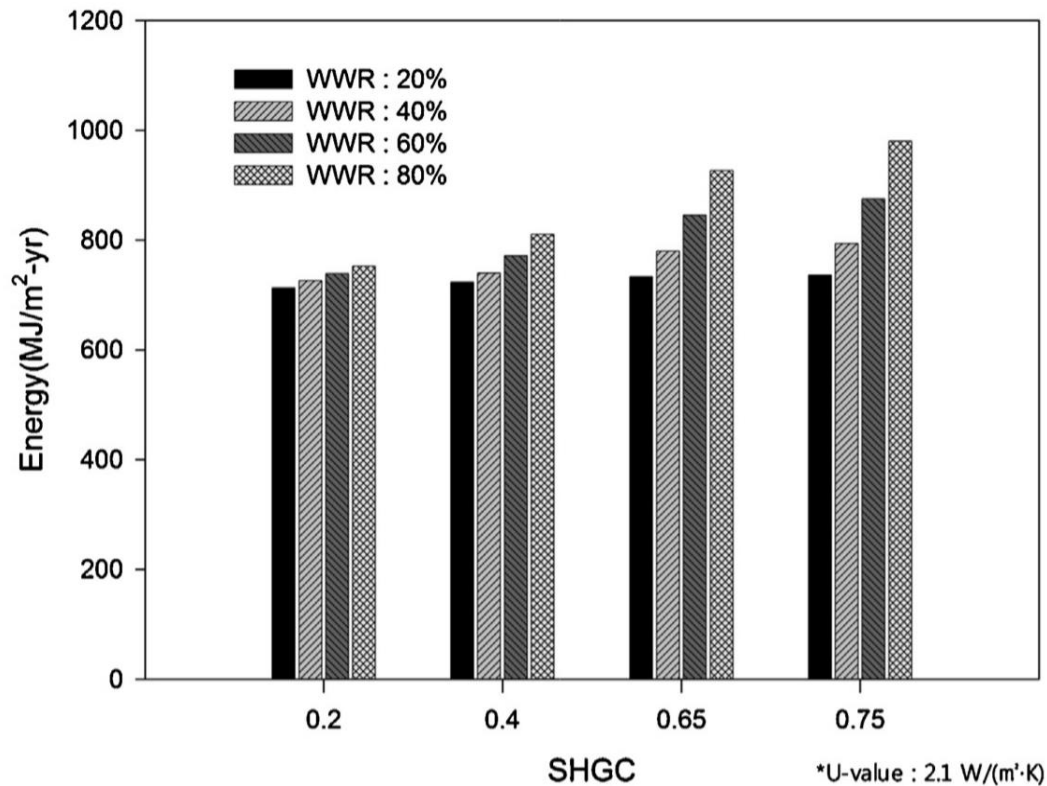


Figure 21 Relationship between the energy consumption and the SHGC in east direction
(Kim et al., 2014)

More importantly, the result of the simulation in south orientation is relatively dissimilar to the result of east orientation. It is obvious that the window to wall ratio should be greater than or equal to 40% when the glazing contains 2.1 of u-value or below in Figure 22 (Kim et al., 2014). Besides, the energy consumption is not fluctuated with the variation of SHGC. Therefore, the area of window can be easily enhanced since it can have higher u-value of glazing in south orientation which is compared with the result from the east orientation. One of the reasons is that the amount of energy from sunlight is lower and it can provide natural ventilation for reducing the indoor temperature by increasing the area of window in south orientation.

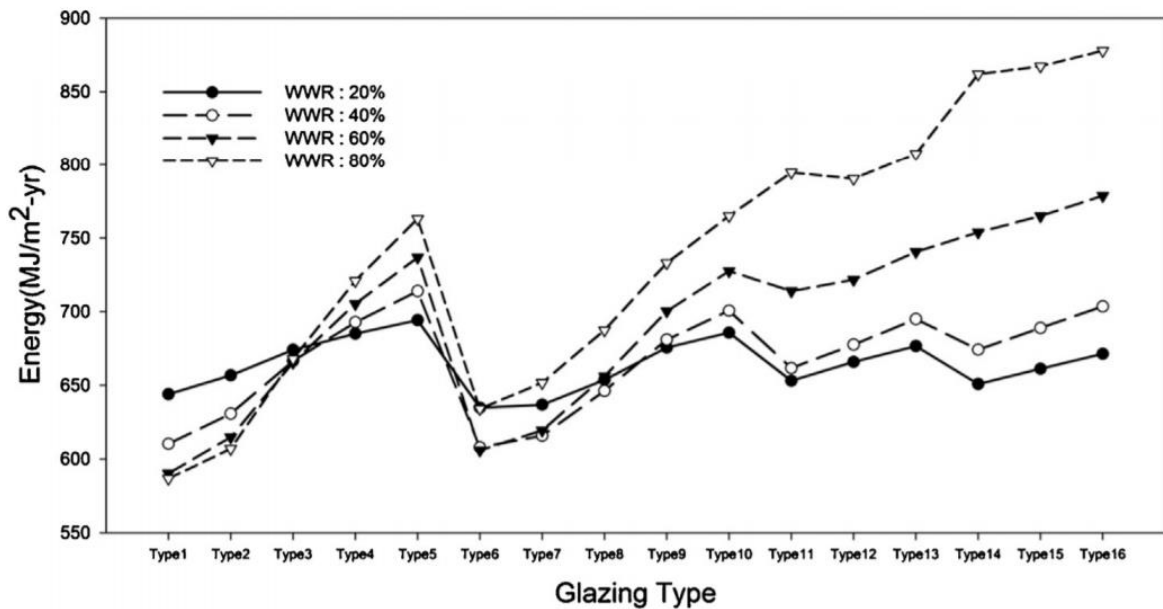


Figure 22 Energy consumption according to different WWR and types of glazing in south direction (Kim et al., 2014)

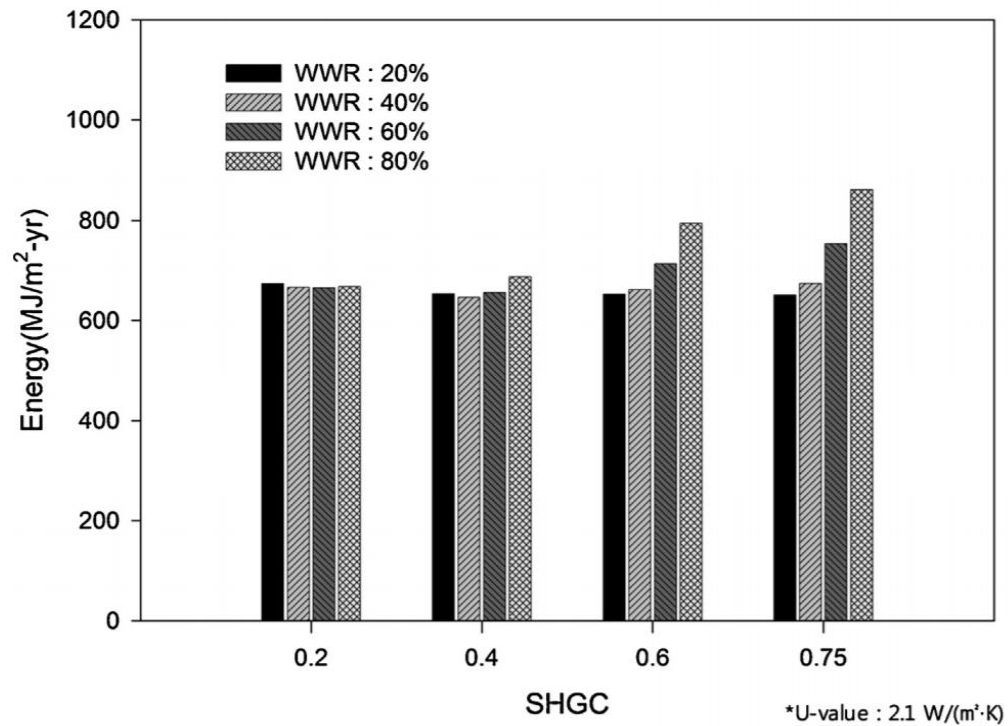


Figure 23 Relationship between the energy consumption and the SHGC in south direction (Kim et al., 2014)

Apart from the effect of different window to wall ratio of the building, the design of shading and lighting control in the building is also examined. Through the design of shading and lighting control, around 200 MJ of energy per year can be saved that it is one of the methods to maximum the area of window in the building for natural ventilation.

In conclusion, it reveals that different orientations and types of window can have large difference of absorption of the radiation. Area of window can be increased in the orientation which absorbs less solar energy in a day. It is also proved that the heat gain from outdoor is not reduced when the area of window is minimized for the low u-value of glazing. In addition, shading and lighting controls should be promoted that it can decrease the heat gain through the window.

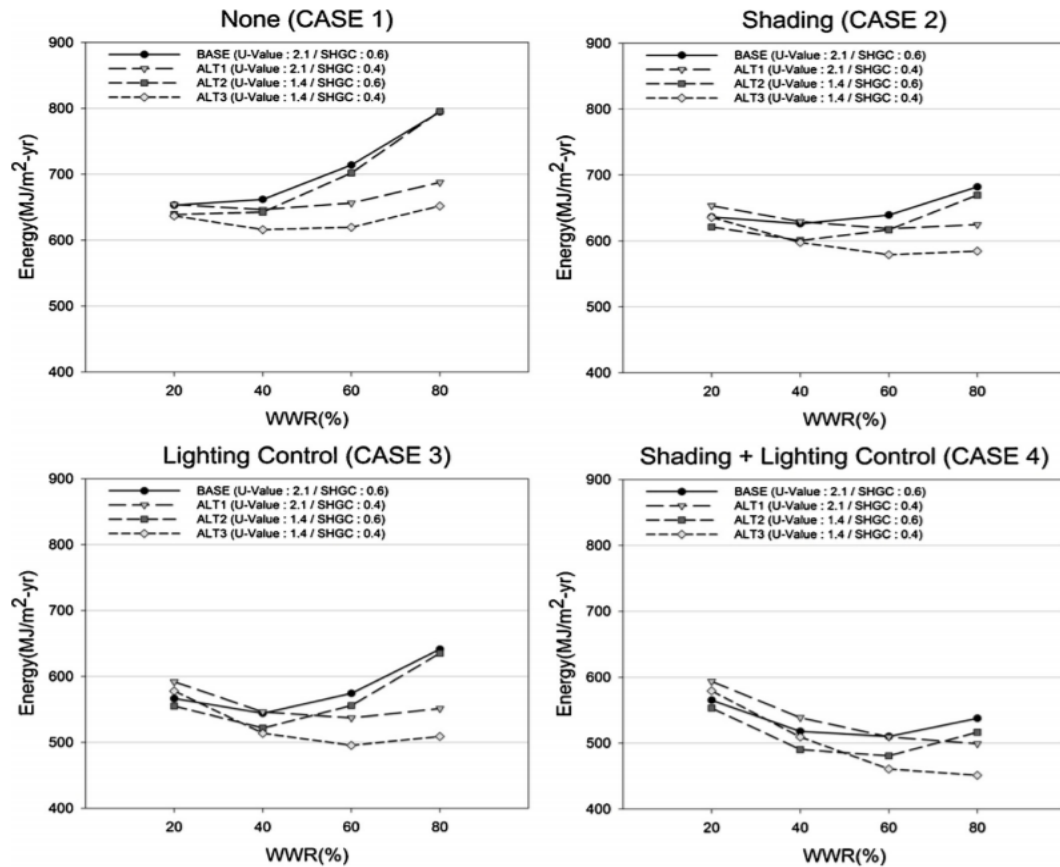


Figure 24 Energy analysis of the shading and lighting control design (Kim et al., 2014)

4.5 Makerere University at Kampala-Uganda

A study of thermal comfort regarding the window to wall ratio of the University at Kampala-Uganda is conducted by the simulation software of Design-Builders-Energy-Plus (Kibaya, 2013). The objective of the study is to discover the most suitable strategy for the energy saving in the University by adjusting the window to wall ratio. Building envelop data and expected cooling load are also clearly calculated for the basic information of the study. The original window to wall ratio of the building only contains around 30% for each orientation that can be adjusted for the natural ventilation. The type of window is the single plane glazing which is similar with the glazing utilized in public housing in Hong Kong.



Figure 25 3D-model from the Design-Builder-Energy-Plus software (Kibaya, 2013)

Parameter	Total	North (315 to 45 deg)	East (45 to 135 deg)	South (135 to 225 deg)	West (225 to 315 deg)
Gross wall area (m ²)	4339.89	1423.01	746.94	1423.01	746.94
Window opening area (m ²)	1282.68	422.08	221.29	422.08	217.23
Window-wall ratio (%)	29.56	29.66	29.63	29.66	29.08

Table 7 Window to wall ratio of each orientation (Kibaya, 2013)

Total discomfort hours regarding to the variation of window to wall ratio is examined in the research. It is revealed that the discomfort hours is significantly decreased with increasing the window to wall ratio from 0% to 20%. Furthermore, it can be clearly observed that the discomfort hours is not much fluctuated when the window to wall ratio is increased from 20% to 100%. Therefore, the minimum 20% or more of window to wall ratio is widely

recommended that it can provide better effect of natural ventilation for enhancing the thermal comfort of the occupants.

Kibaya (2013) also indicates that natural ventilation with the proper scheduled mechanical ventilation and cooling which is the strategy 4 can definitely enhance the thermal comfort for the occupants inside the University. Benefit can be greatly obtained that total 43% of energy consumption from HVAC system can be reduced by adopting more area of windows with proper mechanical ventilation and cooling. Moreover, combining lighting control with above the strategy can also decrease around 4% of electricity from lighting. Therefore, increased window to wall ratio of the building should be applied with the schedule mechanical systems in order to enhance the effect gained from the greater area of window.

As the result, the increase of window to wall ratio is advised in the study because it can provide natural ventilation and enhance the thermal comfort of the occupants by using mechanical cooling system. It is found that the thermal comfort of the occupants is improved when the window to wall ratio is within the range of 0% to 60%. It is practical information for improving the area of window in public housing that the window to wall ratio should not exceed 60% as the type of glazing used of the university is mostly identical to the glass used of public housing.

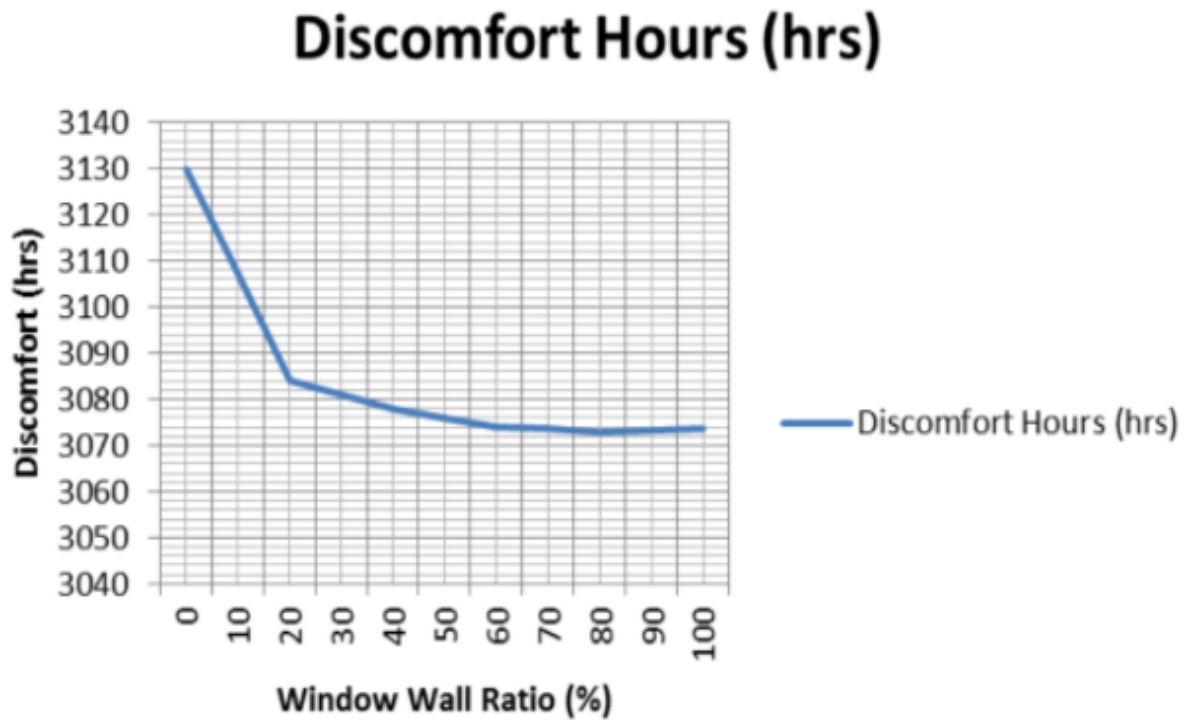


Figure 26 Discomfort hours related to window to wall ratio (Kibaya, 2013)

Strategy	Variable
Case - 1 (Baseline model)	WWR 30% + Natural ventilation
Case - 2 (Lighting control)	WWR 30% + Natural ventilation + Lighting control
Case - 3 (Mechanical ventilation – fans only)	WWR 30% + Natural ventilation + Mechanical ventilation (fans)
Case - 4 (Mechanical ventilation – fans and cooling)	WWR 30% + Natural ventilation + Mechanical ventilation (cooling)
Case - 5 (Window wall ratio)	WWR (0% to 100%) + Natural ventilation

Table 8 Expected strategies for the study of thermal comfort (Kibaya, 2013)

4.6. Experimental Case Study - Public Housing in Tin Shui Wai

Apart from analyzing the case studies in other countries, an experimental study of public housing in Tin Shui Wai is conducted so as to investigate the common window to wall ratio and the thermal comfort affected by the natural ventilation. Moreover, another objective of the study is to discover the relationship between the variation of thermal comfort and the area of windows.

4.6.1 Introduction of the study

Room 4 at block A of Tin Shing Court in Tin Shui Wai is the location of the experimental study which is one of the public housing in Hong Kong that the floor plan is revealed in the below Figure 27. The experimental study was conducted in the end of August that it has outdoor temperature and relative humidity. The orientation of the testing area of wall and windows is E60° which affects the inlet air and the heat gain from the sunlight. Moreover, the area of the window and wall was measured by using the steel tape for the experimental study.

It is assumed that the common window to wall ratio of the public housing is similar to the unit of Tin Shing Court. Although it does not prove and discover the exact proper window to wall ratio for the buildings in Hong Kong, the result of the experimental study can reveal the effect of the area of window on the thermal comfort of occupants.

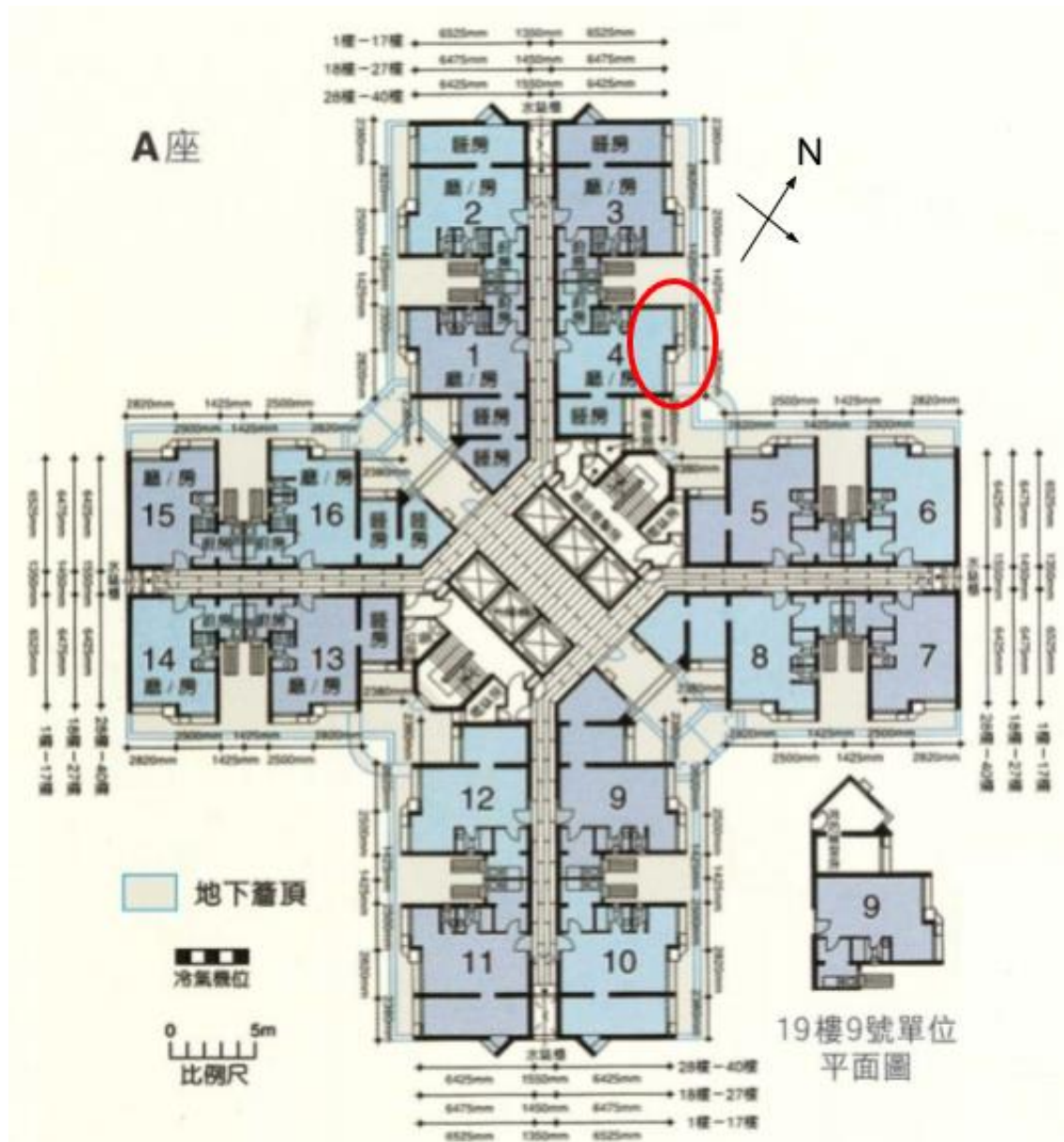


Figure 27 Floor Plan of Block A in Tin Shing Court (Building Department, 2014)

QUESTemp[®]32 and QUEST Air Probe-9 have been borrowed from the Building Technology Lab at ZB207 in Core Z of The Hong Kong Polytechnic University. QUESTemp[®]32 is the equipment that it can measure the essential elements and data of the heat stress such as dry and wet bulb temperature, relative humidity and the globe temperature. Globe temperature is the radiant heat gain from the direct sunlight.

QUEST Air Probe-9 can be connected with the QUESTemp°32 to measure accurately the air speed from the inlet air. QUESTemp°32 and QUEST Air Probe-9 were placed nearby the operable windows of the living room and the middle of the living room in order to investigate the difference of the temperature, relative humidity and air speed at these two conditions of environment. The measurement was conducted from 12:00 p.m to 1:00 p.m on 28 August to 2 September to collect and observe the change of data revealed by the equipment.

4.6.2 Discussion of the Experimental Measurement and Findings

Measurement of the area of window and wall was collected by the steel tape which is shown in Table 9. Part of the window frame contains only glazing which is not operable for providing the natural ventilation to the living room. It is found that common window to wall ratio of the public housing in Hong Kong is around 0.38 and 0.27 which is not calculated the glazing. Therefore, the range of 0.2 to 0.4 was commonly designed for the window to wall ratio in public housing buildings.

Moreover, it is assumed that the single pane glass was adopted for the aluminum frame of window as the residential building of Tin Shing Court was built in 1999 and single pane glass was frequently utilized. Therefore, the aluminum window has around 1.09 of u-value and 0.8 of SHGC.

Area of the window and wall					
	Operable Window	Only Glazing	Concrete Wall	Window to Wall ratio (With glazing)	Window to Wall ratio (Only Operable Window)
Area (m ²)	1.68	0.69	6.25	0.38	0.27

Table 9 Area of the window and wall

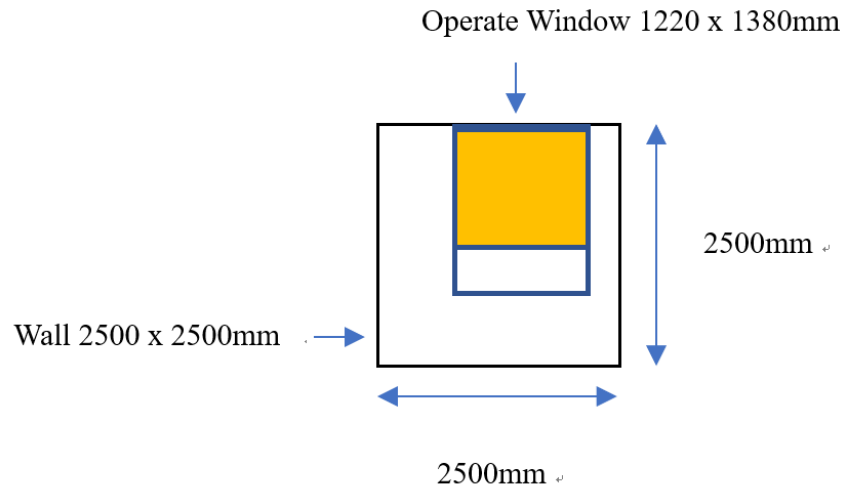


Figure 28 Dimension of window and concrete wall in the experiment apartment

Data from QUESTemp^o32 and QUEST Air Probe-9 was recorded three times per day which was at 12:00 p.m, 12:30 p.m and 1:00 p.m and located at two positions in living room that is total 36 sets of data in the experiment study. Equipment setting is revealed in the below Figure 29.

From the meteorological observations record of Hong Kong Observatory website, the average temperature of the period from 28 August to 2 September is 27.8°C and the mean of relative humidity is 72%. After the simple calculation of the data, average temperature recorded nearby the window is 27.0°C which is around 1°C lower than the temperature of

outdoor environment but the average temperature located at the middle of the living room is almost same as outdoor environment. It is because the orientation of the window is facing eastern front that the annual SHGF is relatively lower than other three fronts. Natural ventilation can be produced without absorbing more heat energy from the sunlight. Therefore, the area of window can bring a contribution to decrease the indoor temperature slightly from the getting more inlet air for the convection process.

It is also discovered that the air speed nearby the window, which is 0.8 m/s^{-1} , is much higher than the air speed at the middle of the living room, which is 0.3 m/s^{-1} . Natural air flow from the outdoor enters the apartment through the operable window. Therefore, it is obvious that the air speed nearby the window should be greater that it can provide the natural ventilation for the space and improve the air flow of the living room. In addition, Natural ventilation can reduce the concentration of carbon dioxide in indoor that the less amount of carbon dioxide is desirable for better comfort of occupants.

Moreover, the relative humidity nearby the window is decreased by 9% while the relative humidity at the middle of living room is also almost same as the outdoor environment. Relative humidity is more important than other factors as humidity in Hong Kong is relatively higher than other countries. According to the comfort zone in the psychrometric chart, lower humidity can lead to clearly enhance the comfort of the occupants. Therefore, relative humidity also can be reduced by more inlet air from operable window.

Average Temperature, Relative Humidity and Air Flow			
	Average Temperature (°C) (Dry & Wet Bulb)	Average Relative Humidity (%)	Mean Air Flow (m/s ⁻¹)
Nearby the window	27.0	61	0.8
Middle of the living room	27.3	69	0.3

Table 10 Data collected and analyzed from the equipment (Total 36 Sets of Data)

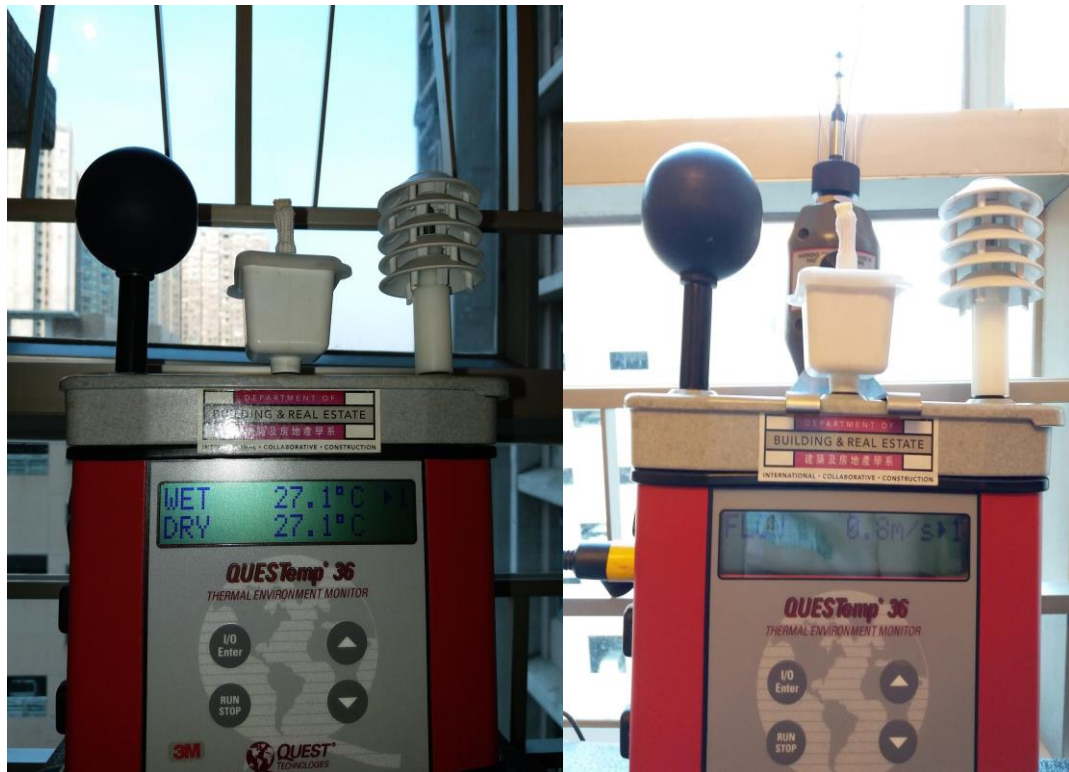


Figure 29 Equipment Setting of QUESTemp³⁶ and QUEST Air Probe-9

As a result, the area of window can attract more inlet air that it can decrease slightly the indoor temperature, relative humidity and increase the ventilation rate of the space. These effects benefit to be more suitable and feasible for better comfort that it is easier to lay on the area of comfort zone in the psychrometric chart. Although these effects are not significant to the middle of the living room, it can enhance the comfort of the occupants who are near the window. Therefore, the area of window of that building does increase the comfort of residents but the effect of it is limited.

4.6.3 Limitation of the experimental Test

There are several limitations for the experimental study that affects the result of the test. Sample size is one of the limitation of the test. There are 18 sets of data for each location that the accuracy of the result can be improved by enhancing the number of data sets. For instance, set of data can be recorded for the interval of 15 minutes that the result of the study is more reliable and accurate.

Air speed from the inlet air is generally affected by the orientation of the window which is E60° in the study. Therefore, the orientation of the building can make influence on the result of air speed. Furthermore, angle of opening the window can make difference to the result that the amount of inlet air and air speed of it are influenced regarding the angle of operable window.

Moreover, the random error of the measurement may be occurred that also affects the result of the experimental study. The data revealed from the QUEST Air Probe-9 is affected by the air flow from surroundings that it does not only calculate the air speed of the inlet air from the operable window.

Chapter 5 Research Finding & Analysis

5.1 Introduction

Questionnaire survey is conducted to examine the comments of construction professionals from main contractor which is Gammon Construction Limited, subcontractor which is responsible for installation of curtain wall and few of architect on the elements of the window to wall ratio of the public housing buildings in Hong Kong. Moreover, one of the objectives of the survey is to investigate the feasibility and flexibility of adjusting the area of the window. Online questionnaire survey was delivered to through the email and printed questionnaire survey was also distributed to the professionals when I was working in the summer internship. Total 34 responses were collected from the questionnaire survey that 23 responses from main contractor and 9 responses from sub-contractor are collected while 2 responses from architects are assembled.

5.1.1 Methods of Data Analysis

Numerous formulas for the calculations of the data collected from the questionnaire survey are adopted in order to analyze different the importance of factors the relationship between these factors.

i) Mean Score

Several factors are listed in the questionnaire survey to rate the score of each factor. Therefore, the mean score which is the average of the total scores of that factor is frequently used in the data analysis. Mean score of each factor is a fundamental element to calculate the correlation of factors and the sequence of rankings.

$$MS = \frac{\sum (f \times s)}{N}$$

Figure 30 Formula of Mean Score (Chan et al. 2003)

ii) Relative Importance Index

Relative important index can be also evaluated by following formula that it includes sum of individual scores (w) given to each factor by the respondents, possible highest score (A) and total number of responses (N) concerning that score. It represents the ranking of different items according to the importance on the questions.

$$RII = \frac{\sum w}{A \times N}$$

Figure 31 Formula of Relative Importance Index (Chan and Kumaraswamy, 1997)

iii) Kendall's concordance

The objective of Kendall's Concordance analysis is to measure and compare the agreement among different respondents in the rankings based on the mean values within a particular group that there are total three groups which are from main contractor, architectural consultant and sub-contractor. When the coefficient of concordance is high, there is a perfect consensus within a group for ranking the items in same standard (Chan et al. 2003). Moreover, if the Kendall's coefficient of concordance is at significance level of 0.05 and the significance level is smaller than 0.05 (p-value is <0.05), the null hypothesis can be rejected. Therefore, there is significant difference of agreement among the respondents in that group in the ranking the items.

$$W = \frac{\sum_{i=1}^n (\bar{R}_i - \bar{R})^2}{n(n^2 - 1)/12}$$

Figure 32 Formula of Kendall's Concordance Analysis (Chan et al. 2003)

iv) Spearman's Rank Correlation

According to Chan (2003), the Spearman's rank correlation is the test that it measures the level of relationship between two groups of respondents by their score of ranking. High value of the coefficient (r_s) represents the positive correlation and good agreement on the rankings between two groups.

$$r_s = 1 - \frac{6 \sum d^2}{N(N^2 - 1)}$$

Figure 33 Formula of Spearman's Rank Correlation Test (Chan et al. 2003)

5.2 Data Analysis of Questionnaire Survey

Indoor temperature, relative humidity of house, rate of ventilation and amount of daylight are the four elements revealed on the survey for the respondents to choose the effect of the area of window on their comfort in the house. Therefore, the element chosen by the respondents represents one score for that element. For instance, 11 respondents from main contractor indicate that indoor temperature is influenced by the area of the window. Therefore, the total scores for the element of indoor temperature is 11 out of 23. The result of the total scores for the four elements are shown in the Table 11.

Total Scores of Four elements				
	Indoor Temperature	Relative Humidity of house	Rate of Ventilation	Amount of Daylight
Main Contractor (Total 23 Respondents)	11	13	23	19
Sub Contractor (Total 9 Respondents)	3	6	9	5
Architect (Total 2 Respondents)	1	1	2	0

Table 11 Total scores of each element

Mean score must be calculated that it is essential to balance the different sample size of three groups of respondents in order to indicate the average and representative score of each element. The range of the mean score is from 0 to 1. By analyzing the mean score of each factor, it is found that rate of ventilation must be affected by the area of window for their comfort.

Moreover, the ranking of the importance of each factor for affecting the comfort is exposed in Table 12. Factors should be organized and arranged in the sequence of importance to observe the importance of the factor for the respondents. For instance, rate of ventilation is the most important factor for the comfort of all respondents. Amount of daylighting is also essential for the respondents of main contractor while relative humidity is important factor for the respondents of subcontractor and architect. Therefore, ventilation rate and relative humidity are the major factors which are mainly concerned by the effect of area of window.

Mean Score				
	Indoor Temperature	Relative Humidity of house	Rate of Ventilation	Amount of Daylight
Main Contractor (Total 23 Respondents)	0.45	0.56	1	0.83
Sub Contractor (Total 9 Respondents)	0.33	0.66	1	0.55
Architect (Total 2 Respondents)	0.5	0.5	1	0
Relative Importance Index (RII)				
	Indoor Temperature	Relative Humidity of house	Rate of Ventilation	Amount of Daylight
Main Contractor (Total 23 Respondents)	4	3	1	2
Sub Contractor (Total 9 Respondents)	4	2	1	3
Architect (Total 2 Respondents)	3	2	1	4

Table 12 Mean Score and Relative Importance Index for four elements

By using the rankings indicated by the three groups of respondents and the equation listed in previous part, the Kendall's Coefficient of Concordance (W) is calculated. 0.778 of Kendall's Coefficient of Concordance indicates that there is a consensus within these three groups of respondents. Null Hypothesis (H_0) can be rejected as the Kendall's Coefficient of Concordance is significant at 5% level of significance (Chan et al. 2003). Therefore, significant degree of agreement within the respondents on the ranking of factor is proved.

Kendall's Coefficient of Concordance (W) (Factor(s) of comfort affected by the area of window)				
	Indoor Temperature	Relative Humidity of house	Rate of Ventilation	Amount of Daylight
Main Contractor (Total 23 Respondents)	4	3	1	2
Sub Contractor (Total 9 Respondents)	4	2	1	3
Architect (Total 2 Respondents)	3	2	1	4
R^2	11^2	7^2	3^2	9^2
W = 0.778				

Table 13 Kendall's Coefficient of Concordance (W) among three groups

Moreover, the Spearman's Rank Correlation between main contractor and subcontractor is calculated as the sample size of architect is too small that it is insufficient size to provide the strength of correlation between other two groups. Therefore, the Spearman's Rank Correlation is conducted for the groups of main contractor and subcontractor. It is observed that the Spearman's Rank Correlation (r_s) is 0.8 that there is a strong and positive correlation between main contractor and subcontractor on ranking the element which is affected by the area of the window of building.

Spearman's Rank Correlation (r_s)					
	Main Contractor	Sub Contractor	Ranking of Main contractor and Subcontractor		d^2
Indoor Temperature	0.45	0.33	4	4	0
Relative Humidity of house	0.56	0.66	3	2	1
Rate of Ventilation	1	1	1	1	0
Amount of Daylight	0.83	0.55	2	3	1
$r_s = 0.8$					

Table 14 Spearman's Rank Correlation (r_s) among main contractor and subcontractor

5.3 Discussion and Evaluation of the survey

5.3.1 Relationship between the area of window and thermal comfort of occupants

Most of the respondents point out that the comfort of the occupants is impacted by the area of window. Half of respondents indicated that it can mainly enhance the rate of ventilation with increasing the area of window while around one-third of respondents discover that the relative humidity can be clearly adjusted to be more comfortable with increasing the area of window. Therefore, improving the rate of ventilation and relative humidity are major benefits to the thermal comfort of occupants by increasing the area of window.

However, only less than one-fifth of respondents expressed that regulating relative humidity is the benefit obtained for their comfort by boosting the area of window. Element of monitoring indoor temperature for the thermal comfort through enlarging the area of window is overlooked by the respondents. Nevertheless, it is explored that it is contrast with the result of case studies in other countries and the experimental study. Therefore, it is disclosed that the effect of monitoring indoor temperature and relative humidity by adjusting the area of window is neglected by the occupants.

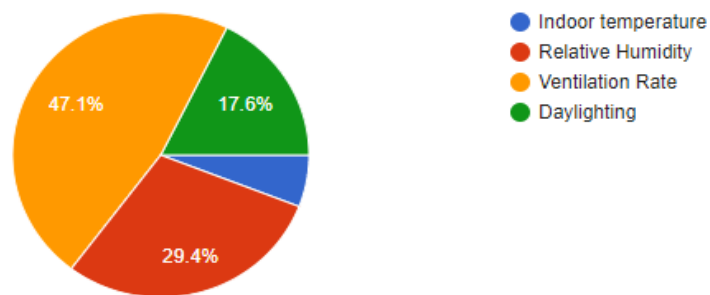


Figure 34 Percentage reported for Four elements

5.3.2 Correlation of the tendency of obtaining more area of window and its reason

65% of respondents pinpointed that the area of window should be re-designed to be larger and minimize the area of concrete wall. It is no doubt that having better natural ventilation and fresh air from outdoor environment is one of the major reasons to get larger area of window. In addition, more than 67% of respondents implied that it can gain more vision of outdoor environment through larger area of window. Therefore, it is discovered that the mental feeling of occupants should be recognized for one of the factors to modify the area of window. Moreover, the effect of regulating the indoor temperature is a minor reason which is negligible of obtaining more area of window.

Furthermore, 35% of respondents pointed out that they might tend to obtain larger area of window. It is conjectured that less than half of occupants do not want to have greater area of window for their house. Therefore, it should not be predicted that all residents require more area of window.

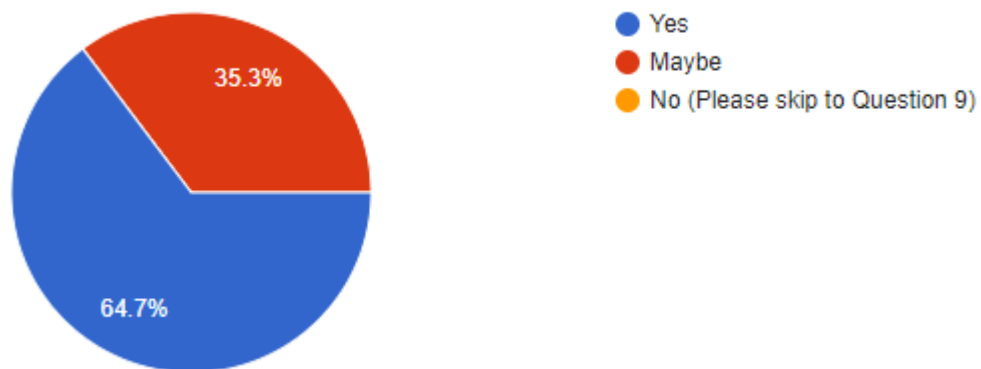


Figure 35 Percentage of tendency of obtaining more area of window

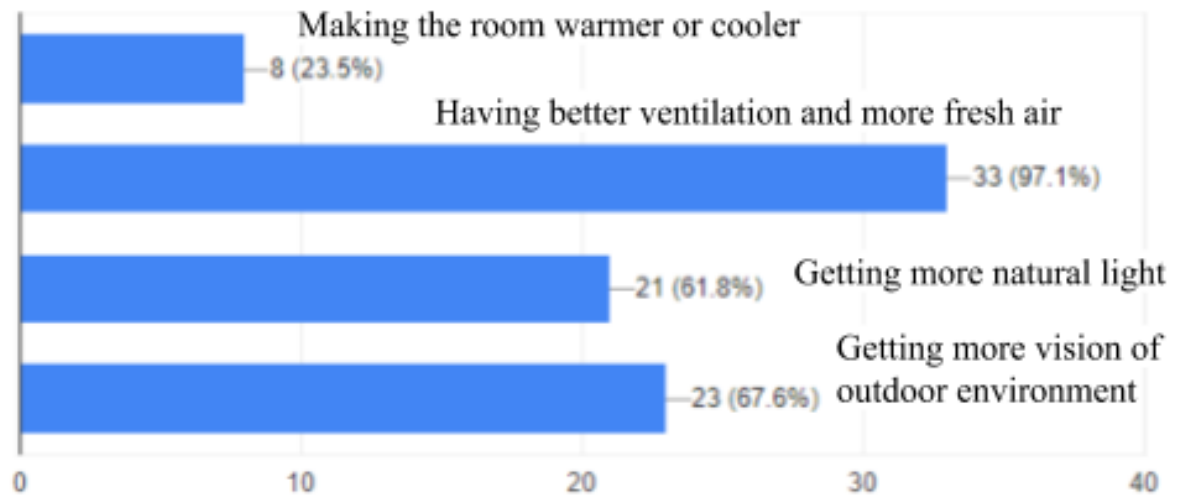


Figure 36 Percentage of causes of obtaining more area of window

5.3.3 Flexibility and Feasibility of modifying the area of window of Public Housing

Construction professionals were requested to rate the feasibility of modifying the area of window of Public Housing in future from 0 to 5 scores. Five scores represents that it is high feasibility of changing the area of window for the better thermal comfort of occupants. Average scores of all respondents is 3.73 that it is possible and feasible to adjust the area of window but it is complicated to implement this alternative approach as the comprehensive study must be conducted for the design of window to wall ratio.

5.3.4 Relationship between effect of area of window and HVAC consumption

Respondents were asked to indicate whether larger area of window is beneficial to decrease the frequency of operating the air-conditioning. 60% of respondents would turn on the air-conditioning or cooling system in less frequency if natural ventilation was improved by the larger area of window. It is discovered that the element of ventilation rate from larger area of window occupies an important role for reducing the consumption of HVAC system. Although it is assumptive for respondent to inference the situation of obtaining more area of window, it can prove that respondents were willing to decrease the frequency of operating the cooling system.

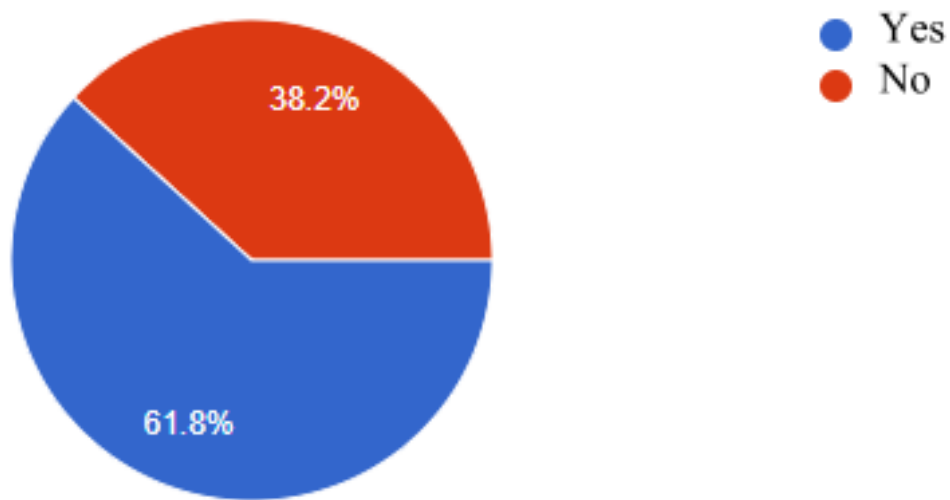


Figure 37 Percentage of turning on cooling system in less frequency due to obtaining larger area of window

5.4 Constraint and Limitation of Survey

5.4.1 Sample Size of each group of respondents

Number of respondents among three groups of professionals is limited and slightly some professionals were not free at all the time. Therefore, the result of survey can be more accurate and reliable if the number of respondents is enhanced. Moreover, sample size of architect and subcontractor is relatively smaller than the sample size of main contractor. The result of these two groups may be not representative to that group of professionals. Architects are predicted to have a profound knowledge about designing the element of window to wall ratio. However, it is not reliable to adopt and analyze the data collected by the architect as it only received two responses from the architect group.

5.4.2 Probability of misunderstanding on the questions

It has the chance for respondents to have misunderstanding on the questions of the survey. Questions on the survey were organized to be straightforward but the respondents may feel confusion about the concept of window to wall ratio. Therefore, few of feedbacks from the respondents may be inaccuracy.

Chapter 6 Interviews

6.1 Introduction

Practical and incredible comments or opinions on the element of window to wall ratio of public housing buildings was collected from several construction professionals. The objective of the interviews is to investigate the concept of designing the proper element of window to wall ratio. They were asked about the advantages and drawbacks of different window to wall ratio condition. Besides, they were also asked to indicate the feasibility and flexibility of adjusting the elements of window to wall ratio. Moreover, some residents were interviewed to provide the comments on the area of the window to wall ratio for their house.

6.2 Category of Interviewees

Residents and construction professionals are the major two classifications in the interviews. One of the construction professional is the professor of Building and Real Estate in The Hong Kong Polytechnic University while four construction professionals are working for the Gammon Construction Limited for several years. Informative comments were collected for the analyzing the effect of window area.

Moreover, two residents of public housing are also interviewed for providing their opinions on the area of window for their house. Detailed background of the interviewees is listed in the following table.

Background Information of Interviewees			
Name of the interviewee	Position	Profession	Date of interview
Mr. Ni	Professor	Building Science	13/09/2017
Mr. Ip	Project Engineer	Chartered Building Engineer	11/08/2017
Mr. Au	Sub-Agent	Building Management	11/08/2017
Mr. Mak	Engineer	Building Engineer	10/08/2017
Mr. Tsui	Agent of Sub Contractor	Installation of Curtain Wall	02/08/2017
Ms. Cheng	Resident	Resident of Public Housing	02/08/2017
Ms. Li	Resident	Resident of Public Housing	01/08/2017

Table 15 Background of the interviewees

6.3 Findings and Analysis

6.3.1 Heat transfer through windows and wall

All construction professionals indicated that the heat transfer through windows is always greater than the heat transfer through the concrete wall. It is because the u-value of window is greater than the concrete wall about 0.4 of u-value that it absorbs more heat by conduction and radiation. Therefore, the area of window should not be large as concrete wall has better heat insulation for reducing the cooling load of the building.

However, several professionals from the Gammon Construction Limited also pointed out that the heat gain through the window can be minimized by using advanced glazing such as low-e coating or double-glazing. Advanced glazing becomes more popular for the public housing and private housing since it can decrease the heat gain from outdoor environment. A few u-value of the advanced glazing is close to the u-value of the concrete wall. Therefore, the cooling load from the area of window can be reduced by using advanced technologies. More importantly, one of the reason of using these green glazing is that some private building projects target to obtain more gross floor area (GFA) by awarding the Beam-Plus certification.

6.3.2 Proper window to wall ratio of the building

Mr. Ni said that the area of window should not be existed for the public housing if it only concerns the heat gain from the outdoor. However, glazing and windows must be installed that it can affect the mental feeling of the residents as it provides a view of outdoor environment. Moreover, the appropriate area of window is designed by considering many factors such as the wind direction and sun path simulation of the building. Some simulation software such as building information modelling (BIM) can contribute to design a proper window to wall ratio of the building. Area of the window makes impact to the thermal comfort of the residents that it generates sufficient rate of ventilation. In other countries

such as Taiwan and Germany, the area of window of buildings is significantly larger than the area of window of buildings in Hong Kong for natural ventilation. It is found that the factor of window to wall ratio is relatively important to be taken into account of the design of energy saving.

Another comment from Mr. Tsui is that the area of window of public housing should be increased. Although the heat gain through window may be greater than the concrete wall, it is desirable to have better natural ventilation in order to enhance the comfort of occupants and reduce the cooling load of the buildings. In addition, area of the window can be enhanced in the orientation where absorbs less radiation from sunlight. Therefore, the simulation of the sun path diagram of the buildings should be comprehensive.

Furthermore, two residents also indicated that the area of window of public housing should be enhanced. It was discovered that getting more vision of outdoor environment is the major reason to obtain larger area of window. Factor of heat gain is not relatively concerned for the area of window. Besides, the area of window of public housing should be all operable that part of the area is only glazing. Larger area of operable window can attract better natural ventilation to the indoor environment

6.3.3 Evaluation on the Feasibility of adjusting area of window in Public Housing

Mr. Ip and Mr. Mak examined that it is flexible to adjust the area of window in public housing since the structure of the external wall can be addressed. Increasing or decreasing the area of window of the external wall is not a difficult issue as the critical loading is not transferred and absorbed by the external wall. However, it is important than larger area of the window must enhance the price of unit. It may be the issue that the price of public housing unit should not be much experience and should be lower than private building unit. Therefore, the commercial aspect should be considered for changing the area of window in public housing.

Moreover, it is feasible to adjust the area of window of public housing. Mr Au pointed out that most of the public housing projects adopt the technology of precast external wall so as to reduce the construction period and avoid the delay of the projects. Therefore, the area and number of window should be modified in the design stage of the projects.

6.3.4 Summary of Interviews

In conclusion, all interviewees agreed that the area of window of public housing should be enhanced and improved for their comfort within the space. It is essential that numerous factors should be contemplated such as wind direction and sun path diagram of the building. Heat gain through the window is normally enhanced if the study of design is incomprehensive. Moreover, it is feasible and flexible to modify the area of window which is involved in the design stage of the projects. Advanced glazing should be utilized when the area of window is increased.

6.5 Restriction and Limitation of Interviews

6.5.1 Sample Size

Number of interviews are limited as it is time-consuming for the interviewees to have a face-to-face interview as they have to work. Therefore, it is one of the difficulties to invite interviewees that the sample size of the interviews is limited.

6.5.2 Length of Interviews

Period of several interviews is relatively short that the information provided in the interviews may not be adequate. It is because several interviewees have another business after the interviews that the length of some interviews is around 10 to 12 minutes. Therefore, the opinions may be insufficient for the each of questions.

Chapter 7 Conclusion

7.1 Conclusion

Energy consumption in the building sector has been greatly increased for many years. Concept of window to wall ratio is relatively overlooked and neglected for energy saving of the buildings in Hong Kong. It is no doubt that the area of window significantly influences the heat transfer from outdoor to indoor due to the u-value of the window. Area of window of the buildings should be reduced if it only examines the u-value of the glazing. However, the heat gain through window is generally affected by numerous factors such as the orientation of the window, sun path diagram, wind direction and types of glazing used. Therefore, it is erroneous to determine that the heat gain or cooling load of the building is definitely enhanced with increasing area of window.

Indeed, increasing appropriately the window to wall ratio of building may minimize the energy consumption from HVAC systems. In the case studies of Guangzhou and Korea, energy consumption from cooling systems such as air-conditioning and fans is clearly decreased with larger area of window. Natural ventilation and adjusted relative humidity of the indoor environment are the major benefits gained from increased area of window that it can significantly modify the thermal comfort of the occupants. Therefore, energy consumption from HVAC system especially in the air-conditioning can be lowered when the conditions of indoor environment satisfies the comfort zone of the occupants.

Although most of the residents desire greater area of window for their houses, it should be deliberate to determine the appropriate window to wall ratio of the building. It is complicated to enhance properly the window to wall ratio of each building as the comprehensive and informative study must be conducted in the design stage of the construction project. All related factors should be calculated and examined by using advanced simulation software such as eQUEST and DeST-h model.

Moreover, it is found that common window to wall ratio of the public housing in Hong Kong is from 20% to 40%. From the result of case studies and literature review, there is a room of increasing the area of window that the window to wall ratio can be improved to the maximum of 60% to provide the better comfort of occupants. It is feasible and flexible to adjust the area of window for the external wall since the technology of precasting external wall has been frequently adopted in the construction industry.

In addition, size of window should be expanded for the northern front and eastern front of walls in Hong Kong since the annual SHGF of these two fronts are lowest. It may enhance the natural ventilation for the indoor without increasing the heat gain from the sunlight. Therefore, it is crucial and essential to investigate the appropriate window to wall ratio of that building during the design stage.

To conclude, the importance of window to wall ratio should not be ignored that it can absolutely alter the thermal comfort of the occupants that leads to influence the energy consumption of the buildings.

7.2 Recommendation

The window to wall ratio of public housing should be modified and expanded as larger area of window may reduce the cooling load of the building. The importance of window to wall ratio should be promoted as a practice of design that it should be properly designed by utilizing simulation software. It is essential to determine the benefit gained from the larger area of window because the climate of Hong Kong is relatively humid.

Moreover, the price of unit in public housing should be monitored when the area of window is enhanced. It has been discovered that the price of unit is obviously increased because of larger area of window. One of the measures is to learn from other countries that the tendency of using advanced or green glazing of the building should be developed in long term. It is important to provide sufficient number of green glazing in the construction industry so as to minimize the cost of glazing.

Furthermore, intelligent building technologies should be implied with the adoption of window to wall ratio. Case studies in other countries revealed that shading and lighting control are adopted in the building for decreasing the heat gain through the window. Heat from the radiation can be effectively reduced by the shading control that better comfort would be provided due to the greater ventilation rate by larger area of window.

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Chapter 9 Appendix

Appendix I Invitation Letter

Dear Sir/Madam

I am Year 4 student of Building Engineering and Management from The Hong Kong Polytechnic University and I am writing to invite you and make an appointment with you for the interview of my dissertation research on the topic “A Study on the Sustainable Building in Hong Kong: Appropriate Window to Wall Ratio (WWR) to minimize energy consumption of high-rise buildings”.

The objective of my search is to examine and investigate the effect of area of window on the comfort of the occupants. Besides, it aims to discover the feasibility and flexibility of modifying the window to wall ratio of the public housing in Hong Kong.

I would be very grateful if you could provide comments and opinions on the area of window of public housing. The interview only takes around 15 to 20 minutes. The information and knowledge you provide is used and analyzed for my academic purpose only.

Please kindly suggest the time for the interview at your convenience. Phone interview is also welcome. If you have any inquiries, please feel free to contact me at 1406@ or via 6092 xxxx.

I am looking forward to receiving your reply. Thank you very much!

Yours faithfully

Chong Mung

Year 4 Student (32405-BEM)

The Hong Kong Polytechnic University

Appendix II Proposed Interview Questions

1. Can you provide comments or opinions about the window to wall ratio of the public housing?
2. Do you want to obtain more area of window for your house? Why?
3. Is the comfort affected by the area of window?
4. What factors mainly affect your thermal comfort by the area of window?
5. Is there a flexibility and feasibility of adjusting the area of window? Why?
6. Will you turn on the cooling system in less frequency if you have better ventilation from larger area of window?
7. Do you think heat gain is increased with increasing area of window for your house? Why?

Appendix III Questionnaire Survey Questions

1. What company are you working for ?

- ☐ Main Contractor
- ☐ Architect
- ☐ Sub-contractor
- ☐ Developer

2. What is your current position in your company? (e.g PM, Engineer, managers, senior workers etc.)

- ☐ Project Manager / Management Team
- ☐ Design Team
- ☐ Engineer
- ☐ Senior Workers
- ☐ Junior Workers
- ☐ Other...

3. Do you have how many year(s) of working experience in construction industry?

- ☐ Below 1 year
- ☐ 2 to 4 years
- ☐ 5 to 7 years
- ☐ 7 years or above

4. Do you think area of window of the building can affect your comfort inside the space?

- ☐ Yes
- ☐ No

5. If yes, what do you think which factor will be influenced for your comfort by the area of window?

- ☐ Indoor temperature
- ☐ Relative Humidity
- ☐ Ventilation Rate
- ☐ Daylighting

6. What is the major benefit you think of having the area of the window ? *

- ☐ Indoor temperature
- ☐ Relative Humidity
- ☐ Ventilation Rate
- ☐ Daylighting

7. From your professional perspective or being a resident, do you want to obtain more area of window for your house?

- ☐ Yes
- ☐ Maybe
- ☐ No (Please skip to Question 9)

Appendix III Questionnaire Survey Questions

8. From the above question, why do you think that? (Please choose the reason(s)) *

- ☐ Making the room warmer or cooler
- ☐ Having better ventilation and more fresh air
- ☐ Getting more natural light
- ☐ Getting more vision of outdoor environment
- ☐ Other...

9. From your professional perspective or being a resident , please rate the flexibility and feasibility to change the typical area of window of external wall in public housing buildings in Hong Kong to have better comfort ? *

	1	2	3	4	5	
Least Possible	☐	☐	☐	☐	☐	Most Possible and Feasible

10. Should the area of windows be adjusted for better comfort? *

- ☐ Yes
- ☐ No

11. In summer, will you turn on the cooling system (e.g AC or Fans) in less frequency because of getting more natural ventilation from the area of window? *

- ☐ Yes
- ☐ Maybe
- ☐ No

12. Any opinions or comments on the area of window on the public housing /private housing buildings in Hong Kong?

Long answer text

Appendix IV Result of Questionnaire Survey

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
	Company	Title	Working Exp.	Affecting Comfort	Factor (Temp.)	Factor (Humidity)	Factor (Ventilation)	Factor (Daylight)	Most Important Factor	Obtain more sun	Warmer or cooler	Better ventilation and more fresh air	More natural light	More vision	flexibility	Should be adjusted	Less frequency
1																	
2	Main Contractor	Project Manager/ Management Team	7 years above	Yes			1	1	Ventilation	Yes		1		1	4	Yes	No
3	Main Contractor	Project Manager/ Management Team	7 years above	Yes		1	1	1	Ventilation	Yes		1	1	1	4	Yes	No
4	Main Contractor	Project Manager/ Management Team	7 years above	Yes	1	1	1		Humidity	Maybe		1			4	Yes	No
5	Main Contractor	Design Team	2 years to 4 years	Yes		1	1		Ventilation	Maybe		1	1	1	4	Yes	Yes
6	Main Contractor	Engineer	7 years above	No	1		1	1	Ventilation	Yes	1	1	1	1	4	Yes	Yes
7	Main Contractor	Engineer	5 years to 7 years	Yes			1	1	Ventilation	Yes		1	1	1	4	Yes	Yes
8	Main Contractor	Engineer	5 years to 7 years	Yes	1	1	1	1	Humidity	Yes		1		1	4	Yes	Yes
9	Main Contractor	Engineer	2 years to 4 years	Yes			1	1	Ventilation	Yes		1	1	1	4	Yes	No
10	Main Contractor	Engineer	2 years to 4 years	Yes		1	1	1	Ventilation	Yes		1	1		4	Yes	Yes
11	Main Contractor	Engineer	2 years to 4 years	Yes		1	1	1	Humidity	Yes		1	1	1	4	Yes	Yes
12	Main Contractor	Engineer	2 years to 4 years	Yes	1	1	1		Ventilation	Maybe	1	1			4	Yes	Yes
13	Main Contractor	Engineer	2 years to 4 years	Yes		1	1	1	Ventilation	Yes		1		1	4	Yes	No
14	Main Contractor	Engineer	Below 1 years	Yes	1		1	1	Daylight	Yes		1	1	1	3	Yes	Yes
15	Main Contractor	Senior Worker	5 years to 7 years	Yes	1	1	1	1	Humidity	Yes	1	1			3	Yes	Yes
16	Main Contractor	Senior Worker	5 years to 7 years	Yes	1		1	1	Warmer or cooler	Yes		1	1	1	4	Yes	Yes
17	Main Contractor	Senior Worker	5 years to 7 years	Yes	1		1	1	Daylight	Maybe		1	1		3	Yes	No
18	Main Contractor	Senior Worker	2 years to 4 years	Yes	1		1	1	Ventilation	Yes		1	1	1	4	Yes	Yes
19	Main Contractor	Senior Worker	2 years to 4 years	Yes		1	1	1	Humidity	Yes		1	1	1	3	Yes	No
20	Main Contractor	Junior Worker	5 years to 7 years	Yes	1	1	1		Ventilation	Maybe		1	1		4	Yes	Yes
21	Main Contractor	Junior Worker	2 years to 4 years	Yes			1	1	Humidity	Yes		1		1	4	Yes	No
22	Main Contractor	Junior Worker	2 years to 4 years	Yes		1	1	1	Humidity	Yes		1	1	1	3	Yes	No
23	Main Contractor	Junior Worker	2 years to 4 years	Yes	1		1	1	Ventilation	Maybe		1		1	4	Yes	Yes
24	Main Contractor	Junior Worker	Below 1 years	Yes		1	1	1	Daylight	Yes	1	1	1		4	Yes	Yes
25					11	13	23	19			4	23	15	16	3.78261		
26	Sub-Contractor	Senior Worker	7 years above	Yes			1	1	Humidity	Yes		1	1	1	3	Yes	No
27	Sub-Contractor	Senior Worker	5 years to 7 years	Yes		1	1	1	Daylight	Yes		1	1	1	3	Yes	No
28	Sub-Contractor	Senior Worker	2 years to 4 years	Yes	1	1	1		Ventilation	Maybe		1		1	4	Yes	Yes
29	Sub-Contractor	Senior Worker	2 years to 4 years	Yes		1	1		Humidity	Maybe		1		1	4	Yes	Yes
30	Sub-Contractor	Senior Worker	2 years to 4 years	Yes	1		1	1	Ventilation	Maybe	1	1	1	1	3	Yes	No
31	Sub-Contractor	Senior Worker	2 years to 4 years	Yes		1	1		Humidity	Yes	1	1	1		4	Yes	No
32	Sub-Contractor	Junior Worker	2 years to 4 years	Yes			1	1	Daylight	Maybe	1	1			4	Yes	Yes
33	Sub-Contractor	Junior Worker	Below 1 years	Yes	1	1	1		Ventilation	Maybe		1		1	4	Yes	Yes
34	Sub-Contractor	Junior Worker	Below 1 years	Yes		1	1	1	Humidity	Maybe		1	1		4	Yes	No
35					3	6	9	5			3	9	5	6	3.66667		
36	Architect	Design Team	5 years to 7 years	Yes		1	1		Daylight	Maybe		1	1		4	Yes	Yes
37	Architect	Senior Worker	5 years to 7 years	Yes	1		1		Warmer or cooler	Yes	1				3	Yes	No
38					1	1	2	0			1	1	1	0	3.5		
39																	
40	Total				29	40	68	48			15	66	41	44	3.7347		