Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 62 (2014) 123 – 131

Energy Procedia

6th International Conference on Sustainability in Energy and Buildings, SEB-14

Informing Energy-efficient Building Envelope Design Decisions for Hong Kong

Xiaoxia Sang[a]*, Wei Pan[b], M. M. Kumaraswamy[b]

[a,b]*The University of Hong Kong, Department of Civil Engineering, Pokfulam, Hong Kong*

Abstract

Building envelope is widely recognized as a key factor that influences building energy consumption. However, the bulk of passive envelope research is based in cold climates. It remains largely unknown how building envelope design measures are selected and to what extent building energy efficiency can be improved in hot-humid climate. This paper explores the energy-efficient envelope design measures through the combination of understanding the environment, identifying potential measures, setting up models, running analysis, and making design decisions. The findings should inform building envelope design decisions and support building energy performance analysis in hot-humid climate.

Keywords: building envelope design; decision-making; energy efficiency; energy modelling; hot-humid climate

---

1. Introduction

According to the International Energy Agency (IEA), the world energy consumption has increased by 48% in the last two decades. There is a growing concern over the exhaustion of resources and related heavy environmental impacts. The building sector is the largest contributor to energy use, accounting for more than one-third of all final energy and one-half of total electricity consumption worldwide. In Hong Kong, buildings consumed 62% of the end-use energy and 91% of the total electricity in 2010 [1]. The IEA identified energy efficiency as the “fuel” to make a difference to underpin a more sustainable energy system. In line with this opinion is the significant share of the potential to improve energy efficiency - more than 80% of building sector’s potential is untapped [2]. It is expected

---

* Corresponding author. Tel.: +852-5643-8898; fax: +852-2559-5337.
E-mail address: sangxx@hku.hk

doi:10.1016/j.egypro.2014.12.373

that growth in population, increasing demand for building services and comfort levels, together with the rise in time spent inside buildings will drive higher energy demand in the future. Therefore, designing buildings for energy efficiency becomes much more urgent.

Building envelope is widely recognized as a key factor that influences building energy consumption [3]. The parameters affecting building envelope energy performances may be design variables (e.g., configuration of the exterior wall) or design given inputs imposed by the context of the project (e.g., outdoor temperature of the site) [4]. While there is a growing body of knowledge of passive building envelope design in cold climatess with a focus on superinsulation, extreme air tightness, high performance window, the feasibility of passive envelope design in hot-humid climate has barely been studied [5]. This paper aims to inform energy-efficient building envelope design decisions in Hong Kong. The paper argues that the informed design decisions can be achieved through the process of understanding the problem, identifying potential design measures, setting up models, running annual cooling load analysis, and making design decisions.

2. Previous research

In the past decade, there is only a limited number of energy-efficient building envelope research in Hong Kong. Bojić reported a study in 2006 [6], which examined the effectiveness of overhangs and side fins to energy savings of high-rise residential buildings. The study showed that the application of overhangs would reduce the electricity consumption by up to 5.3% on high-lever floor since lower floors would be in shadows of surrounding buildings. Bojić and Yik [7] investigated the influence of the thermal insulation position and thickness in walls and partitions on the cooling load of high-rise residential buildings. The results indicated that insulating the envelope and the partitions would be effective in reducing the yearly space cooling load by up to 38%. Another study by the same authors [8] focused on evaluating the impact of using switchable glazing on space cooling energy consumption. The results revealed that a reduction in annual cooling load by up to 6.6% can be achieved. Cheung et al. [9] conducted a study to examine the impact of six passive envelope design strategies on reducing the cooling load for high-rise apartments. The simulation results indicated that the strategies on improving the thermal performance of external wall are more effective than those for windows. These studies have contributed to the analysis of energy efficiency of a particular envelope component. However, considering the hot-humid climate context, how and why the potential design measures are identified is largely unknown.

3. Research method

In determining which methods to adopt, i.e. the research design, the priority is to ensure that the methods maximize the chance of realizing its aim [10]. This research was carried out through the combination of literature review and computer modeling. The literature review covered four components: 1. household energy consumption study in Hong Kong, 2. exterior environment condition analysis (both hot-humid climate features and the dense development mode), 3. building envelope systems and their functionality, 4. energy-efficient envelope design measures in hot-humid climate. The computer simulation was conducted in a user-friendly software eQUEST to examine the energy reduction potential of five selected energy-efficient envelope design measures.

Nomenclature

Abs	absorptance is a ratio that ranges from 0.0 to 1.0 which measures exterior wall's surface absorptivity
R-value	a measure of material's resistance to heat transfer, usually used to evaluate opaque areas
U-value	a measure of heat transmission through materials, usually used to evaluate glazed areas
SHGC	solar heat gain coefficient, a measure of solar heat transmittance
OTTV	overall thermal transfer value, a measure of average heat gain into a building through the envelope
Tv	visual transmittance, a measure of the amount of light in the visible portion of the spectrum that passes through a glazing material

4. Energy consumption analysis

In the residential sector, Hong Kong's households' energy consumption has increased at a rate of by 1.24% per annum [1], double the US figure of 0.68% [11] and quadruple the UK figure of 0.34% [12]. End-use energy consumption in the residential sector can be split into six key segments, namely cooking, space conditioning, hot water, lighting, refrigeration and others. Air conditioning, cooking and hot-water are three major energy end uses, averagely accounting for 22%, 21% and 20% of total energy use in the last decade, respectively [1] (see Fig 2). Unlike cooking and hot water energy use which mainly depend on occupant's living habit, space conditioning energy consumption can be significantly affected by buildings' envelope design [7, 13]. The prime concern thus should be how and to what extent the space conditioning energy can be reduced through envelope design in hot-humid climate.

5. Exterior environment

To explore energy-efficient envelope design strategies and alternatives, a clear understanding of local climatic properties and building development mode is essential. Without knowing the temperature, humidity, solar radiation, and wind velocity, it is impossible to design a building that is energy-efficient. For example, while heating-dominated climates can benefit from the collection of solar radiation to reduce heating demand, cooling-dominated climates may suffer from insufficient protection from direct solar radiation.

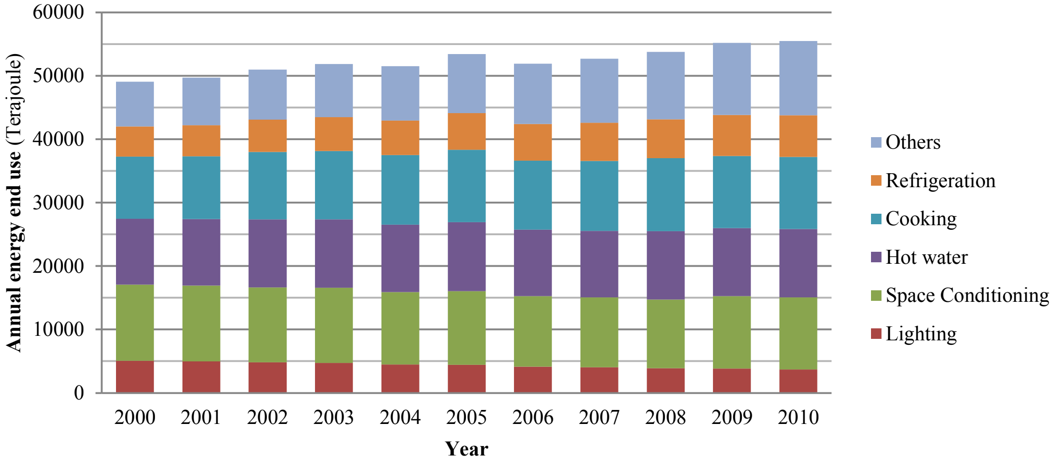

Fig. 2. Housing annual energy end use by segments in Hong Kong [1]

5.1. Hot-humid climate

Hong Kong is located on China's south coast, facing the South China Sea and is classified as humid subtropical climate (Cwa) in the Koppen Climate Classification System. Summer months between May and October are hot and humid with warm wind blows from the south and southeast directions. Substantial electricity is required to remove the excessive heat and moisture during summer months. Winter months between November and April are mild with cold and dry wind blowing from the north and northeast directions. The mean temperature ranges from 16°C in January and February to 28°C in July and August. The relative humidity is high all the year round and does not vary very much in summer and winter seasons (see Fig 3). The solar radiation in Hong Kong is strong all year round; careful attention thus should be paid to reduce heat gain through radiation. Well-designed shading devices thus can significantly reduce building cooling load and enhance daylight utilization in buildings.

5.2. High-dense and high-rise development

Hong Kong is one of the most densely populated areas in the world with an overall population density of 6,487 persons per km^2 [14]. In terms of land resources, the total land area of Hong Kong is 1108 km^2. Only 30% of them are usable for various developments, and approximately 7% (76 km^2) has been used for residential buildings in 2012[15]. The high population and limited land resources together drive the booming construction of super tall residential buildings (e.g. the 68-floor Cullinan Tower). The densely built-up urban area have altered the radiative, thermal, moisture and aerodynamic properties of the environment, and thus aggravated both indoor and outdoor thermal discomfort and increases the space conditioning energy consumption [16]. Therefore, it is worth noting that although the utilization of natural ventilation can save significant energy use in the high-rise residential buildings in Hong Kong [17]; it will only be used by occupants when the exterior environmental conditions are favorable, e.g. cool air and quiet environment. Given the densely built-up conditions in Hong Kong, natural ventilation design measures require careful consideration.

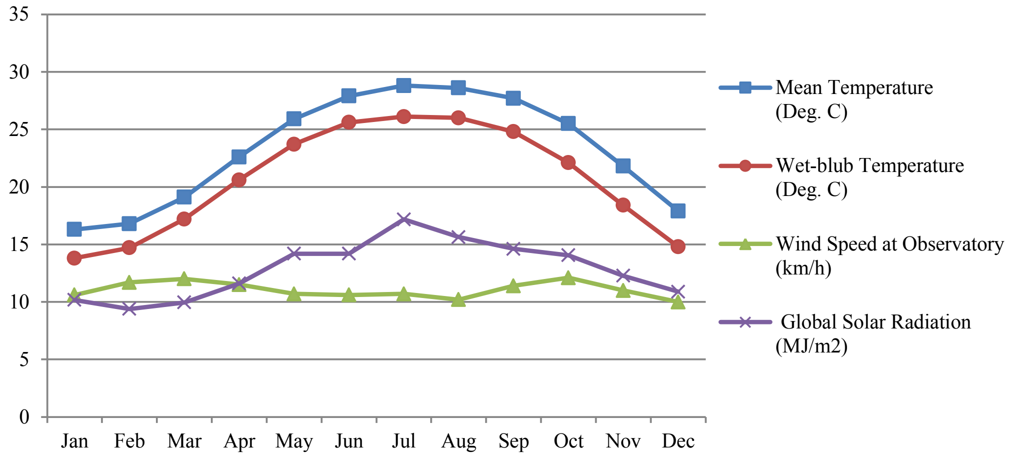

Fig. 3. Monthly Mean Meteorological Normals for Hong Kong from 1981-2010 (Hong Kong Observatory, 2013)

6. Building envelope systems and their functionality

Arnold [18] divided the building envelope into four major systems, namely the roof system, wall system, fenestration system and underground system. Each of the four systems would contribute to the overall functional effectiveness in meeting performance requirements of thermal, acoustic, visual, aesthetic, and etc. [19]. Roof systems are usually designed to weatherproof and improve buildings thermal resistance. Wall systems can be considered as either load bearing or non-load bearing and serve to prevent water or moisture penetration and improve thermal performance. Fenestration systems, which include all the windows, louvers and entrances, play a vital role in lighting, ventilation and thermal performance. According to Arnold [18], wall systems and fenestration systems have been prime targets of innovation since the early twentieth century due to material innovation. Therefore, in order to identify energy-efficient design measures, detail review of the two influential systems is essential.

6.1. Wall system

Exterior wall consists of four elements, namely structural elements, exterior wall finish and exterior color, exterior and interior insulation.

- Structural elements

ASCE 30-00 identified four types of exterior wall structures: mass walls, metal building walls, steel-framed walls, wood-framed and other walls. The majority envelope structures of the residential buildings in Hong Kong are mass walls with 150mm thick reinforced concrete and prefabricated facade.

- Exterior wall finish

Exterior wall finish is used to define the texture of the exterior wall surface, which influences the rate of heat loss/gain. Since the texture effect of exterior wall finish is minor, confirming this is not critical in the building energy performance simulation.

- Exterior wall color

Exterior wall color is used to set the exterior surface absorptivity which influences the rate of heat loss/gain as a function of solar incidence.

- Thermal insulations

Thermal insulations are used to minimize heat loss while serving as a capillary break to block moisture infiltration. In cold climates, regulatory requirements on energy performance of building envelopes dictate the use of thermal insulation; however, applying thermal insulation to buildings in hot and humid climates remains rare. Special attention should also be given to thermal bridge issues which may significantly impair the overall thermal performance. The adverse impacts can be mitigated by using thermally broken materials, e.g. thermally broken aluminum and insulation.

6.2. Window system

High-performance window system with good thermal and optical properties is important in determining thermal comfort and illumination levels. In recent years, significant advances have been made in glazing materials including low emissivity (low-e) coatings, insulating glass units, aerogels cavity fills and thermally break frames. While thermal properties can be measured by U-value or SHGC, optical properties can be evaluated by visual transmittance (Tv). Major glazing components and their properties are discussed below.

- Coatings (e.g. Low-emission coating and Reflective coating)

Low-emission coatings can reduce unwanted solar radiation in summer and prevent heat from radiating out in winter. Reflective coatings consist of thin metallic or metal oxide films can significantly lower heat gain.

- Tinted Glass

Green, grey, bronze and blue are the most common tints. As with tinted glazing, Tv usually declines more than SHGC, which implies that good thermal performance may be at the cost of optical performance.

- Multiple Layers and Fills

SHGC values of window assemblies can be improved by increasing the number of glass lites and by filling the spaces between the lites with inert gases, such as argon instead of air.

7. Energy-efficient envelope design measures

Different envelope design measures are required for different climatic zones. Energy-efficient building envelope design should focus on building's response to the exterior environment, i.e. how to gain the maximum benefit from the local climatic conditions. In hot-humid climate, the properties of high performance envelopes include allowing daylight into the building, preventing unwanted solar heat gain, improving thermal resistance and enhancing natural ventilation [20]. Daylight harvesting measures aim to enhance natural lighting, reduce artificial lighting consumption and improve indoor environment quality. Heat rejection measures include solar and thermal control through proper shading, advanced glazing, insulation and etc. Natural ventilation is an effective measure to save energy consumed in buildings and to improve indoor air quality.

The amount of energy lost through the envelope is influenced by both design and materials. Design considerations affect the placement of windows and doors, the size and location of which can be optimized to reduce energy usage. Decisions regarding the appropriate material also play a vital role in determining the energy performance. Therefore, energy-efficient building envelope design measures can be generally separated into two groups, namely architectural design measures and material design measures.

7.1. Architectural design measures

- Optimize building form to minimize heat gains through surface;
- Orient building towards north-south exposures to take advantage of north–south day-lighting
- Turn long facades toward the prevailing breezes to enhance natural ventilation
- Employ solar shading devices to block direct solar radiation;
- Use innovative wall type, e.g. double skin wall;
- Proper design of window area and size (window to wall ratio);
- Install wing walls to improve natural ventilation;
- Install light shelves to penetrate daylight deep into the building.

7.2. Material design measures

- Insulate the exterior wall and roof to avoid humid air infiltration to reduce dehumidification energy;
- Use high performance concrete for its thermal mass;
- Use reflective exterior wall/roof finishes to reduce solar heat gain;
- Use innovative construction materials, e.g. Fiber-reinforced polymer;
- Incorporate windows with low-e or reflective coating;
- Incorporate windows with tinted or multiple layers of glazing;
- Incorporate windows with thermally improved frame.

Thermal performance of the whole building envelope can be evaluated via overall thermal transfer value-OTTV (when applicable). In Hong Kong, OTTV has only been determined for commercial buildings, and it has been argued that OTTV could fail to correctly reflect the final energy consumption [21]. Therefore, this paper chose annual space cooling electricity use as a parameter to examine the energy performance of building envelope design measures.

8. Comparative simulations

8.1. Establish the baseline building model

The simulation software eQUEST was chosen in this research for examining the energy use reduction efficiency of the identified envelope design measures. The simulation "engine" within eQUEST is derived from the latest official version of DOE-2, which is the most widely recognized building energy analysis program in use today. eQUEST extends DOE-2's capabilities in several ways and changes DOE-2's complex interfaces by stepping users through the creation of a detailed building model using a series of wizards.

A 40-floor high-rise tower with 462 ft^2 gross floor area (GFA) each floor is established as the baseline building in eQUEST. The gross floor area on each floor is divided into 3 zones by activities, namely General living space (161ft^2, 34.8% of the GFA), Bedrooms (204ft^2, 44.2% of the GFA) and Bathroom/Kitchen (97 ft^2, 21% of the GFA). General living space and bedrooms are conditioned from every day from 1 May to 31 October with a set point of 77°F, Bathroom and Kitchen are unconditioned. The details of air conditioner operation schedule are listed in Table 1.

All the windows are installed with a single panel of 1/8 inch thick tint green glass with a visible transmittance of 0.82 and aluminum frames, resulting in a U-value of 1.13 W/m^2K. The exterior wall is composed of three layers: 6 inch heavy weight concrete, 'Medium finish' (Abs=0.6) and R-13 interior insulation. The roof is also composed of three layers: 6 inch concrete, 'Medium finish' (Abs=0.6) and R-6 exterior insulation.

The weather data of Hong Kong was derived from the Department of Energy (DOE) website <http://doe2.com/download/weather/>. The thermostat set points and cooling design temperature are defined with reference to “Code of Practice for Energy Efficiency of Building Services Installation." Other design details of the baseline building are illustrated in Table 1.

Table 1. Details of baseline building design in eQUEST

Building area	18,480ft^2 (1717m^2)	Floor heights	10 ft (floor to floor) (0.93m)
Minimum humidity	50%	%Window	40
Thermostat cooling set points	77 °F	Overhangs	None
Cooling design temperature	77 °F	Cooling equipment	DX Coils
A/C operation	General Living Room: 7pm-11pm every day from 1May to 31 Oct Bedrooms:9pm-7am every day from 1 May to 31 Oct		
Orientation	Long facade side whit General living space and Bedrooms towards north		
Window	Single Green 1/8 inch+ Alum frame with thermal break (SHGC=0.72, Tv=0.82)		
Roof	6 inch Concrete+ ‘Medium’ color (Abs=0.6)+ 1.5 inch polystyrene (R-6)		
Exterior Wall	6 inch Concrete+ No exterior finish+ ‘Medium’ color (Abs=0.6)+ No insulation		

8.2. Verify baseline building model

The annual energy consumption indicators for residential buildings were published by Hong Kong Electrical and Mechanical Service Department to benchmark the energy performance (see Table 2). According to Hong Kong energy end-use data 2012 [1], space conditioning energy use accounts for 16%, 21%, 22% and 30% of total energy use in different housing groups (see Table 2). Therefore, the average annual cooling energy intensity was predicted to be 95 MJ/m^2/annum.

Using the design details described above, the annual space cooling energy use of the baseline building is 51,996kWh; the annual cooling energy use per floor area thus should be 101.3MJ/m^2/annum. This figure is 6.6% higher than the predicted data (95 MJ/m^2/annum) but within the scope of different groups’ variations (84.5 MJ/m^2/annum to 113.4 MJ/m^2/annum), which is considered acceptable.

Table 2. Energy consumption indicators

Group	Annual Energy Consumption per Area (MJ/m2/annum)	Space Conditioning Energy Use/ Total Energy Use	Space Conditioning Energy Use per Area (MJ/m2/annum)
Public Housing	528	16%	528*16%=84.5
HA Subsidized Sale Flat	453	21%	95.1
Private Housing	395	22%	86.9
Other Housing	378	30%	113.4
Average	--	--	95.0

Comparative simulation of five building envelope design measures are selected for evaluation, namely, wall insulation, exterior wall color, window to wall ratio, window system and solar shading devices. Details of the improved design measures are illustrated in Table 3. Roof and underground design measures are excluded in the simulation because heat gain through the roof and underground is small compared with the external walls. The simulation results (see Table 4) revealed that with enhanced envelope design measures applied to the baseline building, the annual space cooling energy can be reduced as much as 46.81%. Among them measures of adjusting window area (17.82% reduction), changing window glass type (20.26% reduction) and incorporating solar shading devices (16.8% reduction) are much more efficient than changing the exterior wall color (2.13% reduction) and insulating the exterior wall (0.28% reduction).

Table 3. Details of five improved design measures of building envelope

	Measures	Baseline Design	Improved Design
1	Exterior wall insulation	No	1and1/2 inch polystyrene
2	Window Overhang	None	2.5 inch Window Overhang
3	Exterior wall color	Medium(Abs=0.6)	White gloss
4	WWR (Window to wall ratio)	40%	25%
5	Window glass type	Single Green 1/8 inch + Aluminum frame with thermal break (SHGC=0.72, Tv=0.82)	Double Low-e Tint1/4 inch+ 1/2 inch Argon+ Aluminum frame with thermal break (SHGC=0.37, Tv=0.44)

Table 4. Cooling energy reduction by applying five improved envelope design measures (compared with baseline building)

	Design Measures	Annual space cooling energy consumption	Percentage of annual space cooling energy reduction
0	Baseline Design	51,996 kWh	---
1	0+Exterior Wall Insulation	51,819 kWh	0.28%
2	0+Window Overhang	43,237 kWh	16.80%
3	0+Exterior Wall Color	50,857 kWh	2.13%
4	0+Window Area	42,706 kWh	17.82%
5	0+Window Glass Type	41,438 kWh	20.26%
6	0+1+2+3+4+5	27,639 kWh	46.81%

The significant difference of energy efficiency between wall and window design measures can be explained by understanding how heat flows through the building. Cooling loads, which directly contribute to space cooling energy use, come from heat transfer from within the building during its operation (internal loads) and between the building and the external environment (external envelope). Heat can be gained from the environment in three principle ways, namely conduction, convection and radiation. In a building, conduction primarily takes place through wall assemblies; convection is caused by wind or pressure-driven air movement; solar radiation transfer through glazing assemblies. In hot climates, the greatest source of heat energy is solar radiation. Solar radiation can be reduced by adequate shading from the sun, light colored surface, low solar heat gain coefficient (SHGC) glazing and small window area. Conduction heat transfer through walls is weak compared to solar radiation heat gain in hot climates. Therefore, measures to reduce conduction heat transfer (e.g. exterior wall insulation), which works quite well in cold climates, are not effective in hot climates.

9. Conclusions

This paper has examined energy-efficient building envelope design decision-making in Hong Kong. The paper has argued that the informed design decisions can be achieved through the process of analyzing housing energy use, highlighting exterior build environment, exploring window and wall systems and material properties, and identifying potential design measures. This process integrates energy modeling into the design which enables continual information exchanging, analyzing and comparing. Five representative design measures, namely wall insulation, exterior wall color, window to wall ratio, window system and solar shading devices are selected to be examined in eQUEST. A key finding is that the annual cooling energy use can be reduced significantly, as much as by 46.81%. The measures of reducing the solar heat gain are more effective than those of reducing conduction through external walls. The results suggest that there is a large potential to significantly reduce cooling energy consumption with readily available design measures and materials. Also, the paper emphasizes the importance of incorporating energy modeling into design decision-making in producing more energy-efficient buildings.

References

[1] EMSD. Hong Kong energy end-use data 2012. Electrical and Mechanical Service Department, HK.2012

[2] IEA. World Energy Outlook 2012. International Energy Agency. 2012.

[3] Aksamija A. Sustainable Facades: Design Methods for High-performance Building Envelopes. Canada: John Wiley & Sons; 2013.

[4] Massetti M, Corgnati SP. Energy Simulation Supporting the Building Design Process. SIMUL 2011, The Third International Conference on Advances in System Simulation 2011; (1): 136-141

[5] Ochoa CE, Capeluto IG. Strategic decision-making for intelligent buildings: Comparative impact of passive design strategies and active features in a hot climate. Building and Environment, 2008; 43(11): 1829-1839.

[6] Bojić M. Application of overhangs and side fins to high-rise residential buildings in Hong Kong. Civil Engineering and Environmental Systems, 2006; 23(4): 271-285.

[7] Bojić M, Yik F. Cooling energy evaluation for high-rise residential buildings in Hong Kong. Energy and Buildings, 2005; 37(4): 345-351.

[8] Yik F, Bojić M. Application of switchable glazing to high-rise residential buildings in Hong Kong. Energy and buildings, 2006; 38(5): 463-471.

[9] Cheung CK, Fuller RJ, Luther MB. Energy-efficient envelope design for high-rise apartments. Energy and buildings, 2005; 37(1): 37-48.

[10] Fellows RF, Liu AMM. Research methods for construction. U.K.: John Wiley & Sons; 2009.

[11] EIA. “Annual Energy Review”. Energy Information Administration, U.S., 2012

[12] DECC. “Energy Consumption in the UK”. Department of Energy & Climate Change, U.K., 2013.

[13] Yang L, Lam JC, Tsang CL. Energy performance of building envelopes in different climate zones in China. Applied Energy, 2008, 85(9): 800-817.

[14] PRB. “World Population Data Sheet”, Population Reference Bureau, U.S., 2012.

[15] PD. “Land Utilization in Hong Kong 2012”, Planning Department, HK, 2012.

[16] Giridharan R., Ganesan S, Lau SSY. Daytime urban heat island effect in high-rise and high-density residential developments in Hong Kong. Energy and Buildings, 2004, 36(6), 525-534.

[17] Yik WH. Development of Environment Responsive Façade Engineering to enhance Liveability, Sustainability and Energy Conservation in Optimized Design of Public Housing. The Hong Kong Polytechnic University and the Hong Kong Housing Authority, HK, 2006.

[18] Arnold C. Building Envelope Design Guide– Introduction. http://www.wbdg.org/design/env_introduction.php (accessed 24 April 2014).

[19] SEI. Guideline for condition assessment of the building envelope. American Society of Civil Engineers, U.S., 2000.

[20] Attia S. A Tool for Design Decision Making Zero Energy Residential Buildings in Hot Humid Climates. Presses univ. de Louvain, 2012.

[21] Wan KSY, Yik F W. Representative building design and internal load patterns for modelling energy use in residential buildings in Hong Kong. Applied energy 77, no. 1 (2004): 69-85.