Climate-Adaptive and Optimized Building Envelope Designs in East Asia

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ABSTRACT

Large scale, multi-use commercial developments are trending in major cities development in East Asia. With more mega scale buildings constructed, the impact on energy consumption and carbon emissions would be great. Climate-adaptive designs and optimized building energy strategies would be imperative to enhance the building adaptability to the local climates and improve the overall building energy efficiency. Next generation of the energy interactive building design provided a platform to address complicated combination and optimize different building design parameters on the impact towards the building energy consumptions.

Optimized envelope design strategies could be an effective approach to shelter building to its own climates and create pleasant indoor environment. Interactive and parametric optimization at early stage design will allow for the identification of design parameters in which the design team can take into consideration. A generic commercial office building is identified and in two locations with distinct climate zones in East Asia are chosen. With the energy interactive optimization, a clear combination of design parameters can be identified. An annual thermal load decrease of 8.2% and 6.5% as compared to the ASHRAE 90.1-2007 envelope baseline for Hong Kong and Seoul respectively.

Keywords: *adaptable design, climate responsive architecture, facade optimization, building energy use*

1. INTRODUCTION

The scientific work by the Inter-governmental Panel on Climate Change (IPCC) have raised public concerns about energy use and revealed the impact towards the environment (Solomon et al., 2007). It is generally acknowledged that the drivers of climate change were due mainly to the anthropogenic activities in raising the greenhouse gas concentration in the atmosphere. High-rise office building development is one of the fastest growing areas in the building sector especially in major cities in East Asia (Jiang, 2005). On a per unit floor area basis, energy use in large office building development with full air-conditioning can be 70-300 kWh/m^2, 10-20 times that in residential buildings (Jiang, 2006). With more tall buildings constructed (with 20 stories or more), the impact on energy consumption and carbon emissions are expected to growth (2% increase of carbon dioxide annually between 1971 and 2004) (UNEP, 2007).

Energy efficiency and sustainability issues are important considerations during the architectural design, and at all stages of the evaluation procedures. Two important issues that building architects and engineers need to identify is climatic responsive design and identifying the most effective strategy that the building should adopt to ensure true energy savings (Wan et al., 2012). The new generation of high-performance envelopes has transformed the way in which architects approach building design with a shift in emphasis from built form to performance and from structure to envelope. In the realm of high-performance buildings, the envelope has become the primary site of innovative research and development (Velikov and Thun, 2013). Climate responsive design and energy interactive design approaches are believed to be key to drive for the next generation smart building envelope designs.

2. NEXT LEVELS OF SUSTAINABLE BUILDING ENVELOPE DESIGNS

Buildings, energy and the environment are key issues faced by building professions worldwide, and energy is a key element in the overall efforts to achieve sustainable development (Jiang 2005 & 2006). Sustainable building designs provide a good solution to enhance the overall building energy performance. Overall thermal transfer value (OTTV) has been used as a conventional indictor to evaluate the building envelope performance particularly in subtropical climates due to its effectiveness in the consideration of the three major envelope heat gain components: (i) conduction through opaque walls, (ii) conduction through window glass and (iii) solar radiation through window glass (Hui, 1997). Previous sustainable building design experiences focuses on optimizing each design parameter individually, where the sensitivity of each design parameter is generally known. However, the dynamic interaction of all the different design parameter is less studied, providing an opportunity for improvement in the design process through the simultaneous optimization of different parameters.

2.1 Conventional sustainable building designs

The aforesaid design approach provides a useful guideline for the architect or designer to have an idea about the impact of key design parameters to the thermal performance of the building facade. Through considering the thermodynamics and the energy flux between the external built environment and the internal loads, a basic understanding of the thermal behaviour of the building envelope is established, but the overall building energy usage cannot be fully establish. Accounting for the interactions between the multiple design parameters, simultaneously optimizing multiple envelope design parameters and establishing the energy building consumption at the zone level would be extremely useful and desired the building design process.

2.2 Energy interactive building designs

Architectural design would have close interaction with the indoor climate and the environment (Givoni, 1998). Defining the values of the input parameters is often a difficult task and there is no one way solution to address all design concerns (Lam et al., 2008). Maximizing the window opening would enhance the daylight penetration but imposing the solar heat gain and increase the building cooling load. Balancing the window-to-wall ratio and the darkness of the glazing as well as optimizing the length of the extended building shading are complicated and every combination would have different implication towards the building energy consumptions. Along with the blooming of computation power, interactive building design approach is realized via the integrative and open-source platform (Figure 1). EnergyPlus have been chosen as the energy simulation software and there are a few compatible optimization solvers for EnergyPlus including Grasshopper's Galapagos, OpenStudio, GenOpt, and JEPlus. Grasshopper's Galapagos was chosen for its simplicity and user friendliness. The parametric optimization tool is integrated with the five components as below:

- Rhinoceros
- Plugin: Grasshoper
- Plugin: Honeybee and EnergyPlus
- Optimization solver component: Galapagos

A 3D building geometry is developed on the platform of the parametric optimization tool and the key building envelope design parameters are defined, such as the window U-value, solar heat gain coefficient (SHGC), wall U-value, window-to-wall ratio (WWR), and shading depth. A building description file for Energyplus (.idf file) including the building envelope and system details would be generated. Building energy simulations will be carried out and the zone cooling energy and heating energy use based on a combination of the design parameters would be visualized on the 3D model in parallel. The parametric optimization could also analyse the interaction between parameters by the genetic algorithm and optimize the best combination of the parameter values towards the zone energy consumption. The methodology would be further discussed in the next section.

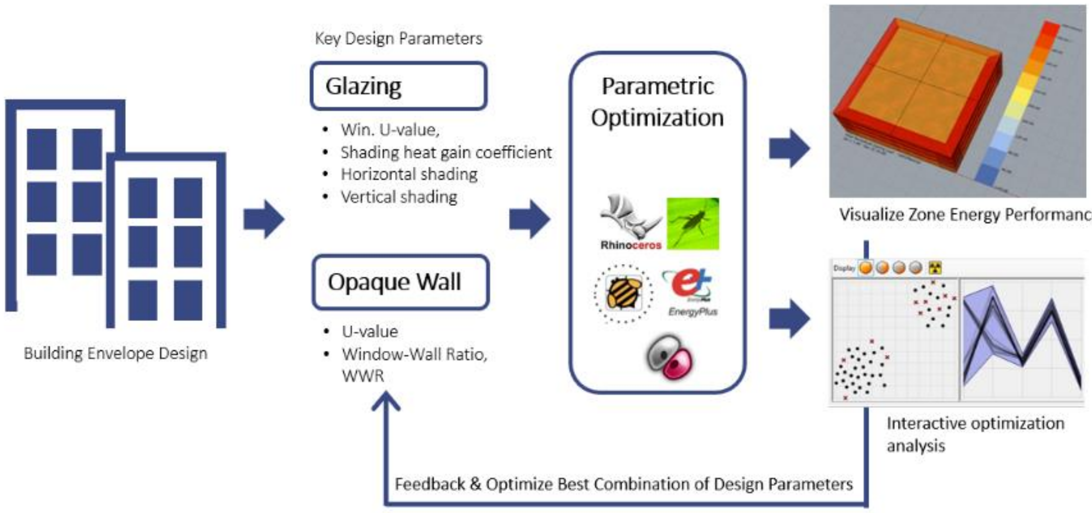

Figure 1: Energy interactive design approach

3. METHODOLOGY

Simulated Annealing (SA) was chosen as the optimization solver for this study, where it follows one solution candidate's iterative jumps across the solution space to approximate for the global optimum point (Kirkaptrick et al., 1983). Each iterative jump and its legitimacy are affected by the temperature of the system, where the candidate should converge towards the global optimum. The design approach focuses on the building envelope parameters, which are mentioned in Section 2.2. These parameters are limited to a certain range, reflecting actual building designs. A step function is also introduced to reduce the number of cases and allowing the solver to refine its search.

A generic office building was developed to serve as a baseline reference for comparative energy studies. The a base case is a 35x35m, 20 stories building with perimeter zone of 4m depth, an interior zone of 6m depth, and an internal core area of 15x15m. The interior zone and perimeter zone are set as open office area and the interior core, for simplicity, is set as corridor area. The bottom and uppermost floor are simulated for their thermal load, with an adiabatic block in between. The building's annual thermal load is calculated by multiplying the bottom floor's thermal load by 19, to reflect the floors replaced by adiabatic block. A range is set for each design parameters for envelope through experience of a typical office building, with a step introduced to reduce the number of possible iterations while maintaining a fine enough resolution to observe differences (Table 1). The indoor loads and ventilation requirements references ASHRAE 90.1-2007 and ASHRAE 62.1-2007 (Table 2) (White et al., 2007; Stanke et al., 2007). The equipment load uses 20W/m^2 (EMSD, 2007) a typical load density as found in office buildings.

Key Design Parameters for Envelope	**Range**	**Step**
Window-to-Wall Ratio	0.3 – 0.8	0.05
Window SHGC	0.2 – 0.9	0.05
Window U-Value (W/m^2·K)	1.5 – 6.0	0.5
Wall U-Value ((W/m^2·K)	0.4 – 2.0	0.2
Horizontal Shade Depth (m)	0 – 1.0	0.25
Vertical Shade Depth (m)	0 – 1.0	0.25

Table 1: Key design parameters for building envelope

Design Parameters	**Open Office**	**Corridor**
Lighting Power Density (W/m^2)	12	5
Equipment Power Density (W/m^2)	20	0
Occupancy Density (prs/m^2)	0.05	0
People Outdoor Air Rate (L/s·person)	2.5	0.3
Area Outdoor Air Rate (L/s·m^2)	0	0.3

Table 2: Building internal load and ventilation requirements

	Hong Kong	**Seoul**
ASHRAE Climate Zone	2 – hot climate	4 – mixed climate
Cooling Set-Point	23°C	26°C
Heating Set-Point	22°C	20°C

Table 3: Climate zone and set-points

In this study, two major financial cities within Asia with two distinct climate zones are chosen, them being Hong Kong and Seoul. The cooling and heating set-points of the buildings are based on the local energy codes (EMSD, 2012; MOLIT, 2015). Hong Kong is located in ASHRAE climate zone 2, with a hot climate, where cooling is dominant. Seoul is located in ASHRAE climate zone 4, with a mixed features of hot summer and cold winter, where heating is slightly dominant.

The air conditioning system is defined as an Ideal Air Load system, thus it is possible to simulate the annual cooling energy load and annual heating energy load. The optimization study aims to reduce the total annual thermal load, which would thus reduce the energy consumption of the HVAC system, normally found to be over 40% of the total building energy consumption.

4. BASELINE CASE

A baseline case is developed for each of the city, where the indoor set-point and internal load are set as described in Section 3. The baseline building envelope are developed based on ASHRAE 90.1-2007 (White et al., 2007) and summarized in Table 4. Table 5 shows the simulated annual cooling and heating load of the building located in the two studied cities.

Design Parameters	**Hong Kong**	**Seoul**
Window-to-Wall Ratio	0.4	0.4
Window SHGC	0.25	0.4
Window U-Value (W/m^2·K)	3.97	2.84
Wall U-Value ((W/m^2·K)	0.70	0.37
Horizontal Shade Depth (m)	-	-
Vertical Shade Depth (m)	-	-

Table 4: Baseline envelope configuration

Building Energy Component	**Thermal Energy Use**	
	Hong Kong	**Seoul**
Annual Cooling Load (kWh)	7,633,743	552,250
Annual Heating Load (kWh)	608,866	5,504,085
Annual Thermal Load (kWh)	8,242,609	6,056,335
Thermal Load (kWh/m^2)	336.4	247.2

Table 5: Summary of the thermal load for the simulated baseline

5. OPTIMIZATION RESULTS

The optimization solver will generate large amounts of cases as it searches for the optimal solution. The results are plotted on a multi-dimensional graph (Figure 2), where the first three axis depicts the simulation output, them being the annual thermal load (total), annual cooling load (cooling), and annual heating load (heating). The six remaining axis depicts the building envelope parameters. Each line shown on the plot depicts one design scenario, where the intersection of each axis describing the results (first three axis) or the input parameters (remaining seven axis). The colour scheme of the plot follows that of the annual thermal load, with blue being lower value and red being higher value.

5.1 Building envelope optimization for Hong Kong

Hong Kong's thermal load is dominated by cooling load. It is also well known that the external solar radiation is a dominating factor in heat gain through building facade. This echoes to the local OTTV calculation where the shading coefficient have a heavier weighting factor than wall U-value. From the results plot, a lower annual thermal load is achieved when the following factors are met:

- Minimize envelope U-value to minimize heat transfer from outdoor to indoor in hot summer months
- Lower window SHGC to reduce solar heat gain
- Reduce WWR to reduce solar heat gain through window.
- Window's U-value is also higher than that of the wall, thus reducing WWR will also reduce heat transfer
- Maximize shading depth to reduce solar heat gain through window

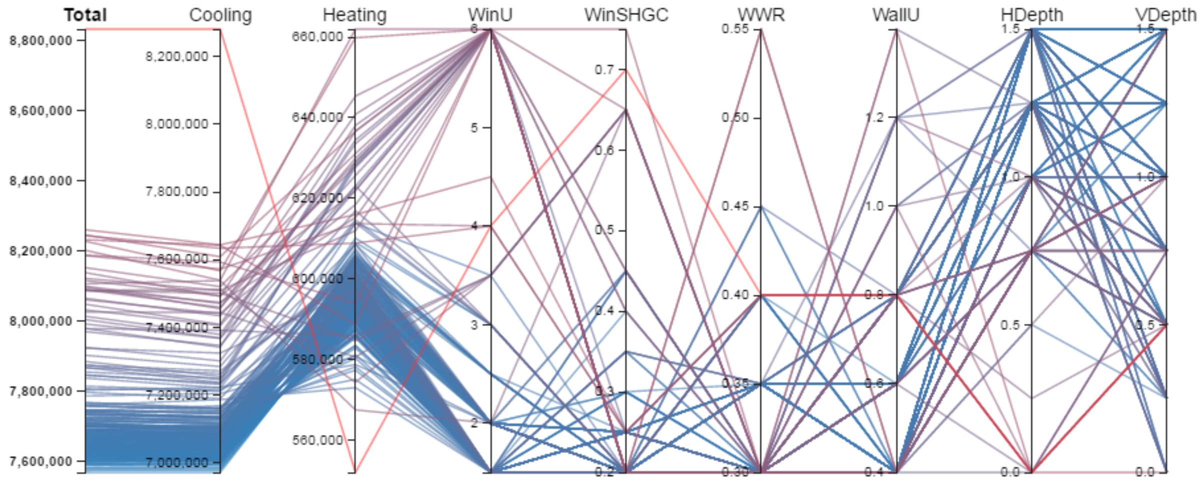

Figure 2: Optimization results – Hong Kong

The optimal case was found to have the below configuration, which resulted in thermal loads as shown in Table 6. Noting that the HVAC system takes up approximately 40% of the annual energy consumption of the building, an 8.2% decrease in annual thermal load will approximately lead to a 3% decrease in annual total energy consumption. Other than finding the optimal case, the solver also populated the solution space with numerous different cases. This allows for the consideration of different envelope designs which may yield similar reduction in annual thermal load.

Figure 3 shows the top 10% results of the optimization run, where the annual thermal load decrease from the baseline case ranges from 7.7% to 8.2%. An observation from the above plot is that the solver prefers a longer horizontal shading depth over a longer vertical shading depth. This can be explained by Hong Kong's high solar angle over the year, thus a longer horizontal shading depth would block out more solar radiation.

Design Parameters (Hong Kong)	**Design Values**
Window-to-Wall Ratio	0.3
Window SHGC	0.2
Window U-Value (W/m^2·K)	1.5
Wall U-Value (W/m^2·K)	0.4
Horizontal Shade Depth (m)	1.5
Vertical Shade Depth (m)	1.5

Table 6: Optimal envelope configuration of Hong Kong

Building Energy Component	Thermal Energy Use	% Difference
Annual Cooling Load (kWh)	6,972,526	-8.7%
Annual Heating Load (kWh)	594,896	-2.3%
Annual Thermal Load (kWh)	7,567,422	-8.2%
Thermal Load per Area (kWh/m^2)	308.9	

Table 7: Optimized case energy simulation results of Hong Kong

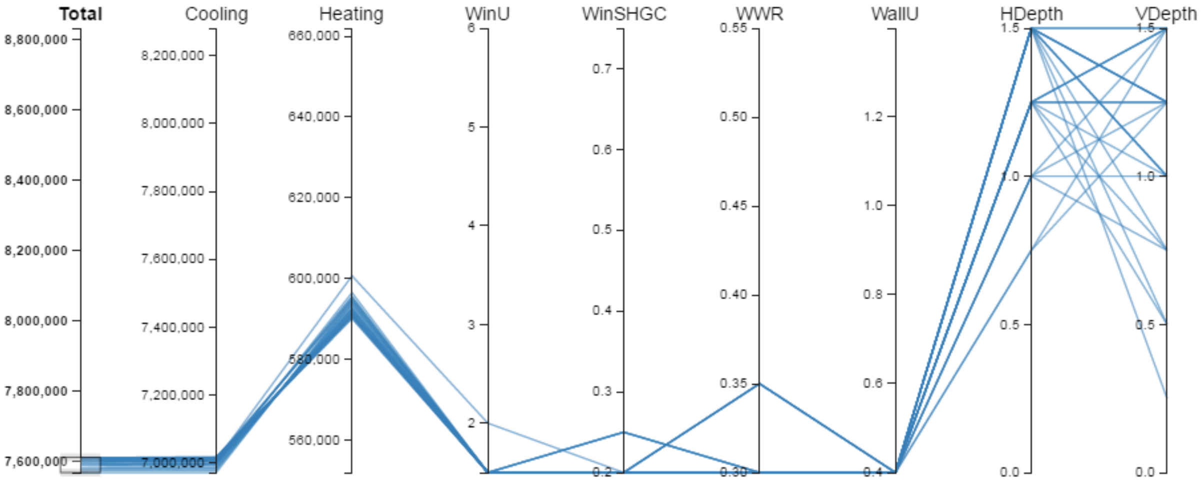

Figure 3: Optimization results – Hong Kong (Top 10% Results)

5.2 Building envelope optimization for Seoul

In Korea, the annual thermal load is dominated by the heating load. An optimal building design is required to balance the building cooling and heating load in different seasons. From the results plot (Figure 4), a lower annual thermal load is achieved when the following factors are met:

- Minimize envelope U-value to reduce heat loss during winter
- High SHGC to allow for higher solar heat gain during winter, even though there will be an increase of cooling load during summer
- Minimize shading to maximize solar heat gain during winter
- A balanced WWR to minimize heat transfer through the window but also to allow for incoming solar radiation

The optimal case was found to have the configuration as shown in Table 8 and the thermal loads results as shown in Table 9.

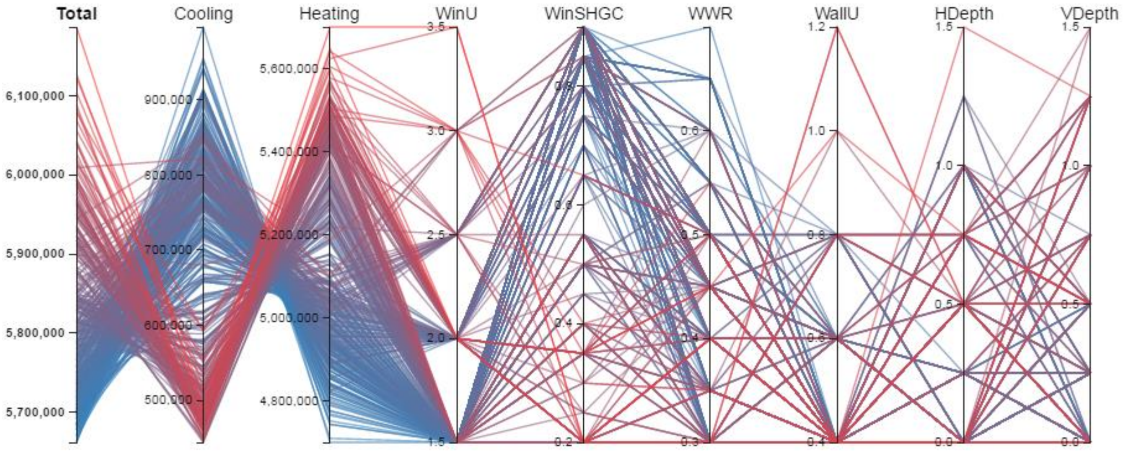

Figure 4: Optimization results – Seoul

Design Parameters (Seoul)	**Design Values**
Window-to-Wall Ratio	0.45
Window SHGC	0.9
Window U-Value (W/m²·K)	1.5
Wall U-Value (W/m²·K)	0.4
Horizontal Shade Depth (m)	0
Vertical Shade Depth (m)	0.45

Table 8: Optimal envelope configuration of Seoul

Building Energy Component	**Thermal Energy Use**	**% Difference**
Annual Cooling Load (kWh)	865,187	56.7%
Annual Heating Load (kWh)	4,796,533	-12.9%
Annual Thermal Load (kWh)	5,661,720	-6.5%
Thermal Load per Area (kWh/m²)	231.1	

Table 9: Optimized case energy simulation results of Seoul

The optimal case would greatly increase the annual cooling load. As the study case only reports the thermal load, special care should be taken when choosing for the optimal case, where energy cost saving should also be taken into account.

Observing the top 10% results, where the annual thermal load decrease ranges from 6.0% to 6.5%, the factors leading to a lower annual thermal load can be clearly showcased. It is also observed that there are leeway in the selection of window SHGC and of shading depth. There are also no strict restriction in choosing a WWR. The plot also shows that the cooling load can be significantly decreased while maintaining a high overall decrease of annual thermal load. By lowering the WWR and slightly increasing the shading depth, the cooling load can be decreased while not significantly compromising the heating load nor annual thermal load.

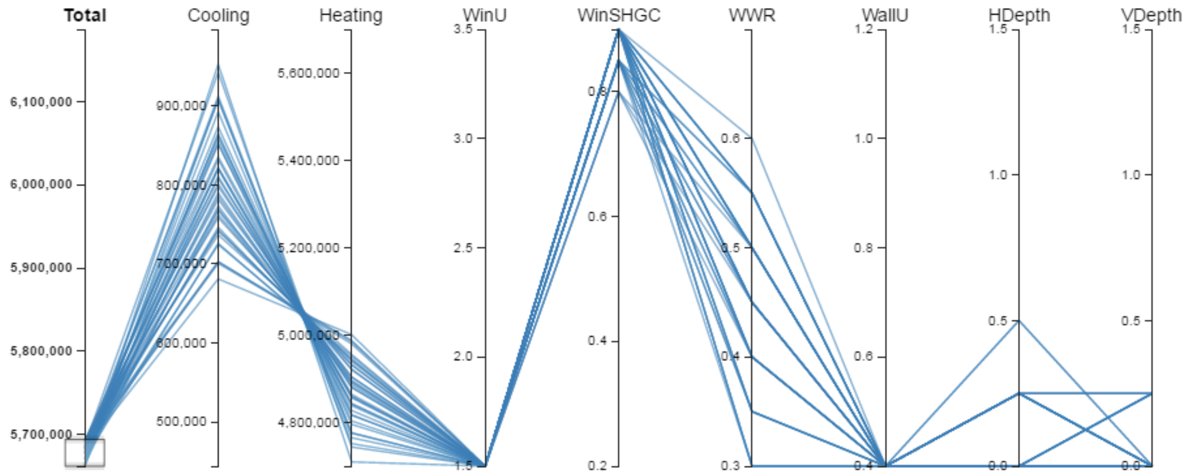

Figure 5: Optimization results – Top 10% results – Hong Kong

6. CONCLUSION

Interactive and parametric optimization at early stage design will allow for the identification of design parameters in which the design team can take into consideration. With the initial settings in the above two cases, clear design parameters can be found after utilizing the optimization solver within Grasshopper. The optimal case found by the solver returned results with annual thermal load decrease of 8.2% and 6.5% as compared to the ASHRAE 90.1-2007 envelope baseline for Hong Kong and Seoul respectively.

Over 200 cases were generated by the solver during each run, giving the design team numerous design iterations where similar savings may also be achieved. The optimization parameters are not limited to those in the above study. Internal load, other envelope properties, nearby surrounding building shading effects, and HVAC settings can all be simultaneously studied. As each parameter will dynamically affect each other and the overall thermal load, by utilizing the increasing computational power available, numerous optimized design options can be generated for better designs. It is believed that energy interactive design approaches would be the driver for future sustainable and climate responsive designs.

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