Modeling the Housing Energy Efficiency Optimisation in EnergyPlus: The Study of Current Two-storey and New Three-storey Rural Housing in Hong Kong

[1]Ali Cheshmehzangi, [1]BoWei Zhou
[1]The University of Nottingham Ningbo China

Key words: Housing Energy Efficiency Optimisation, EnergyPlus, Modelling, Rural Housing, Hong Kong.

1.0 Introduction

Latest figures from summer 2015 indicate that home ownership rate in Hong Kong is just 50.6% of the total 2,474,200 households (the Census and Statistics Department of Hong Kong, 2015). For several years (since 2004), there is a steady decline in home ownership rate in Hong Kong and a larger proportion of households (66.4%) are in private sector (ibid). With almost half of the 7.3 million population of Hong Kong living in rental houses, this can be considered as a major indicator for a weaker concern about improvement of housing energy efficiency. There are two clear conflicting reasons for this: 1) the owners or developers are not the ones paying for the energy bills, hence would have less concern about energy efficiency of houses and mostly meet the minimum requirements or benchmarks; and 2) the residents living in rental properties would not invest on energy efficiency improvement since they do not own the properties. Therefore, majority of the households of low to medium income would rather choose energy-saving measures (i.e. mainly reduction of energy use) than energy efficiency improvement of their households. As a result, we can argue that there is scope for development in the field of energy efficiency optimisation and improvement in the housing sector of Hong Kong, where this study focuses on a case of optimisation.

Table 1 – Statistics on Domestic Households in Hong Kong (Source: Social Analysis and Research Section (2), Census and Statistics Department, 2015)

Period	Number of domestic households ('000)	Average domestic household size	Owner-occupiers as a proportion of total number of domestic households (%)	Owner-occupiers in public sector housing as a proportion of total number of domestic households in public sector housing (%)	Owner-occupiers in private sector housing as a proportion of total number of domestic households in private sector housing (%)
2012	2 389.0	2.9	52.0	33.2	68.2
2013	2 404.8	2.9	51.2	32.9	66.7
2014	2 431.1	2.9	51.0	32.8	66.4
3/2014 - 5/2014	2 425.1	2.9	50.9	33.1	66.2

5/2014 - 7/2014	2 433.2	2.9	50.8	32.5	66.5
7/2014 - 9/2014	2 437.7	2.9	50.5	32.4	66.2
9/2014 - 11/2014	2 436.4	2.9	50.4	32.5	65.9
11/2014 - 1/2015	2 443.0	2.9	50.2	32.6	65.5
1/2015 - 3/2015	2 449.4	2.9	50.2	32.4	65.7
3/2015 - 5/2015	2 454.4	2.9	50.7	32.4	66.6
5/2015 - 7/2015	2 474.2	2.9	50.6	32.3	66.4

Research on housing energy efficiency is becoming increasingly important in the cities and communities of the developed world. Examples of research in the sector of housing vary in between energy-related disciplines, including but not limited to: energy efficiency retrofit strategies in the U.S. (Bardhan et al, 2014), financing mechanisms for energy-saving investments in housing (Borgeson et al, 2012), housing energy efficiency database, demand and issues of energy performance in the U.K. (Hamilton et al, 2013), improvement of energy efficiency in community housing sector in Australia (Urmee et al, 2012), programmed interventions for energy efficiency retrofits in Italian social housing units (Gagliano et al, 2013) and etc. The wide range from economics to scientific research studies indicates various mechanisms and focuses on housing energy efficiency improvement, where possibilities are endless. In this study, the focus is on housing energy efficiency optimisation through modelling and simulation techniques.

Although The World Bank's data indicates that since 1990, there is 0% of rural population in Hong Kong (The World Bank, 2015), there still remain several rural districts, including many village communities outside the urban regions of Hong Kong Island and Kowloon. The Village of Sai Kung is one of these communities in the Sai Kung District, one of the largest districts of Hong Kong. This research is based on study of a typical two-storey housing typology (i.e. rural housing) in the village of Sai Kung, where there is a new emerging trend of converting the traditional two-storey houses in to three storey houses. In this process of change, the traditional two-storey houses are now converted in to three storey unit of three apartments, keeping the same overall height of buildings. The floor area remains the same and the floor-to-ceiling height for each unit is lowered significantly. Previously, a large proportion of the traditional two storey houses were converted in to two self-contained individual units, with significant internal layout changes. Some of these changes are highlighted in a later section of this study. Currently, the increase in number of apartment units per floor area is a growing trend of reconstructing the traditional houses. In this study, it is aimed to evaluate this reconstruction model based on energy efficiency optimisation of the units. The study firstly focuses on the comparison between current two-storey and new three-storey houses and then simulates energy use for cooling of the each of the apartment units in a three-storey model before modelling a range of energy efficiency optimisation models. In light of this, this research paper addresses the following two questions: 1) How the modelling approach can help evaluating measures for energy efficiency optimisation of the new three-storey housing model?; and 2) What are the additional energy load matters that need to considered for the new type of 3-storey houses?

1.1 Housing Energy Efficiency Optimisation

Energy efficiency and energy saving measures are amongst key contemporary energy-related housing studies, most of which are focused at optimisation of building design (Ihm and Krarti, 2012; Yao, 2012; Roufechaei et al, 2014;) or design optimisation of building services (Bojic et al, 2014; Fuentes-Cortés et al, 2015). Some newer trends are multi-objective (Evins, 2013) with cost analysis (Koo et al, 2015) or economic optimisation (Morelli et al, 214). The modelling approach, however, is becoming a major method in this field of research.

1.2 The Current Situation: Two Cases of Housing Models

The cross-ventilation strategy in two-storey houses is no longer operable due to the extensive change of internal layouts that have happened in recent years. The main internal layout changes include, the closure of internal staircase, inclusion of one additional bedroom (as the third bedroom), and closure of internal air circulation through and between above of the internal partitions between the rooms. While the internal walls were previously constructed at ¾ of the overall floor-to-ceiling height, the current two-storey houses no longer have such mechanism in place for natural ventilation.

1.3 Methodology

In responding to the rebuild of two-floor-buildings to three-floor-buildings, a typical model of 2-floor house in Hong Kong is simulated in EnergyPlus, testing its potential to be more energy-efficient. Conclusion is drawn based on results of energy consumptions and possible capital cost. The following conditions are considered as part of the analysis:

Location	Suburb area in HK
Orientation	0-degree North
Simulation Period	July, August
Weather File	Adapted from EnergyPlus online resources
Ground Temperature	23 Degree Celsius

All Walls shown in the model are drawn without any thickness for the purpose of simulation in EnergyPlus. Moreover, they have the same thermal performance as in the real case.

2.0 Introduction to Cases of Research

add

Two alternative options are tested, which are a three-floor building with the same total height and a same building but with a pitched roof. Although the houses with three floors could contains 4 more occupants, making great contribution to the economic growth in the future, the energy it consumes would be an issue. While the building with pitched roof is aiming to cool down the beneath room to some extent.

Four phases are conducted progressively to test the energy-saving performance of building in each phase.

2.1 Setting the Scene

Phase 1

The original building is first modelled as a two-floor building without windows installed. It is the simplest case in the simulation. Construction information is listed in next section. As a comparison, Model B has three floors, but maintains the same total height (7.5m). Buildings are not regulated with air-conditioning, aiming to give a general idea of temperatures in both buildings.

Phase 2

After that, window and doors are installed in both houses. Each floor has six strip windows, two large windows and one metal door installed. Windows and doors are two components that are venerable in thermal conductivity, which could penetrate direct sunlight into inside or transfer heat between two sides. This phase shows the influence of windows and doors on heat received by the house and therefore the temperature. This simulation more imitates the real case in HK.

Phase 3

In Phase 3, internal compartments are built on each floor. Each floor has four small compartments, three of which are bedrooms and one is toilet. Each bedroom has one strip window installed while the toilet has two windows. The rest of floor is considered as living room, it has two windows and a metal door. Two adults are assumed to be in one living room while the other two bedrooms each contains one child. The activity schedule of occupants is following the real case one. In Model C, a 70cm pitched roof is added to the same building to test is contribution to the energy conservation. It could be predicted that the added roof could increase thermal resistance to heat transfer and lower down the indoor temperature in summertime.

Phase 4

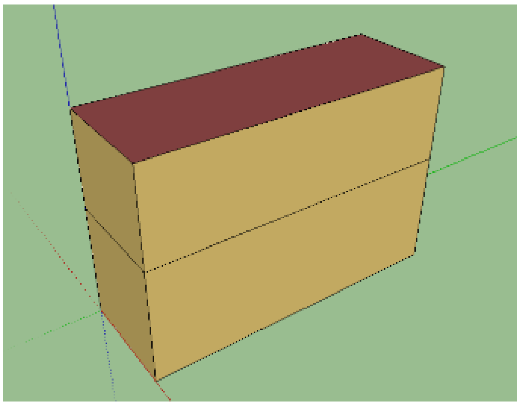
In order to find feasible solutions, tests and combinations were carried out during this phase. For building B, in Test B1 and B2, the thickness of construction is increased to its 120% of original and thermal conductivity of all material were decreased to be 80% and 50% of former values. Then in Test B3, the orientation of the house is changed according to the indication from Ecotect. In Test B4, combinations of these changes are then conducted to show its energy-saving potential. It was worth being pointed out that a goal of saving 30% of energy consumption could be reached by combining B1, B2 and B3. A goal of reaching 50% of energy consumption cut would not be economically efficient due to large capital cost and high embodied carbon.

2.2 Modelling and Analysis in Phases: Simulating the Cases of Research

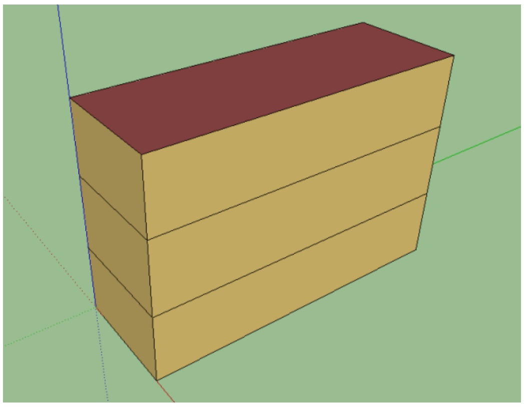
Phase 1 Detail

Basic Material Information List

Material	Construction	Thickness (m)	Conductivity (W/m*k)
Gypsum	Wall	0.013	0.160
Clay	Wall	0.102	0.895
Gypsum Board	Wall	0.013	0.160
Roof Membrane	Roof	0.010	0.160
Roof Insulation	Roof	0.169	0.049
Timber Joints	Roof	0.010	0.140
Slate	Roof	0.013	1.590
Wood	Interior Ceiling/Floor	0.200	0.140
Plasterboard	Interior Ceiling/Floor	0.015	0.170
Poured Concrete	Ground	0.300	1.700
Metal	Door	0.100	0.170
Glass	Windows	0.003	1.050



Phase 1 Model A



Phase 1 Model B

Model Size

	Model A	Model B
Length	11.1m	
Width	3.9m	
Height	7.5m (2Floors)	7.5m (3floors)

Results:

Model A

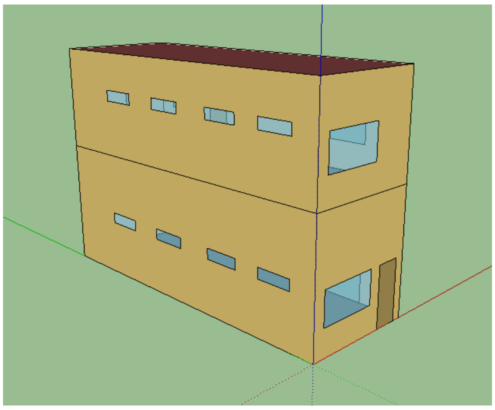
Temperature	Ground Floor	1st Floor
July	26.03	30.55
August	25.63	29.91

Model B

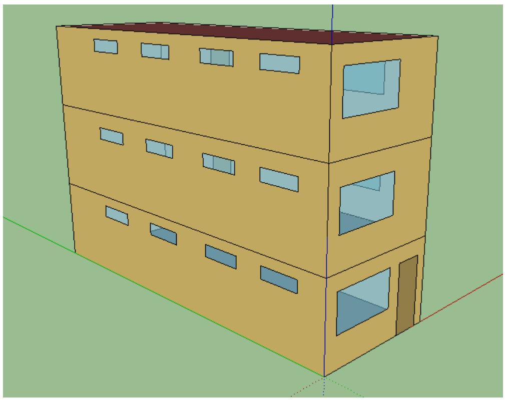
Temperature	Ground Floor	1st Floor	2nd Floor
July	24.56	30.06	30.99
August	24.23	29.47	30.33

Phase 2 Detail

Keeping the same material, both models are simulated with windows and doors installed. It considers the effect of sunlight which may heat up the room and other minor heat transfer through windows and metal doors.



Phase 2 Model A



Phase 2 Model B

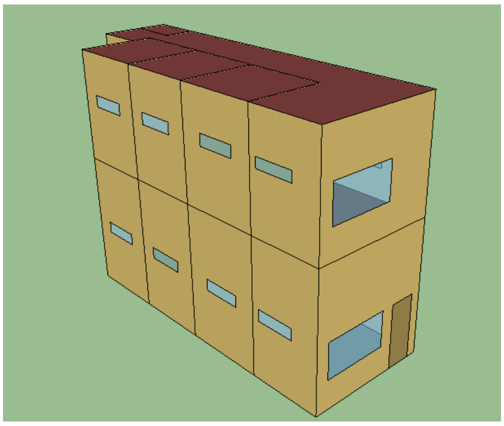
Temperature	Ground Floor	1^{st} Floor
July	28.1	30.9
August	27.7	30.2

Temperature	Ground Floor	1^{st} Floor	2^{nd} Floor
July	27.2	30.3	30.9
August	26.8	29.7	30.2

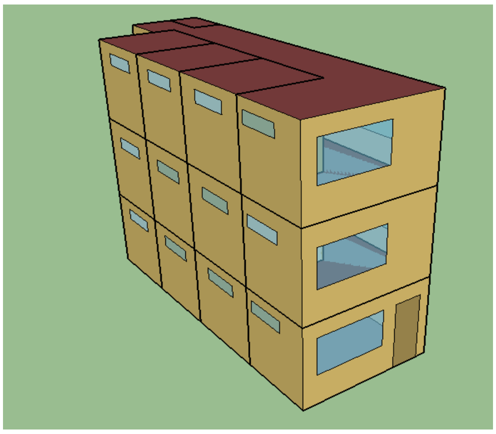
It could be seen that the temperature in both ground floors experience a significant 2 to 3-degree increase, while the top floors only a negligible change. Ground may perform as a cooler with a constant temperature of 23 degrees to cool the ground floor, while the roof of top floor increases the area that exposed to sunlight. These two reasons could account to the temperature difference. A three-floor construction could effectively lower down the air temperature of ground floor (nearly 1 degree), while it cannot cool down the first floor. Therefore, a three-floor building significantly increase the energy consumption of a certain building. A detailed energy consumption results would be shown in phase 4.

Phase 3

In this phase, models are added with internal compartments. With limited air exchange between internal spaces, air in individual compartments would be heated up by surrounding air, sunlight and people inside. An additional pitched roof is added in a new model C, to test if a well-thermal-insulated roof could resist the heat from direct sunlight.



Phase 3 Model A



Phase 3 model B, Pitched roof

Average Air Temperature in Each Zone (Model A)

		June	July
Ground Floor	Living Room	28.96	28.51
	Bedroom 1	28.97	28.53
	Bedroom 2	29.02	28.56
	Bedroom 3	29.11	28.62
First Floor	Living Room	31.06	30.50
	Bedroom 1	31.47	30.86
	Bedroom 2	31.49	30.87
	Bedroom 3	31.21	30.57

Phase 3 Model B

Average Air Temperature in Each Zone (Model B)

		June	July
Ground Floor	Living Room	28.63	28.20
	Bedroom 1	29.45	29.03
	Bedroom 2	30.46	29.96
	Bedroom 3	28.68	28.31
First Floor	Living Room	30.45	29.90
	Bedroom 1	30.79	30.29
	Bedroom 2	30.88	30.36
	Bedroom 3	30.65	30.17
Second Floor	Living Room	30.59	30.02
	Bedroom 1	30.94	30.42
	Bedroom 2	30.95	30.43
	Bedroom 3	30.91	30.40

Average Air Temperature in Each Zone (Model C)

		June	July
Ground Floor	Living Room	28.51	28.08
	Bedroom 1	28.68	28.31
	Bedroom 2	30.46	29.96
	Bedroom 3	28.68	28.31
First Floor	Living Room	30.65	30.09
	Bedroom 1	30.68	30.19
	Bedroom 2	30.87	30.36
	Bedroom 3	30.65	30.17
Second Floor	Living Room	30.90	30.32
	Bedroom 1	30.90	30.39
	Bedroom 2	30.91	30.40
	Bedroom 3	30.86	30.37

It could be noticed that while the ground floor temperature maintains nearly no change between both models, all zones in first floor in model B have lower temperature than that in corresponding zones in model A. Besides, an enhanced roof is shown to have little effect of the air temperature in top floor (less than 0.05 degree decrease). For economic reasons, this enhanced roof solution is given up. Model B with other energy-efficient-options is then tested in Phase 4.

2.3 Modelling the Housing Energy Efficiency Optimisation

Phase 4

Three different solutions are suggested, which are increasing the wall thickness, using insulation materials replacing current ones and changing building orientation.

First, Model B with windows ad internal compartments is simulated. The energy consumption of two months is shown below.

	Total Energy [GJ]
Total Site Energy	7.13

In B_1 test, thickness of all constructions are increased to its 120%. The increased thickness could reduce the heat transfer from outside to inside, lowering down the internal temperature.

Material	Thickness before(m)	Thickness after (m)
Gypsum	0.01270	0.01524
Clay	0.10160	0.12192
Gypsum Board	0.01270	0.01524
Roof Membrane	0.00950	0.01140
Roof Insulation	0.16930	0.20316
Timber Joints	0.01000	0.01200
Slate	0.01270	0.01524
Wood	0.20000	0.24000
Plasterboard	0.01500	0.01800
Poured Concrete	0.30000	0.36000
Metal	0.10000	0.12000
Glass	0.00300	0.00360

	Total Energy [GJ]	Reduction Percentage
Total Site Energy	6.74	5.5%

In B_2 test, materials with 80% of original thermal conductivity are adopted.

Material	Original Conductivity (W/m*k)	80% of original Conductivity (W/m*k)	50% of original Conductivity (W/m*k)
Gypsum	0.1600	0.1280	0.0800
Clay	0.8950	0.7160	0.4475
Gypsum Board	0.1600	0.1280	0.0800
Roof Membrane	0.1600	0.1280	0.0800
Roof Insulation	0.0490	0.0392	0.0245
Timber Joints	0.1400	0.1120	0.0700
Slate	1.5900	1.2720	0.7950
Wood	0.1400	0.1120	0.0700
Plasterboard	0.1700	0.1360	0.0850
Poured Concrete	1.7000	1.3600	0.8500

Metal	0.1700	0.1360	0.0850
Glass	1.0500	0.8400	0.5250

	Total Energy [GJ]	Reduction Percentage
Total Site Energy	6.64	6.9%

To test the potential of reducing energy consumption by choosing lower thermal conductivity material, a 50% conductivity test is the conducted.

	Total Energy [GJ]	Reduction Percentage
Total Site Energy	5.79	18.8%

In test B_3, the orientation is changed to an optimum position which saves the energy most. According to Ecotect and the result from EnergyPlus, the best orientation is 269-degree from north.

	Total Energy [GJ]	Reduction Percentage
Total Site Energy	6.65	6.7%

In Test B_4, combinations of methods are provided.

Combination 1: Thickness of construction increased to 120% and thermal conductivity reduced to 80% of original.

Combination 2: Thickness of construction increased to 120% and thermal conductivity reduced to 80% of original. Orientation changed to optimum position.

Combination 3: Thickness of construction increased to 120% and thermal conductivity reduced to 50% of original.

Combination 4: Thickness of construction increased to 120% and thermal conductivity reduced to 50% of original. Orientation changed to optimum position.

	Total Energy [GJ]	Reduction Percentage
Combination 1 Total Site Energy	6.26	12.2%

Combination 2 Total Site Energy	5.85	17.9%
Combination 3 Total Site Energy	5.46	23.5%
Combination 4 Total Site Energy	5.12	28.3%

From the results, it is reasonable to conclude that an energy reduction of nearly 30% could be a realistic goal at expense of certain investment and careful construction. Considering the cost of low thermal conductivity material, reaching a goal of 50% energy reduction would be unrealistic, which could take a large amount of capital cost and could not be profitable during its lifetime.

Energy consumption could increase significantly once the family turned on air-conditioning in living room.

Since the ground acts as a relatively constant cool reservoir, it is suggested to increase the thermal conductivity of house ground to make use of that.

Notes:

Avoiding direct sunlight could be another method in decreasing energy consumption;

Building up shading device and installing Low-E window could both make contribution;

Installing shading device and thermal conductivity of ground could be B_5 and B_6 but the overall reduction of energy consumption is limited.

References

Bardhan, A., Jaffee, D., Kroll, C., and Wallace, N. (2014) Energy efficiency retrofits for U.S. housing: Removing the bottlenecks. Regional Science and Urban Economics, Vol. 47, pp. 45-60.

Bojic, M., Miletic, M. and Bojic, L. (2014) Optimization of thermal insulation to achieve energy savings in low energy house (refurbishment), Energy Conversion and Management, VOl. 84, pp. 681-690.

Borgeson, M., Zimring, M., and Goldman, C. (2012) The Limits of Financing for Energy Efficiency. Berkeley Lawrence National Laboratory (available at http://eetd.lbl.gov/ea/emp/reports/limits-financing-ee-2012.pdf).

Evins, R. (2013) A review of computational optimisation methods applied to sustainable building design, Renewable and Sustainable Energy Reviews, Vol. 22, pp. 230–245.

Fuentes-Cortes, L. F., Ponce-Ortega, J. M., Napoles-Rivera, F., Serna-Gonzalez, El-Halwagi, M. M. (2015) Optimal design of integrated CHP systems for housing complexes, Energy Conversion and Management, Vol. 99, pp. 252-263.

Gagliano, A., Nocera, F., Patania, F., and Capizzi, G. (2013) A Case Study of Energy Efficiency Retrofit in Social Housing Units, Energy Procedia, Vol. 42, pp. 289-298.

Hamilton, I. G., Steadman, P. J., Bruhns, H., Summerfield, A. J. and Lowe, R. (2013) Energy efficiency in the British housing stock: Energy demand and the Homes Energy Efficiency Database, Energy Policy, Volume 60, pp. 462–480.

Hong Kong Census and Statistics Department (2014) Table 005: Statistics on Domestic Households, from http://www.censtatd.gov.hk/hkstat/sub/sp150.jsp?tableID=005&ID=0&productType=8, Retrieved 10-October-2015.

Ihm, P. and Krarti, M. (2012) Design optimization of energy efficient residential buildings in Tunisia, Building and Environment, Vol. 58, pp. 81–90.

Koo, C., Hong, T., Kim, J. and Kim, H. (2015) An integrated multi-objective optimization model for establishing the low-carbon scenario 2020 to achieve the national carbon emissions reduction target for residential buildings, Renewable and Sustainable Energy Reviews, Volume 49, pp. 410-425.

Morelli, M., Harrestrup, M. and Svendsen, S. (2014) Method for a component-based economic optimisation in design of whole building renovation versus demolishing and rebuilding, Energy Policy, Vol. 65, pp. 305-314.

Roufechaei, K. M., Abu Bakar, A. H. and Tabassi, A. A. (2014) Energy-efficient design for sustainable housing development, Journal of Cleaner Production, Vol. 65, pp. 380-388.

The World Bank (2015) Table 3.1, Data on ‘World Development Indicators: Rural environment and land use’ from http://wdi.worldbank.org/table/3.1, Retrieved 12-October-2015.

Urmee, T., Thoo, S., and Killick, W. (2012) Energy efficiency status of the community housing in Australia, Renewable and Sustainable Energy Reviews, Vol. 16, pp. 1916-1925.

Yao, J. (2012) Energy optimization of building design for different housing units in apartment buildings, Applied Energy, Vol. 94, pp. 330-337.