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To cite this article: Iman Ashraf Asmuni *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **268** 012148

View the article online for updates and enhancements.

A computational analysis of construction – operation – environment cost of real estate development projects

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Abstract. Similar to many highly populated cities in South East Asia, Ho Chi Minh City (HCMC) is the largest city of Vietnam acting as the economic driver for the whole country. Its urban life attractions and economic opportunities have drawn people across the country and the region, resulting in a high demand of housing. HCMC becomes a hot spot for many local and foreign real estate investors and developers. Many property development projects in HCMC have been rapidly increasing in recent years. However, many real estate developers usually pay more attention on profit-related criteria while neglecting sustainable aspects, partly due to lack of knowledge and an appropriate tool. A construction - operation – environment cost analysis workflow based on an urban simulation tool coupled with other scripting and modelling tools is proposed to quantify environmental cost and operational cost besides construction cost for a real estate development project in HCMC. Three alternative design scenarios are derived from a baseline at the early stage of design process originally provided by a developer. Computational analysis from these scenarios on construction cost in comparison to operational and environmental cost provides more information to the investment decision making process allowing the developer not only to meet their investment return expectation but also to take environmental impact and residents' expense during the project's life cycle.

1. Introduction

Among many Asian countries, Vietnam has enjoyed a quite constant economic growth for a long time, resulting in a high urbanization rate which is up to 3.5% per year since 2000. It is projected that by 2040, nearly half of Vietnamese people will live in the urban areas, especially in big cities such as Hanoi and Ho Chi Minh City (HCMC) [1]. High population and urbanization growth have placed a lot of pressure on housing demand of these cities. Annually, house demand has increased about 10% which is equivalent to an additional 394,000 housing units that need to be built every year. However, supply has failed to meet demand, leading to a housing shortage in urban hubs like Hanoi and HCMC [2].

High demand of housing becomes a good opportunity for many local and foreign real estate investors and developers. In recent years, foreign developers' market share has been an upward trend, accounting for about 15% of total units in HCMC [3]. A boom in the real estate market in Vietnam also affects growth of land prices, especially well-located lands with the benefit of infrastructure improvements. Land prices in some places have surged up to 25-40% [4]. High housing demand and land price issues have driven high-rise apartment construction in Vietnam in recent years [3] [5].

When it comes to sustainability aspects, buildings in Vietnam account for 40% of total electricity consumption [6]. Rapid urbanization and economy growth are the main reasons causing an increase in

energy consumption. Total electricity consumption in 2015 was more than 143 Bwh[1] which is double of that in 2010 [6]. Most electricity in Vietnam is from burning fossil oil (natural gas and coal) which is the main source of carbon dioxide and other greenhouse gas emissions into environment [7].

Recently, the shortage of land fund for new property development projects has increased land-related costs. As result, many real estate developers usually pay more attention on profit-related criteria by maximizing construction floor areas (CFA) regulated by a fixed floor area ratio (FAR). Environmental cost like CO_2 emission and operational cost are usually neglected partly due to lack of knowledge and an appropriate tool.

This paper is aimed to demonstrate a workflow of parametric analysis in computing construction cost, environmental cost, and operational cost of a building project. This workflow, developed by the author, is built on the top of a simulation software called Urban Modeling Interface (UMI) developed by MIT, running within in the 3D modeling software named Rhino3D. The workflow uses Python scripting and Grasshopper graphical programming for some calculation processes which proceed in the background. This workflow will then be used to demonstrate on a complex residential building project in HCMC, Vietnam under a certain number of alternative scenarios.

2. Literature review

2.1. Construction cost and building height

A study of the relationship between construction cost and building height by Blackman et al. (2008) surveyed construction costs of residential buildings in Hong Kong and Shanghai and found that construction costs changed with an increase in building height accordingly to a U shape. The study implied that the optimal building height of building in Hong Kong and Shanghai are 12 stories and 8 stories respectively since land size and cost conditions in Hong Kong and Shanghai are different [8].

In Vietnam, a new method proposed by Nguyen et al. (2016) for construction cost estimation with not only building heights but also other parameters such as soil conditions, wind and seismic loads. This study looked at construction of high-rise buildings in Can Tho, a city in Mekong delta and located 300 km away from HCMC [9]. The Vietnam government issued financing guidance of construction project funding of different building types for state-funded projects, dictating investment unit cost and construction unit cost based on building types and building heights. Private-funded projects can also use this for reference [10]. The relationship between construction unit cost and building height of residential projects is shown in Figure 1. For its simplicity, the quadratic regression equation will be used to calculate construction costs in this study.
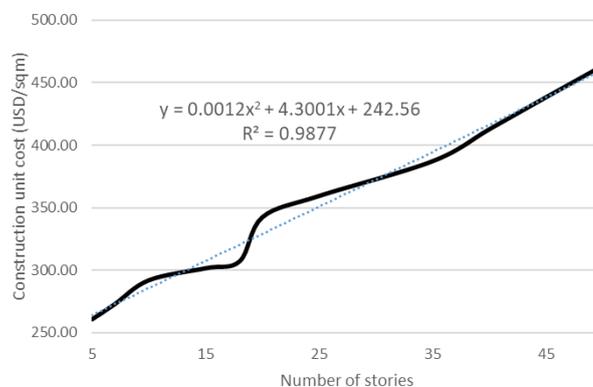
Figure 1. Construction unit cost versus building height of residential projects [10]

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[1] billion watt hour (10^9wh)

2.2. Environmental cost

Buildings consume a lot energy throughout their lifespan stages from construction to demolition. Total energy associated with buildings during their lifespan of 50 to 100 years is called embodied energy. Embodied carbon emission, which is a measure of greenhouse gas (GHG) emission during a lifecycle of buildings, is highly correlated to energy consumption during material production [11].

Ecological cost or Eco-cost, a term introduced by Dr. Ir. Joost G. Vogtländer (2010) at Delft University of Technology, is an economical measurement for combining all issues of human health, ecosystems, resource depletion and global warming [12]. Kaspersen et. al (2016) studied environmental cost in terms of GHG emissions (or CO_2 emission) of buildings according to building height. They found that the relationship between CO_2 emissions and building height only depends on the complexity of technical systems of a building whose building height is less than 12 floors. For higher buildings, CO_2 emission impact on building height is negligible regardless of their technical installations [13].

2.3. Operational cost

Operational cost is related to energy consumption during operation stages. Throughout a building's lifespan, the operational cost accounts for 80-90% of total the building's overall energy use [14]. Xu et al. (2017), in comparing energy consumption of residential buildings with different height, found that the energy consumption per area unit does not rely on building height but the insulation quality of those buildings [15].

Jalayerian (2016) used building data from the Commercial Buildings Energy Consumption Survey (CBECS) database to compare against predicted building performance of energy models at varying building heights. His findings were that building energy consumption is optimized at a building height between 40-50 floors. Buildings taller than 50 floors consume more energy for the additional mechanical systems and vertical transportation, resulting in decline in energy performance [16].

CIBSE (2015) indicates that vertical transportation constitutes 3-8% of the overall building energy consumption [17]. In European countries, lifts consume about 4% building electricity [18] and in densely populated Asian cities like Hong Kong where high-rise buildings are indispensable, lift operation for high-rise commercial and residential buildings contributes 7%-15% of electricity use [19].

In order to formulate an equation for predicting energy consumption of vertical transportation in high-rise buildings, Schroeder (1986) proposed a general equation which is based on lift motor rating in kw, number of starts per day and typical trip. However, this method is only applied for buildings with less than 18 story height [20]. Bannister et al. (2011) empirically predicted lift energy consumption of buildings in correlation to four significant factors like occupied net floor area (NFA), lift floors, building heights and lift technology [21]. Predicted annual lift energy (kwh) is calculated as following formula:

$$Annual\ lift\ energy\ (kwh) = [28 \times Lift\ Floors + 5.47 \times NFA(m^2)] \qquad (1)$$

This study uses this equation for lift energy consumption which is added into total building energy consumption. Lift Floor can be calculated from a building's stories and lift number. Lift number is assumed that each lift car serves for every 40 units or 3,200 square meters of NFA, referring to Circular No. 31/2016/TT-BXD – the classification and recognition of Vietnam apartment buildings [22].

3. Methods

The methodological framework of the study can be summarized into the following steps:
1) Introduction of a workflow for parametrically predicting construction cost, environmental cost and operational cost of a construction project using energy urban modeling tool called UMI [23].
2) Parametric study of a single building with different shading scenarios by adjacent buildings.
3) Demonstration of three alternative design scenarios of a residential project targeting the maximum CFA (construction cost, thus expected profit) while meeting the low operational cost and environmental cost.

3.1. A workflow of for predicting construction cost, environmental cost and operational cost

The workflow consists of four steps: (1) construction of building blocks with parametric massing and assigning building templates; (2) parametric simulation with UMI; (3) simulation data extraction; and (4) post processing. These four steps were scripted under a Grasshopper graphical scripting environment and shown in Figure 2.

The workflow is built on the top of the Urban Modeling Interface (UMI). UMI is a Rhino3D-based modeling tool for evaluating environmental performance in terms of operational, embodied energy, daylighting availability and other social measures such as mobility of a neighbor or city-scale projects. It was developed by the Sustainable Design Lab at the Massachusetts Institute of Technology (MIT) [23]. Underlying UMI are two open source simulation engines called Energy Plus and DAYSIM. Energy Plus is a whole building energy simulation software developed by the U.S. Department of Energy while DAYSIM is a Radiance-based daylighting analysis software [24].
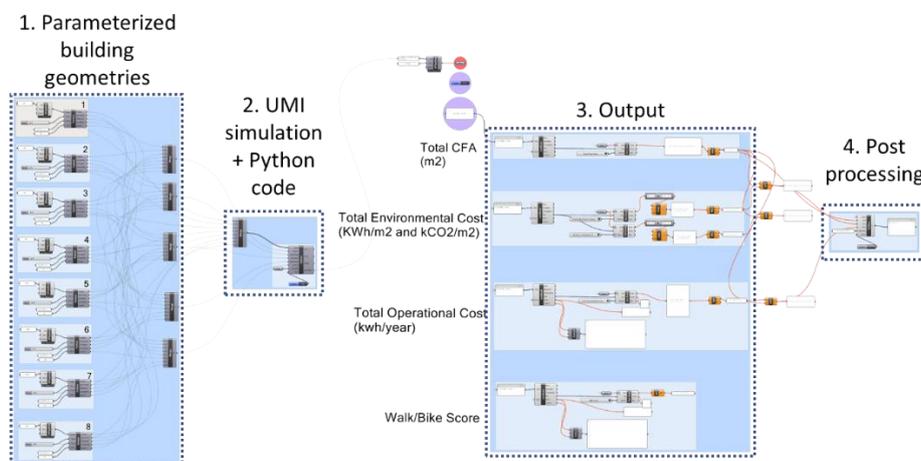
Figure 2. Grasshopper definition of the workflow

3.2. Parametric studies of a single building with different adjacent shading scenarios

The workflow is first used to test on a single building under different adjacent shading scenarios. The building has a footprint of 20 m x 50 m and parametrically modelled with building height ranging between five and 50 stories (4-m floor-to-floor height). Adjacent blocks are fixed in size but their locations and orientation to the study building creates different two shading scenarios (Figure 3): East-West adjacent blocks and North-South adjacent blocks.
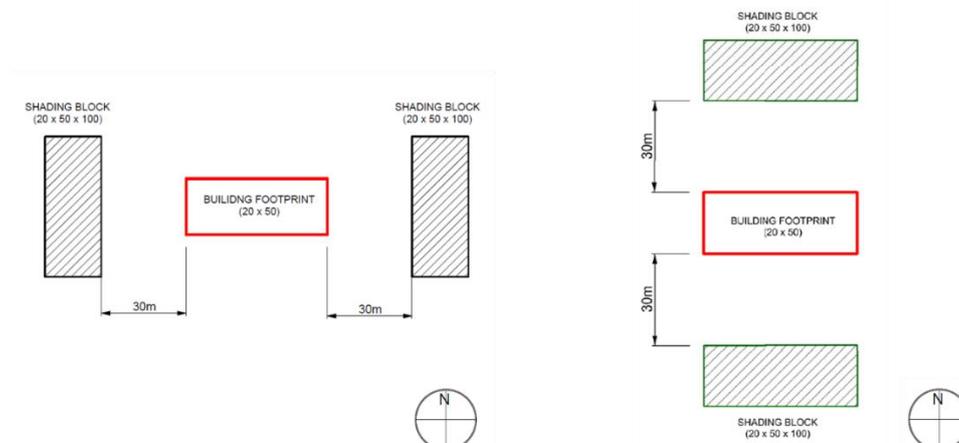
Figure 3. Two shading layouts: East-West adjacent blocks and North-South adjacent blocks

3.3. Studies of three alternative design scenarios of a complex residential project

3.3.1. Site conditions

A complex residential project is required to develop high-rise social apartments for low-income people in Ho Chi Minh City, Vietnam (Figure 4). The site is located in a currently residential neighbourhood with adjacent buildings having heights ranging from 12 to 30 stories (30 – 100 m).

Figure 4. Residential project location in Ho Chi Min City

The site has three zones whose total land areas are 56,500 m^2 (Figure 5). There are 12 blocks with a fixed building footprint, accounting for the maximum land coverage ratio of 30%. The maximum floor area ratio (FAR) is limited to 4.5 times which means the total construction floor area (CFA) of the entire project should not exceed four folds and a half of the land area. In reality, real estate developers always want to maximize the FAR for investment return. Thus, in the complex residential project, three scenarios have the FAR of 4.5. Scenario 1 has all buildings with the same height of 15 floors. The other two scenarios are more interesting in design with varying building heights. Scenario 3 is the most extreme in height ranging from nine to 35 stories while Scenario 2 is in the middle having buildings' height ranging from 10 to 25 stories.
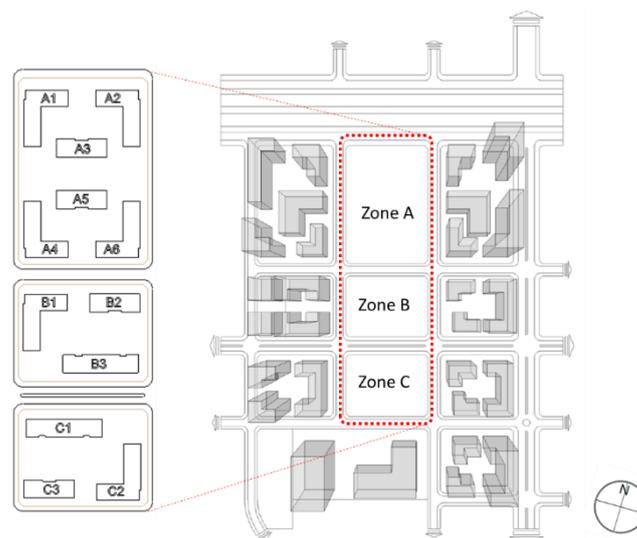
Figure 5. Project site with adjacent buildings and building footprint with labels

3.3.2. Climatic data and internal loads

All UMI models were simulated using the TMY3 (Typical Meteorological Year 3) weather data of HCMC, Vietnam. The internal loads of typical residential buildings were defined in Table 1:

Table 1. Building internal loads

Load type	Value	Unit

Occupancy density	0.025	person/m^2
Equipment power density	4	w/m^2
Lighting power density	7	w/m^2
Heating setpoint	20	℃
Cooling setpoint	24	℃
Cooling COP	3	
Infiltration rate	0.35	ACH

3.3.3. Geometric building parameters

For buildings' geometrical parameters such as window-to-wall ratio (WWR) and floor-to-floor height were set as shown in Table 2. Other detailed parameters in the advanced setting section were left default for simplification and consistency.

Table 2. Buildings' geometrical parameters

Building parameter	Value
Window-to-wall ratio (North)	40%
Window-to-wall ratio (South)	40%
Window-to-wall ratio (East)	40%
Window-to-wall ratio (West)	40%
Floor-to-floor height	4m
Core depth	3m
Room width	3m
Perimeter offset	3m

3.3.4. Energy-related construction parameters

Energy-related building parameters are defined in the building template which consists of typical building construction material properties such as thickness, thermal conductivity, density, embodied energy, embodied CO_2, transportation energy, and transportation CO_2, etc. The assigned construction type is typical reinforced concrete structure with masonry walls which is widely used for residential projects in Vietnam. A summary of energy-related construction assembly parameters based on the construction material properties is shown in Table 3.

Table 3. Thermal resistance (R-value) and environmental data (CO_2, energy during manufacturing and transportation) of building construction assemblies

| Construction type	Thermal Resistance (m^2.K/w)	Embodied Carbon (kgCO$_2$)	Embodied Energy (MJ)	Transportation Carbon (kgCO$_2$)	Transportation Energy (MJ)
Façade	2.06	32.15	455.83	6,976.38	97,877.50
Ground floor	0.71	145.45	1,490.52	18,313.11	256,930.20
Partition	0.25	13.10	189.60	1,538.32	21,582.40
Roof	3.25	22.95	375.09	1,798.28	25,229.60
Slab	0.30	137.19	1,422.49	17,381.81	243,864.20
Window *(Solar transmittance 0.83 and Visible transmittance 0.89)*	0.25	75.90	1,441.50	502.50	7,050.00

3.3.5. Elevator energy

Elevator energy use in high-rise buildings is quite substantial but no whole energy building simulation tool takes vertical transportation activities into account. the calculation of operational energy consumption by whole energy building tools has discarded a considerable amount of energy consumption from these types of activities in high-rise buildings. As mentioned in Section 2.3, operational energy consumption of high-rise buildings in this study includes elevator energy consumption using the equation (1).

4. Results

4.1. Single building case:

Building height rise accelerates construction cost but decrease the building embodied energy shown in Figure 6. The optimal building height is between 20 and 25 stories (70 m and 90 m). To compare annual operational cost in cases of different shading from adjacent blocks, energy use intensity (EUI) is converted from annual total energy use per one square meter of total building area. Building without any shading adjacent block has the highest EUI. When shading adjacent blocks are in place, shading from East and West sides is more effective than that from South and North (Figure 7).
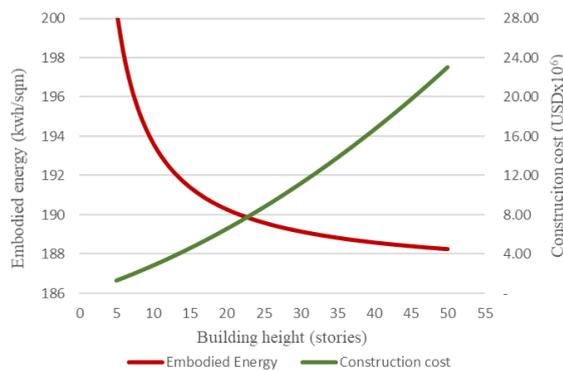
Figure 6. Building embodied energy (kwh/sqm) and construction cost (USDx10^6) versus building height

Figure 7. EUI versus building height at different shading scenarios

4.2. Complex residential project case:

As three scenarios have slight variation of CFA (±0.2%), all presented results are normalized with adjustment of those variations. Results from three design scenarios with varying building heights show that lift energy consumption is about 5% of total building energy consumption. Building height clearly contributes to percentage variation of energy use for vertical transportation over total building energy use. A detailed calculation of lift energy use is shown in Table A1. The scenario 3 which maximizes building height in the design has the highest percentage (5.8%) among the three (Table 4).

Table 4. Predicted annual building energy consumption and lift energy consumption.

	Building energy consumption (kWh)	Lift energy consumption (kWh)	Percentage (%)
Scenario 1	31,693,000.00	1,608,507.23	5.1%
Scenario 2	32,280,000.00	1,681,574.18	5.2%
Scenario 3	30,516,000.00	1,775,903.86	5.8%

Construction cost, EUI, annual embodied energy and annual embodied emission of three design scenarios are presented in Table 5. Economically, scenario 1 meets the economic target with the lowest

construction unit cost while scenario 3 has the highest construction unit cost (Figure 8). In terms of sustainability, scenario 1 has the lowest embodied energy and embodied emission in comparison to those of the other two. Since embodied energy is linearly correlated with embodied emission, only embodied energy is compared to EUI at three different design scenarios (Figure 9). Scenario 3 has the lowest EUI while the highest EUI is found at scenario 2.

Table 5. Construction cost, EUI, embodied energy and annual embodied emission of three scenarios.

	Total Construction Floor Area (CFA) (sqm)	Averaged Construction unit cost (USD/sqm)	Energy Use Intensity (EUI) (kWh/sqm)	Embodied energy (kWh/sqm)	Embodied emission (kCO$_2$/sqm)
Scenario 1	251,742.97	307.33	132.28	190.84	2,732.28
Scenario 2	252,030.66	316.71	135.06	190.97	2,734.06
Scenario 3	251,506.36	330.55	128.15	191.14	2,736.68
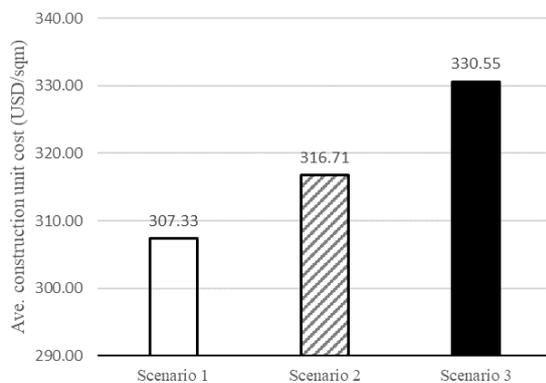
Figure 8. Construction unit cost (USD/sqm) at three different scenarios
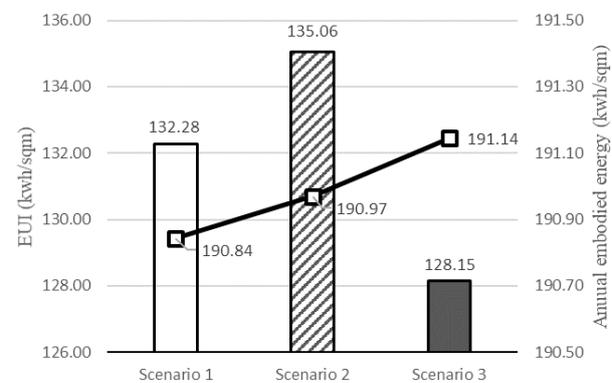
Figure 9. EUI (kwh/sqm) versus annual embodied energy (kwh/sqm)

5. Discussion

The single building case reveals that shading effect from adjacent blocks takes an important role in energy consumption in high-rise buildings. Unsurprisingly, EUI of a building that receives shade from East-West side is lower than that of one protected by blocks from North-South side. The EUI curves are flattened when the buildings are getting as high as the adjacent blocks which have the height of a 30-story building or about 100m. Thus, shading design should be well-considered for adversarial orientations like East and West or when building height reaches beyond sun light protection from adjacent buildings.

In the complex residential project, a design with less variation of building heights is economical. The design with the same building height saves a real estate developer with the lowest averaged construction cost unit but this might not be the best choice in terms of requirement of pleasant and attractive views as well as environmental and operational cost.

Embodied energy is relatively consistent with construction cost unit as Scenario 1 has both the lowest construction cost unit and the lowest embodied energy. Embodied energy decreases as building height rises. While this relationship cannot be proved from the literature review, it can be explained from the simplified 3D modelling of buildings for simulation. The ratio (S/V) of building surface (S) over building volume (V) might contribute to the relationship between embodied energy and building height. In cases of Scenario 2 and Scenario 3, the reduction of embodied energy from taller buildings cannot compensate for the increase of that of all shorter buildings.

An increase in building height clearly increases vertical transportation, thus lift energy consumption. However, when looking at the overall performance of the whole project, the averaged EUI is the lowest with the Scenario 3 in which it has tallest buildings in comparison to that of other scenarios. The savings are due to shading effects from adjacent buildings and buildings themselves of the project. In Scenario 3, few tall buildings might have high EUI (both operation and lift energy) but savings from many other shorter buildings within the shading protection range of adjacent buildings help to reduce EUI of the entire project.

6. Conclusion

This study introduces a workflow for parametric simulation of construction cost, environmental cost and operational cost of a residential project. The workflow developed under Rhino3D modelling software, Python scripting, Grasshopper graphical scripting and coupling with Urban modelling Interface (UMI) tool is implemented on a complex residential project with different design scenarios, providing their prediction to not only construction cost but also environmental cost and operational cost for better consideration. Construction cost is an important factor of projects' investment return for a residential project but environmental cost and operational cost should be equally carefully considered for the sake of the environment and residents' expense during the whole project's life cycle. This workflow demonstrate its ability to provide with better information, helping the project's stakeholders, like developers, clients, and designers make better decisions in a real estate project development.

Appendix A

Table A1. Estimation of annual lift energy use

Block Name	CFA (sqm)	Scenario 1		Scenario 2		Scenario 3	
		Height (stories)	Annual lift energy consumption (kWh)	Height (stories)	Annual lift energy consumption (kWh)	Height (stories)	Annual lift energy consumption (kWh)
A1	1601.12	15	152,617.48	10	91,184.99	9	82,066.49
A2	1601.12	15	152,617.48	10	91,184.99	10	91,184.99
A3	1024.29	15	98,914.71	25	204,457.85	10	60,663.14
A4	1601.12	15	152,617.48	21	235,840.48	10	91,184.99
A5	1024.29	15	98,914.71	25	204,457.85	10	60,663.14
A6	1601.12	15	152,617.48	21	235,840.48	10	91,184.99
B1	1601.12	15	152,617.48	15	152,617.48	29	371,620.47
B2	1024.29	15	98,914.71	15	98,914.71	35	323,200.99
B3	1539.48	15	148,571.74	10	88,487.83	29	363,798.70
C1	1539.48	15	148,571.74	10	88,487.83	10	88,487.83
C2	1601.12	15	152,617.48	10	91,184.99	10	91,184.99
C3	1024.29	15	98,914.71	15	98,914.71	10	60,663.14
			1,608,507.23		**1,681,574.18**		**1,775,903.86**

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