Assessment of energy and economic performance of office building models: a case study

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Abstract. Energy consumption of building accounts for more than 37.3% of total energy consumption while the proportion of energy-saving buildings is just 5% in China. In this paper, in order to save potential energy, an office building in Southern China was selected as a test example for energy consumption characteristics. The base building model was developed by TRNSYS software and validated against the recorded data from the field work in six days out of August-September in 2013. Sensitivity analysis was conducted for energy performance of building envelope retrofitting; five envelope parameters were analyzed for assessing the thermal responses. Results indicated that the key sensitivity factors were obtained for the heat-transfer coefficient of exterior walls (U-wall), infiltration rate and shading coefficient (SC), of which the sum sensitivity factor was about 89.32%. In addition, the results were evaluated in terms of energy and economic analysis. The analysis of sensitivity validated against some important results of previous studies. On the other hand, the cost-effective method improved the efficiency of investment management in building energy.

1. Introduction

According to the announcement of ASHRAE Handbook HVAC Applications, building sector is responsible for more than 40% of the global end-use energy consumption [1]. As the second largest building energy user around the world, China ascends first in residential energy consumption and ranks third in commercial energy consumption [2]. The final energy consumption in Chinese buildings grew by 37.3% in 2015; if this trend continues, the energy use could increase by 70% in 2050 [3-5].

Kelly [6] reported that 33% of all global carbon emission could be attributed to existing buildings.

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It is broadly recognized that conducting cost-effective retrofits on buildings exerts it crucially to achieve the goals of green buildings; this is due to the large ratio of existing buildings to new constructions [7, 8]. Additionally, functional reform or more stringent energy-efficiency standard embraces the retrofitting market of building energy conservation. For instance, the "Green Building Action Plan" released by the Chinese central government stated that the total floor area of retrofitting existing buildings will reach 570 million square meters by 2015 in China [9, 10]. Therefore, it is significant to enhance the existing buildings' energy efficiency.

Technology and management are the vital impact factors that influence the effectiveness of building energy retrofitting [11]. As to technology aspects, reference literatures in the related area were concerned about the thermic insulation materials, the windows replacement and thermal performances [12-15]. Different building environmental assessment tools by occupants or life cycle phases of buildings were also analyzed in literatures [16, 17]. Many of the studies were based on theoretical calculation. Additionally, the simulation-based integration of dynamic calculation and experimental studies guarantees the possibility of model-checking and the accuracy of further simulation, and TRNSYS is one of the appropriate tools [18]. As to the management aspects, the application of energy-saving measures (ESMs) usually needs to be supported by economic assessments. Gero et al. [19], for example, proposed a multi criteria model and explored the trade-offs between the building thermal performance and capital cost of the building. Goodacre et al. [20] applied a cost-effective method to assess the potential scale of the benefits from upgrading heating and hot-water energy efficiency in English buildings. A desired efficiency label at the minimum cost with the multi-objective optimization method was also obtained in literature [21]. Terés-Zubiaga et al. [22] employed different envelope retrofitting methods and evaluated the results under an economical NPV approach.

However, although the methods of envelope retrofitting have been extensively studied, there is little information available about the sensitivity of energy saving in office building envelopes in Southern China simulated by TRNSYS; and literature about the economic way of evaluating the retrofits in office building energy is still insufficient in Southern China. In this study, 27 combined methods have been applied with TRNSYS software to enhance the office building envelope. These measures are exterior wall insulation, infiltration repairs and windows replacement. Some important contributions of this paper have been found, including that the daily energy demand has been well recorded for the usage of model checking. On the other hand, unlike the traditional retrofits, the sensitivity factor of the envelope that signifies the capacity of energy saving in different parameters has been applied, playing a key role in combining diverse ESMs. Moreover, these combined scenarios' results are evaluated under an economic and energy analysis, which could be useful for the future building retrofitting practices and the policy making.

2. Methodology: case study selection

In this study, a multi-office building named Jicheng Mansion (JCM), which is located in Tianhe District of Guangzhou, China, was selected as the reference building. The building was constructed in 2003, a specific period in which a significant number of similar office buildings had been built up before legislative acts on energy efficiency was carried out.

The 10-storey building has a net floor area of 612 m², of which the overall floor area is 6120 m². The ceiling height of JCM is 33.6 m, and the window-wall ratio is 0.3. The construction is mainly consisted of reinforced concrete.



Figure 1. General view of JCM.

3. Monitoring

In sure of obtaining data to calibrate the building simulation model, the reference JCM building has been monitored. The four external walls of JCM oriented to the main four directions: South, West, North and East. Obviously, there are three zones in each floor, i.e., a storage room with two toilets, a workplace and a staircase with an elevator. The Workplace is the thermal zone, with a net floor area of 456 m². The building outline is depicted in Figure 2.

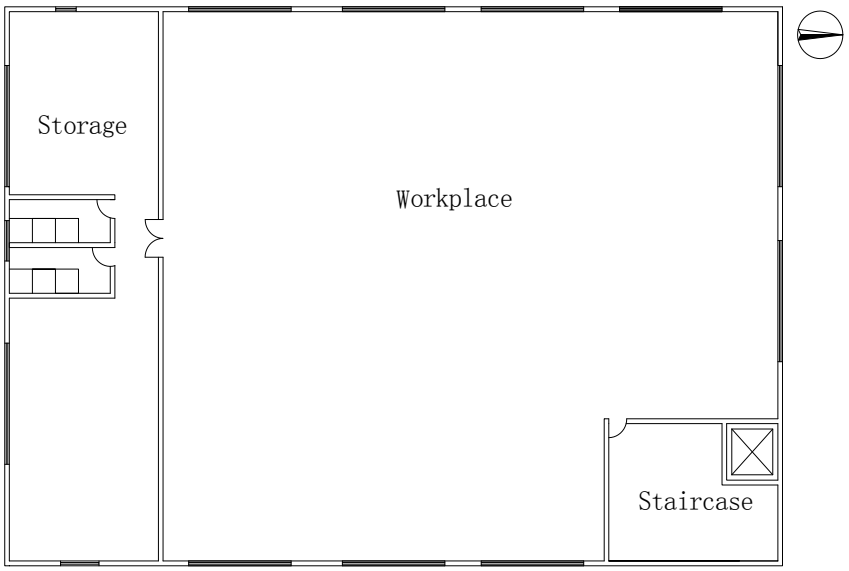


Figure 2. Layout of the studied building

Figure 2 shows the outline of each floor. As to Workplace, the south wall is an interior wall without solar heat gain. The office building is equipped with the central air-conditioning system. Southern China is located in a subtropical area, and the refrigeration season is yearly from May to November, thus cooling demand is solely concerned in this case. Due to the rated refrigerating capacity of the system, the chiller supplies cooling load for seven floors, and the 1st, 5th and 9th floors are not equipped with air conditioners.

The data of the inlet water temperature, outlet chilled water temperature and flow rate of chilled water has been well recorded from the field work in order to calculate the cooling load of the building. Detailed information on sensors' characteristics is presented in Table 1.

Table 1. Characteristics of the used sensors.

Parameter	Units	Sensor	Uncertainty
Temperature	K	SIN-RC-4HC/A	±0.50 K
Flow rate	m³/h	LDG-MK	±0.04 m³/h

The data has been integrated in a 10-minute frequency for the stable measurement of the JCM building energy consumption, and the accuracy of the obtained data is well guaranteed.

4. Model definition and validation

4.1 Building model definition

The building model has been developed by TRNSYS software. The first step is to set up a building model in TRNSYS with the actual JCM construction data; the second is to define the thermal parameters of the building and the operation schedule of the building; and the final procedure is to calculate the dynamic energy consumption with the TRNSYS simulation studio. The Workplace is defined as a thermal zone in which the temperature is set as 26 ℃. The internal heat gains are set as

follows: a person occupancy density is 20 W/m^2, an equipment load is 16 W/m^2 and a lighting load is 11 W/m^2. The building system operated on a 5-day week basis of which the work schedule is between 9am and 5pm. Moreover, the detailed description of the related envelope data constructed in TRNSYS model is presented in Table 2, and the main characteristics of windows are described in Table 3.

Table 2. Detailed construction data.

Envelope	Thickness [m]	Conductance [kJ/(h·m·K)]	Capacitance [kJ/(kg·K)]	Density [kg/m^3]
WALL (exterior walls)				
Fiberglass quilt	0.002	0.144	0.84	12
Gas_concrete	0.18	1.04	1	800
Fiberglass quilt	0.002	0.144	0.84	12
Exterior walls U-Value	1.120 W/(m²·K)			
Floor (roof and floors)				
Roof deck	0.06	0.504	0.9	530
Poly_urethane	0.01	0.11	1	40
Gas_concret block	0.08	0.97	1	700
Roof U-Value	0.831 W/(m²·K)			

Table 3. Windows constructed in TRNSYS model.

Frame (%)	U_{frame} [W/(m²·k)]	Glass	U_{glass} [W/(m²·k)]
15	3.06	Single	5.16

4.2 Building model validation

As mentioned above, the data of temperature and flow rate had been gathered from six days out of August and September, 2013. The selection of this period is according to its representativeness of the torrid weather conditions, during which the operation status of refrigerating unit is relatively typical. The basic setting of the simulated model is introduced in Table 4, in which the parameter of "vol" represents for the volume of Workplace. Meanwhile, the ventilation rate of the building is calculated by the function: 2*TIME, and the parameter of "TIME" is related to the work schedule of which the value is set as follow: from 8:00am to 9:00am is 0.5, from 9:00am to 12:00pm is 0.95, from 12:00pm to 14:00pm is 0.8, from 14:00pm to 17:00pm is 0.95.

Table 4. Parameters simulated in the model.

Parameters	Workplace
Infiltration (from outdoors) [vol/h]	2
Ventilation [vol/h]	2*TIME

To ensure the degree of accuracy, simulated results are validated by the measured electricity data which is demonstrated in Figure 3.

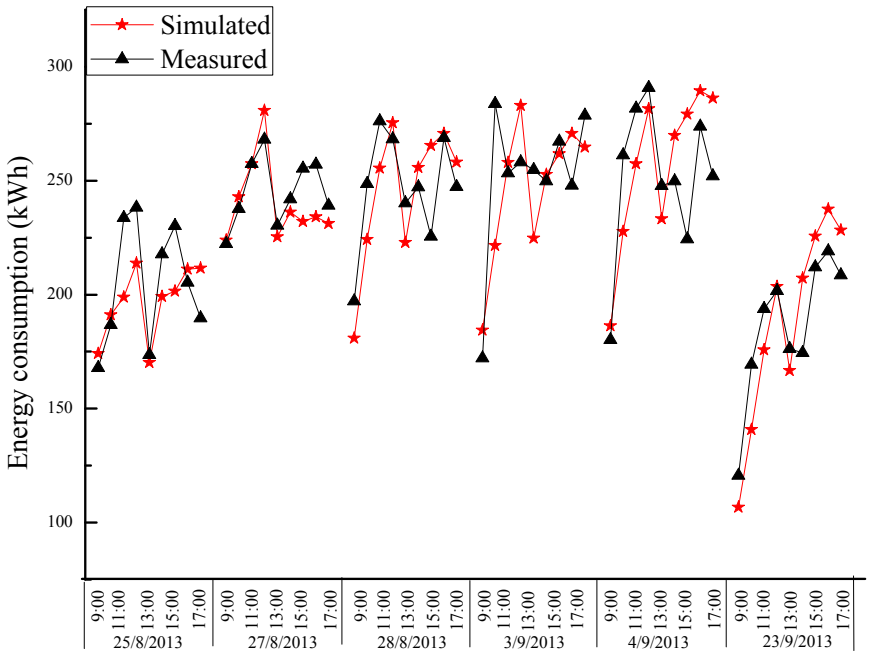


Figure 3. Simulated versus measured energy consumption.

The calculated values are likely to keep in pace with the measured energy consumption of the office building.

To quantify the differences, the percentage error and NMBE are calculated by equation (1):

$$\begin{cases} PE = \dfrac{x_i - y_i}{y_i} \\ NMBE = \displaystyle\sum_{i=1}^{n} \dfrac{x_i - y_i}{y_i} \end{cases} \quad (1)$$

where PE is the percentage of error between simulated and measured energy consumption, NMBE is the normalized mean bias error, x_i is the simulated electricity consumption (kWh), y_i is the measured electricity consumption (kWh) and n is the simulation hours. The result of percentage error is depicted in Figure 4.

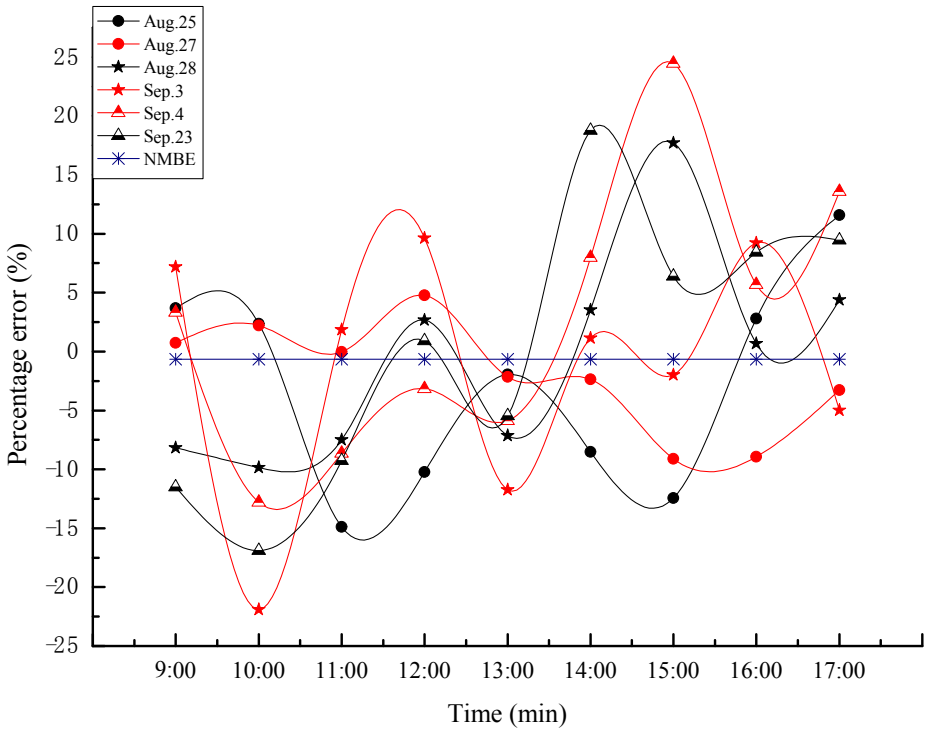


Figure 4. Simulated versus measured percentage error.

Refer to the simulated research on office buildings from J. Terés-Zubiaga and J. Yoon [22, 23], the usual practice should be to follow the criteria set by established professional standards [24, 25], and normalized mean bias error (NMBE) between simulated and measured energy consumption should not exceed ±5%.

As shown in Figure 4, the NMBE is -0.66%, which is within ±5% and thus the simulation model is reliable. The model accuracy is considered to be good in view of these results, and the simulation model turns out to be believable.

5. Sensitivity analysis of building envelope

After the validation of the model, the sensitivity of building envelope has been analyzed in order to indicate how sensitive the simulated output would be in response to changes made to the input parameter.

The sensitivity factor, denoted as IC, is essentially a ratio of the percentage change (with respect to the base case value) [26], as suggested in Eq. (2):

$$IC=\frac{OP-OP_{bc}}{OP_{bc}} \div \frac{IP-IP_{bc}}{IP_{bc}} \qquad (2)$$

where OP and IP are values of corresponding output and input, OP_{bc} and IPbc are base case values of

output and input respectively. IC is essentially a ratio of the percentage change (with respect to the base case value) in computed output (i.e., total annual energy consumption) to the percentage change in input design parameter.

Based on the aforementioned equation, the relative sensitivity has been worked out, as shown in Figure 5.

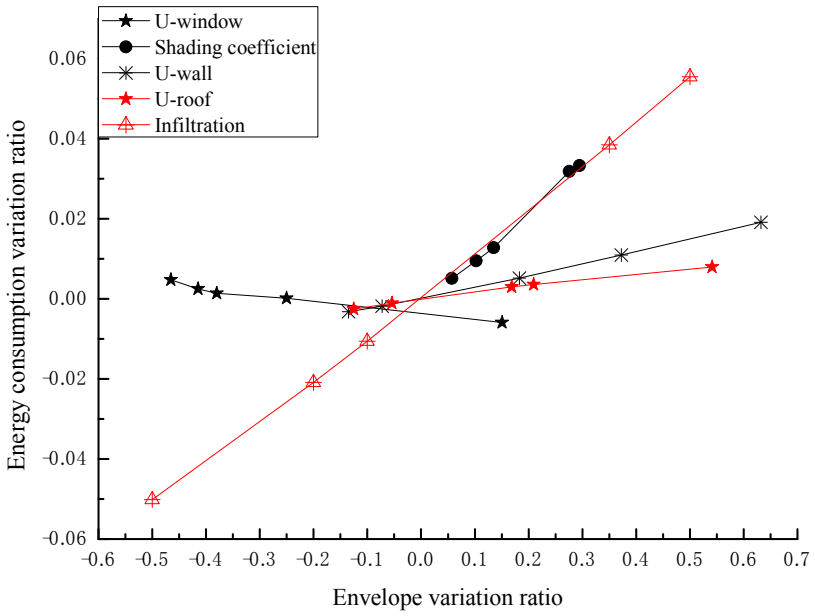


Figure. 5 Envelope sensitivity.

As Figure 5 illustrates, the slope of the linear regression signifies the sensitivity factor of the parameter [26].

The relative sensitivity, ω_i, is denoted as the quotient of the single sensitivity factor to the sum sensitivity of all parameters, as shown in Equation (3):

$$\omega_i = \frac{|IC_i|}{\sum_{i=1}^{n} |IC_i|} \tag{3}$$

where n is the amount of parameters.

The results are clearly summed up in Table 5.

Table 5. Envelope sensitivity factor and relative sensitivity.

Number	Parameter	Sensitivity factor	Relative sensitivity
1	Shading coefficient	0.1234	42.59%
2	Infiltration	0.1062	36.67%
3	U-wall	0.0291	10.06%
4	U-roof	0.0158	5.46%

5	U-window	-0.0151	5.22%

Table 5 indicates that the most effective impact factor of energy consumption is the shading coefficient. Southern China is located in a humid subtropical zone with durable insolation, thus the shading coefficient could pose significant impacts in energy consumption. The infiltration rate directly impacts building energy consumption, depending on the tightness of building enclosure. The most insensitive parameter lies in the U-window, because of the small ratio of window-wall and the particular location of building. Due to the low rate of the roof to wall, the heat-transfer coefficient of the roof exerts less influence than the wall in energy consumption. Indeed, different energy-saving measures can be fully analyzed with the comprehensive consideration of these aspects discussed above. The individual sensitivity could help building designers get some idea about the potential energy savings of prospective ESMs.

6. Energy saving measures of envelope

The ESMs for improving the building energy efficiency could be studied based on the results mentioned above. The sum relative sensitivity of U-window and U-roof are 10.68%, far less than the other factors. Therefore, the intensive ESM should focus on the enhancement of exterior walls, infiltration rate and shading coefficient. Additionally, the exterior walls are enhanced with the EPS, a common engineering insulation material with low thermal conductivity. The infiltration rate is repaired with the building glue. The shading coefficient is enhanced through the method of windows replacement; the windows are replaced with insulating glass windows of lower solar heat gain coefficients. Namely, economic results presented in this paper would be applicable.

According to the assumption given by Terés-Zubiaga et al. [22], three scenarios are proposed in this study: scenario 0, when no thermal improvement is carried out; scenario 1, when the building is slightly improved; scenario 2 when a highly improvement is conducted. The resulted models are named according to the combinations of the ESM adopted in each case. Thus, model (1 2 0) represents exterior wall scenario 1, infiltration rate scenario 2 and shading coefficient scenario 0.

It is assumed that the costs in each scenario are the material costs, other costs (e.g. scaffolding) are assumed to exist in the maintenance work of the building and are not taken into account of the calculations.

The detailed information about ESM is described in Table 6.

Table 6. Summary of data regarding ESM in exterior walls, infiltration rate and shading coefficient.

ESM in Exterior walls	Addition of EPS in walls		
	Currently	Slightly improved	High standard
Scenario	0	1	2
Thermal ins thickness [cm]	0	4	10
U[W/(m²·K)]	1.12	0.489	0.265
Total investment [Yuan]	0	10817.28	29797.72

ESM in Infiltration rate	Infiltration improvement		
	Currently	Slightly improved	High standard
Scenario	0	1	2
U[Vol/h)]	2	1.5	1.0
Total investment [Yuan]	0	26761.51	53723.42
ESM in Shading Coefficient	SC improvement		
	Currently	Slightly improved	High standard
Scenario	0	1	2
SC Value	0.78	0.55	0.23
Total investment [Yuan]	0	47754.72	96305.35

Table 6 reveals the detailed information of ESM. In the case of exterior walls, infiltration rate and shading coefficient, costs assumed in scenarios 1 and 2 are actually compared with scenario 0. Obviously, the investment is in positive correlation to the standard of retrofits.

7. Results

After the validation of the model, the simulation has been operated under 27 scenarios. The assumed operating conditions are based on the actual work schedule. Using a 1-hour time step, the simulation runs with TRNSYS software (Note: in the analysis, the input data are same as the typical values given in Tables 2, 3 and 4, except the parameter whose effect is discussed varies.). The cooling load is depicted in Figure 6.

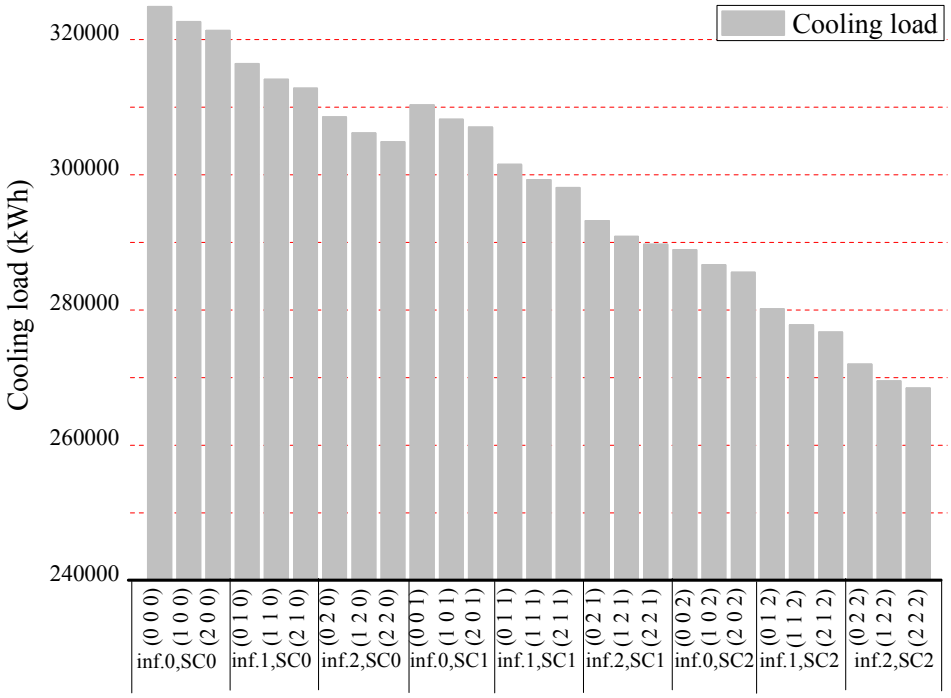


Figure 6. Simulated cooling load.

As Figure 6 illustrates, it is ascertainable that when enhancing the envelope gradually, the amount of cooling loads will decrease accordingly. The biggest amount of cooling load is the reference building (0 0 0) that climbs up to 324.8 MWh per year. The smallest amount of cooling demand is the all-high-standard enhanced building (2 2 2), which consumes 268.4 MWh.

The energy-saving ratio is the energy demand reduction compared to the reference scenario (0 0 0). As a result, the ratios range from 0.69% to 17.37%. The most energy-efficient method owns to the all-high-standard enhanced building (2 2 2), which saves about 17.37% of the cooling demand with respect to the reference case.

8. Discussion

The influence of exterior walls, infiltration rate and shading coefficient on the energy demand has been analyzed in detail. On the other hand, the application of ESM usually needs to be supported by the economic evaluation. Net present value (NPV), payback period and profit rate [23] are chosen as financial elements to analyze the economic feasibility of these measures. Payback period is denoted as the period of time that is required to repay the cost of the initial investment. The profit rate is the rate of NPV to initial investment. At the same time, the NPV sums the initial capital investment and the present net cash flows over the lifespan of the building. No maintenance costs are assumed in this

study, the only cash flow existing there is the yearly-savings. Therefore, NPV is calculated as Equation (4):

$$\begin{cases} \mathrm{NPV} = -I + \sum_{n=0}^{\mathrm{LS}} \frac{S_n}{(1+r)^n} \\ S_n = S_0(1+p)^n \end{cases} \tag{4}$$

As the formula expresses, I is the initial investment, LS is the lifespan of the building and n is the time period, S_n is the savings of the year n and S_0 is the initial savings, r represents the cost of capital (%) and p is the increase rate of energy cost (i.e., the increase cost of natural gas or electricity). An investment should be undertaken only when the NPV is greater than 0, and the best solution comes to the highest NPV scenario in a fixed lifespan.

Different r values (4-8%) were assumed in [27]. In a brief premise, the cost of capital and the increase rates in this project are taken to be 4% in these scenarios, because each studied region could analyze the NPV according to the specific economic data of the actual p and r values. The lifespan of JCM building is about 30 years.

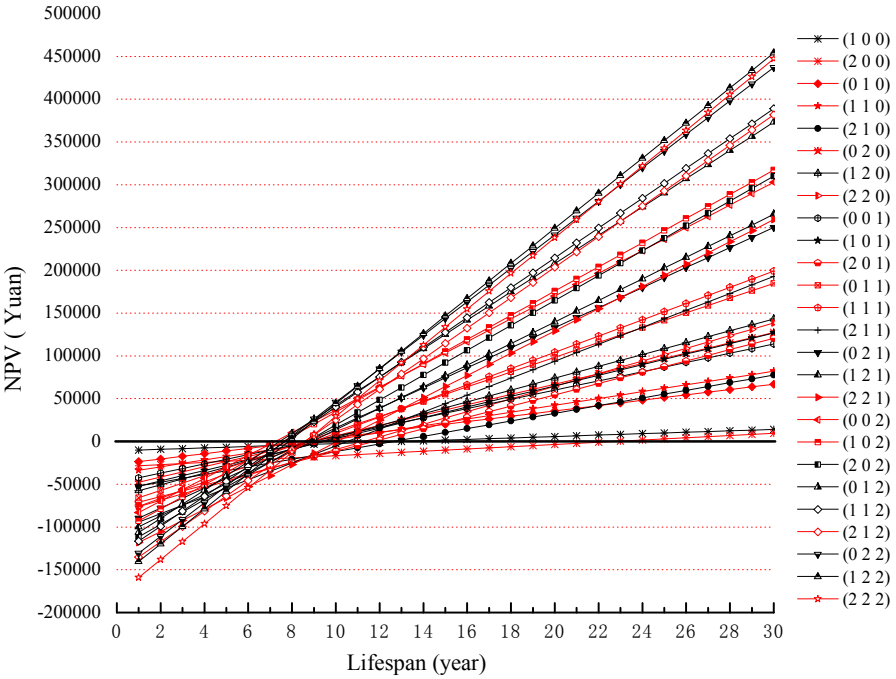


Figure 7. Cash flows of the 26 scenarios.

The cash flows of these 26 scenarios are illustrated in Figure 7 (scenario (0 0 0) is the reference case without cash flow). The intersection of the curve and Y axis (x=0) is the initial investment of the enhanced scenario and the node of the curve and the transverse line (y=0) is the payback period of the scenario. The performance of these scenarios is presented in Table 7.

Table 7. Solutions for optimal scenarios.

(Wall, Inf., SC)	Energy Saving (Yuan)	Initial investment (Yuan)	NPV (Yuan)	Payback period (year)	Profit rate
(1 0 0)	829.32	10817.28	14062.46	13.04	1.30
(2 0 0)	1311.10	29797.72	9535.27	22.73	0.32
(0 1 0)	3122.18	26761.51	66903.77	8.57	2.50
(1 1 0)	3990.02	37578.79	82121.91	9.42	2.19
(2 1 0)	4473.88	56559.22	77657.12	12.64	1.37
(0 2 0)	6034.93	53723.42	127324.50	8.90	2.37
(1 2 0)	6921.76	64540.69	143112.07	9.32	2.22
(2 2 0)	7400.80	83521.13	138502.77	11.29	1.66
(0 0 1)	5387.30	47754.72	113864.26	8.86	2.38
(1 0 1)	6177.39	58572.00	126749.72	9.48	2.16
(2 0 1)	6601.80	77552.44	120501.51	11.75	1.55
(0 1 1)	8645.49	74516.23	184848.60	8.62	2.48
(1 1 1)	9477.35	85333.51	198987.01	9.00	2.33
(2 1 1)	9904.34	104313.94	192816.13	10.53	1.85
(0 2 1)	11719.90	101478.14	250118.81	8.66	2.46
(1 2 1)	12595.01	112295.41	265554.86	8.92	2.36
(2 2 1)	13022.31	131275.85	259393.47	10.08	1.98
(0 0 2)	13311.62	96305.35	303043.15	7.23	3.15
(1 0 2)	14144.18	107122.63	317202.65	7.57	2.96
(2 0 2)	14542.59	126103.07	310174.59	8.67	2.46
(0 1 2)	16545.63	123066.86	373301.94	7.44	3.03
(1 1 2)	17424.40	133884.14	388847.82	7.68	2.90
(2 1 2)	17825.32	152864.57	381895.04	8.58	2.50
(0 2 2)	19576.83	150028.77	437276.02	7.66	2.91
(1 2 2)	20498.10	160846.04	454097.02	7.85	2.82
(2 2 2)	20899.84	179826.48	447168.65	8.60	2.49

Table 7 indicates that the cost of investment is in positive relation to the capacity of energy saving. The biggest energy-saving capacity comes to the scenario (2 2 2), which saves 20899.84 Yuan for each year; the amount of initial investments are also the maximum number, and the payback period is 8.60 years. The NPV of scenario (2 2 2), which wins a profit of more than double of its initial investment, ascends the 2nd among these scenarios. Thus the aforementioned method is cost-effective. As to the payback period, the shortest time is the scenario (0 0 2), which takes 7.23 years to pay for the initial investment. A point worth emphasizing is the comparison of scenario (2 2 1) and scenario (0 0 2), namely, the energy savings of these two plans are nearly the same, while the former scenario costs 1.4 times of the initial investment than the later one, which signifies the effectiveness of shading coefficient retrofitting.

When considering the rate of NPV to investment cost, scenario (0 0 2) is evidently the best profit rate, which obtains a profit rate of 3.15 times. The scenario profit rate of (0 2 0) is 2.37, and the least

scenario (2 0 0) owns a profit rate of 0.32. Thus shading coefficient retrofitting is much cost-effective than the other two methods.

According to the results, in the lifespan of 30 years, the best solution comes to the scenario (1 2 2), which is the NPV winner with the profit of 454097.02 Yuan. The payback time of the case is 7.85 years, an economic time cost for shareholders or investors. Base on the TRNSYS simulation model, it is very helpful to find the best economical pathway for energy saving of building envelope retrofitting by changing the character of the building material and construction procedure in the model instead of reconstruction of the existing building. Generally, for homogeneous office buildings, this method is time saving and economical efficient; and for the other buildings, the process of researching an optimal solution is cost-effective. Therefore, the sufficient results are helpful for technology improvement and efficient management.

9. Conclusions

This paper presents the representative of the early 21st Century office building in southern China. The test model has been constructed and validated for implementing different retrofitting measures of the building envelope. The sensitivity of related parameters has been obtained in assistant of organizing different energy-saving measures. As a result, the placement of exterior wall enhancement, infiltrations repairing and windows replacement were three of the most significant parameters. Then the 27 ESM results were obtained to analyze the capacity and efficiency of the envelope retrofitting. Furthermore, these ESM results were appraised through an economic approach.

Results show that the saving ratios of cooling demand range from 0.69% to 17.37%, and the all-high-standard enhanced building scenario (2 2 2) could save the most energy. It appears that the retrofitting of shading coefficient is cost-effective; in a lifespan of 30 years, the scenario (1 2 2) with a 454097.02 Yuan NPV turns out to be the optimal scenario of envelope enhancement.

The results of this research are expected to be submitted to the Guangdong Provincial Science and Technology Department and Construction Department, and the government will promote a legislative program for office building energy-saving assessment. Finally, the optimum applicability of such energy and economic performance of office building models will be written in the engineering technical guide. The optimum applicability of such energy and economic performance is corresponding to the legislative protection and initiatives; the methodology is helpful for guidance of office building retrofit works.

Acknowledgements

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