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MODELLING TECHNICAL AND ECONOMICAL BENEFITS OF THREE LOW ENERGY TECHNIQUES APPLIED TO A COMMERCIAL OFFICE BUILDING

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ABSTRACT

This paper reports a modelling study on quantitative assessment of economical benefits of three low energy solutions that could be easily applied to a large number of office buildings in the delta area of Yangtze River, where climate is characterised as hot summer and cold winter. The solutions include solar shading plus fabric insulation, sufficiently use of natural ventilation, and combination of these two. Using a real office building in Shanghai, the centre of the Delta area, a dynamic thermal model was developed to calculate the annual energy demands when each of the three solutions was applied. Then a basic full life cycle model was built and the energy demands were converted into running cost to assess the payback when the three energy saving solutions were combined.

INTRODUCTION

Shanghai is arguably the most developed city in China in economy, productivity and living standard. With 10 percent annual increase on GDP since the year 2001 till 2004, and more than 5600 dollars Per-capita GDP in year 2004, Shanghai has been the wealthiest place among all Chinese cities. Due to the rapid economic growth in the area, the living standards have also gone up substantially. This includes larger living/working spaces and more comfort indoor condition, where the local climate is characterised as hot summer and cold winter. All of these inevitably result in a rapid increase in building energy consumption (Ding et al, 2002).

Background

In 2005, a giant electronic component manufacturer extended their business into real estate by building a group of six blocks of office buildings and let them out to individual tenements. During the first year occupation, the operation cost, particularly the electricity bill for air conditioning was extremely high in these highly glazed buildings. Through stated funded project, a research institute offered a solution which combined multiple low energy technologies, including double glazing windows, wall insulation, roof gardens, ventilation wells, external shading device, PV panel and solar water heating systems, and geothermal heat pump system. According to their prediction, the institute claimed that the renovated buildings would save annually 180.7kWhm^{-2} or 4,100,000KWh in total (Ye et al., 2008). This theoretical prediction included contributions made from both the low energy measures and renewable technologies applied.

But applying multiple low energy and renewable technologies into one building is very rare for various reasons. The most obvious reason is high investment cost and uncertain profit on the investment, as many of these technologies are either newly introduced to China from abroad or recently developed locally. The renovation here was carried out as a trial and, if successful, a demonstration example to promote green building practise in the region.

In reality, building owners or developers are more likely to accept one or two low energy measures that do not involve high initial costs and pay return quick, such as solar shading, fabric insulation and natural ventilation. There was a need to develop a method to calculate the costs of the investment and operation and consequently to predict the return on the investment.

Objectives

The aim of this study was to assess quantitatively both technical and economical benefits of the three low energy solutions mentioned above, as they were believed applicable to a large number of office buildings in Shanghai and its nearby area and acceptable for developers. The results of the work were expected to provide an example that how technical and cost benefits could be predicted and more reliable data could be acquired for better decision making. The method could be easily used by design institutes or commissioned by building owners, estate developers and municipal building officers and planners.

To achieve the objective, firstly a dynamic thermal model was developed that could simulate the effects of external shading, fabric insulation, and controlled natural ventilation on the annual energy demands to maintain indoor comfort. Therefore the energy savings due to these renovation measures could be quantitatively calculated. Then a Life Cycle Cost model was developed and data input were carefully prepared, including the calculated energy demands and assumed prices, so that the pay back could be predicted.

THE METHOD

The study was carried in four stages:

1. Specifying internal and external conditions, including defining heat and cooling seasons for the dynamic simulation.
2. specifying four typical cases of building and system operation, including one basis case which represent the original building without any low energy technology applied and another three improved cases, each with one or more low energy technology solutions applied.
3. developing a dynamic thermal model to simulate the four cases so that the predicted energy consumption for each case could be compared against others, and technical benefit for each of the solutions could be assessed.
4. developing a whole life cycle cost model to assess the economical benefit for combining the low energy solutions.

Outdoor and indoor conditions

Located in the Delta of Yangtze River, Shanghai is featured with humid and hot summer wet cold winter. Other features include small diurnal temperature, rich precipitation, and timid solar radiation due to air pollution (Ding et al., 2002).

Due to the effects of green house and heat island phenomena, the local climate has become significantly warmer. This is not only clearly felt by most local residents, but is evident by the statistics: the number of continuous high temperature days has increased recently, and average temperature in the winter has also risen (Table 1).

Table 1 Change of Average Temperature in summer and winter in Shanghai (Lu SL, 2004)

Year	Winter Av. Temp<5℃	Summer Av >26.5℃
1951~1980	54d	39.4d
1985~1994	38.1d	54.7d
2001~2003	31.3d	57.3d

Shanghai weather data were analysed so that the cooling season was set from Day 144 to 265, when average outdoor temperature was over 21 ºC; and the heating season, from Day 339 to 65 according to Chinese Standards for heating and air conditioning(Chen et al 2006),

In China, the internal conditions for most commercial buildings are set to 18ºC to 26ºC for resultant temperature during weekdays, and no service in weekend(Lu, 2004). Table 2 lists major internal heat gains in for new offices in China.

Table 2 Internal conditions (Chen et al, 2006)

Gains	Value
Infiltration	1.0 ACH
Lighting Gains	12.0 w/m^2
Occupancy Sensible/latent Gains	10.0/5.0 w/m^2
Equipment Sensible Gains	15.0 w/m^2

The building and refurbishment

The buildings were completed in 2005, with total floor area of 22685m^2, including six blocks (Fig 1). E-block, examined in this study, had three stories, with a full height single glazed curtain wall for its main facades. The total treated floor areas in the E-block was about 2970m^2.

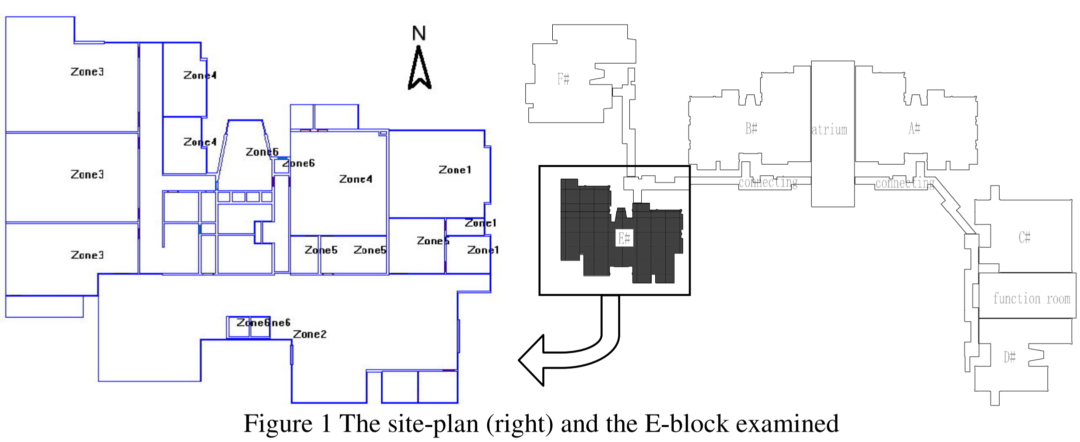

Figure 1 The site-plan (right) and the E-block examined

All floors were rather similar in terms of functions, and the majority of the rooms were used as open plan offices, some of which could be further partitioned to be cellular offices. All rooms were zoned according to their orientations.

As most other buildings designed and built before that time, the buildings were single glazed for all glazing areas; there is some insulation on roofs but no wall insulation. Concrete framed structure and large glazed façade gave the building a modern look but no low energy measures were applied. The glazed facades resulted in excessive solar heat gain in summer and high cooling cost, which was the major drive for carrying out the refurbishment.

During the refurbishment, several low energy and renewable technologies were applied, including solar thermal, PV panels, roof gardens, ventilation wells, geothermal heat pumps, external wall insulation and external shading. This study examined only three low energy measures:

- external shading;
- fabric insulation, including double glazing, external wall insulation and roof garden and
- controlled natural ventilation.

External shading: fully controllable blinds

The refurbishment tackled the excessive solar gain by installing external shading devices to the east, south and west facades and making use of retractable aluminium alloy blinds, with adjustable slat angle controlled by step motors to gain maximum solar protection during clear days and maximal daylight intake during overcast days (CLEAR, 2008). (Table 3).

Table 3 Area of shading

E-block	East	South	West	Total
Shading area (m²)	413.9	266.1	289.3	969.3
Number of motors	45	26	33	104

Double Low-E double glazing

All glazed area was entirely replaced by Low-E double glazing panels during the refurbishment. Low-E coating was on the external surface for heat rejection.

The cases modelled for comparison

Four cases were designed and modelled by TAS to compare the technical and financial benefits of the low energy solutions specified above:

Case 1 the original building. This was the base case, representing the original building without any thermal treatment: single glazed, solid wall, limited roof insulation and all openings were closed.

Case 2: the original building with natural ventilation. This was an improved version of the base case: the original building with natural ventilation in which all windows were open to allow outdoor air to remove indoor heat whenever it was possible.

Case 3: the building with fabric insulation and solar shading. The case represents the building after refurbishment, in which the roofs and walls were insulated to the standards and double glazed with low-E coating and all windows were closed. The retractable blinds were simplified by a fixed overhang. The operation of the air conditioning system remained the same as that in the base case – no natural ventilation applied.

Case 4: the building with fabric insulation, solar shading and controlled national ventilation. This was a combination of Case 3 and ventilation, representing a building properly designed to meet thermal standards and smartly controlled for natural ventilation.

Dynamic thermal modelling

All four cases were modelled using TAS, a popular commercial software package mainly dealing with building thermal simulation(Environmental Design Solutions Ltd). There were two major challenges of modelling: the external blinds and natural ventilation.

Modelling the shading devices

Due to the limitation of TAS, the actual retractable external shading devices with adjustable slats were simplified in the modelling as a fixed overhang on the top of the windows that was to cover a same shading area at noon on Day 265, as the highest indoor gains occurred according to the simulation of the base case. The width of the overhang was then sized as 696mm for ground floor and 582mm for the other floors (Fig 2).

To model the overhang, each storey was split into two levels, the lower level included the curtain wall and the upper one included the ceiling void.

As fixed shading was modelled, solar gain could not be fully cut out and solar gain in winter was reduced, both of which resulted in higher running costs than the actual one with retractable/adjustable blinds. Two models could be used in future to simulate the retractable shading device, one with fixed shading for summer operation and the other no shading for winter. It was also assumed that the shading device affected only solar penetration but not day-lighting. Hence the solar gain was affected and so were the heating and cooling loads. But the energy needed for lighting was assumed not to be affected by the external shading.

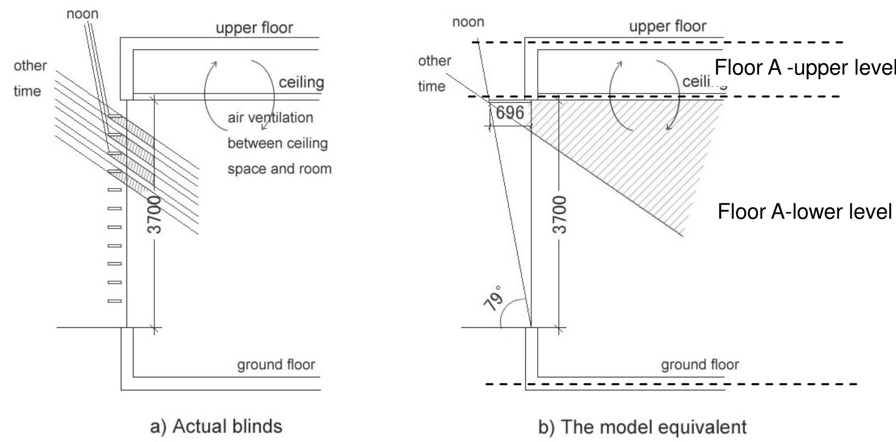

Fig 2. The blinds with horizontal slates and the overhang with equivalent shading effect.

Natural ventilation

As the whole year was divided into four sections, TAS simulation was carried for the five periods:

- Day 1-65, the beginning of the year, windows closed for heating;
- Day 66~143, the spring, mild season, windows open when possible;
- Day 144~265, the summer, windows closed for cooling. During this period, night ventilation was also tested;
- Day 266~340, the autumn, mild season, windows open when possible and
- Day 341~365, the winter, windows closed for heating.

To simulate the natural ventilation, windows and other openings were scheduled open for two sessions: daytime ventilation from 8 to 18 and night cooling from 18-8.

Life-Cycle Cost model

During the period of rapid economic growth, initial cost of any project is inevitably a prominent concern. Applications of low energy solutions cost more to build although they might cost less to run. These solutions have to be assessed throughout their life cycle. Then the developer who will also be the owner of the building will be more likely to agree to pay for the solutions. The simplest life-cycle cost mode has this form:

$$LCC = W + X + M + Y$$ (Fuller, 2000),

where: W is the initial costs including purchase, construction and installation; X, the operational costs, such as energy bills; M, the costs for maintaining and repairing; Y, the replacement costs.

The length of the study period and estimated life span for the system are two main factors of capital replacements (Gluch, 2004).

In this study, the costs accounted were only those related to the low energy measures: solar shading, insulation, natural ventilation:

Initial costs

This part covers design, construction and installation of the low energy solutions. More specifically, it includes installation of the solar shading devices and double glazing panels. Installation of glazing panels includes those operable units, which are the basic elements for national ventilation. There were no individual figures for the costs to build the ventilation towers and automatic devices that controlled windows openings. Therefore this part of initial costs was omitted.

Length of life cycle

It is difficult to set the length for the life cycle assessment due to numerous uncertainties, such as further redevelopment, changes in policies that affect energy price and taxes, nature disasters, building demolishment and so on. A 30~60 duration is normally recommended as sufficiently long for such cost analysis in many developed countries. In China the rapid changes in every aspect makes such analysis a more challenging task. Here in our project, a 50 year period was chosen simply because this is the normal life time of the blinds claimed by their manufacturer.

Operation costs: electric costs

This running cost was calculated using the energy demands predicted by the TAS model and it was simplified that the same amount of electricity was used to meet the demands. It was further assumed that the demands remained unchanged throughout the whole life cycle and no effect was considered due to the degradation of the HVAC systems. The energy price was increasing! The increasing rate during the 50 years whole life cycle was calculated by projection of the value based on statistical data of the local electricity supply from 1993 to 2006, which resulted in an average increment of 11%. Adjusted with the fact that the price remained same for five years, a moderate increase of 6% was used as i, the projected annual increase on electricity price for the running cost calculated.

Table 4. The electricity Indices in Shanghai from 1993 to 2006(SMSB, 2007)

	Electricity	1996	109.50	2002	100.00
Year	Index	1997	123.90	2003	100.00
1993	--	1998	107.70	2004	100.00
1994	131.30	1999	103.10	2005	100.00
1995	126.50	1996	109.50	2006	100.60

Along the projection of electricity price, the electricity cost in addition to the glass curtain wall and shading devices for the next 50 years is:

$$X = \sum_{k=1}^{50} x \times P_{2008} \times \left(\frac{1+i}{1+d} \right)^k \qquad \text{(Yuan)} \qquad (1)$$

where x is the total year electricity consumption for heating, cooling and running the shading device

i is the projected annual increase on electricity price(6%),

P_{2008} is the initial electricity price in 2008, (1.074 Yuan/kWh) (NDRC, 2008) and

d is the assumed annual interest rate (2%).

The electricity consumption for this project is the sum of heating load, cooling load and load on blinds motors.

Maintenance and repair costs

By consulting the suppliers of the materials, the maintenance and repair cost in 50 years is around 10% of the initial cost, which was 179,729.23 Yuan a year.

Replacement costs

Although the whole structure of the solar device had a life span of 50 years, the manufacturer suggested partial-replacement for every 10 years at 20% of initial cost. This would include replacing bearings, motors, cables and most likely the blind slats. Note that, similar to electricity conservation, it is the present value of these arrangements that matters rather than the simple accumulated value. Hence the total replacement cost can be derived as follow:

$$Y = \sum_{k=1}^{5} \frac{y}{(1+i)^{10 \times k}} \qquad \text{(Yuan)} \qquad (2)$$

where y is the replacement cost for each arrangement, and i is the annual interest rate.

The fees for removing of the devices at the end of the life cycle had to be neglected, as firstly they were considered relative small comparing with the costs of installation and operation of these systems and the actual figure was not available. Such treatment could be reasonable for just now, taking into account the current situation in China. However, it might not be so appropriate in the near future because the labour and demolishment may all cost more than they do now. Hence, how to set a proper figure could be a topic for further study.

Therefore, the LCCA model for the refurbished building would be:

$$LCC = \sum_{k=1}^{50} (C+Z) \times P_{2008} \times \left(\frac{1+i}{1+d} \right)^k + \sum_{k=1}^{5} \frac{y}{(1+i)^{10 \times k}} + M + W \qquad \text{(Yuan)} \quad (3)$$

where C is the annual electricity consumption of the HVAC system, kWh

Z is the annual electricity consumption of the shading devices,

y is the replacement cost, Yuan

M is the total maintenance cost in 50 years deducted to the present value and

W is the initial cost, Yuan

This result is to be compared with the total electricity cost of the original building predicted for running 50 years:

$$X_0 = \sum_{k=1}^{50} Q \times P_{2008} \times \left(\frac{1+i}{1+d} \right)^k \text{ Yuan} \qquad (4)$$

where Q is the annual electricity consumption of the original building.

Hence the advantage of the refurbishment is quantified as:

$$profit = \sum_{k=1}^{50} (Q-C-Z) \times P_{2008} \times \left(\frac{1+i}{1+d} \right)^k - \sum_{k=1}^{5} \frac{y}{(1+i)^{10 \times k}} - M - W \qquad (5)$$

RESULTS AND DISCUSSION

Technical benefits

Effects of solar control and fabric insulation

These effects are assessed by comparing Case 1, the original office building (no energy saving measures) and Case 3, the building with external shading and fabric insulation, including double glazing.

Table 5 A energy breakdown for all serviced zones (Case 1 and Case 3)

Zone	Heating $kWhm^{-2}$		Cooling $kWhm^{-2}$		Dehumidify $kWhm^{-2}$		Solar $kWhm^{-2}$		Internal
	Case 1	Case 3	Case 1	Case 3	Case 1	Case 3	Case 1	Case 3	casual
1	3.23	0.02	98.13	74.83	0.19	0.84	226.55	58.24	126.24
2	2.04	0.09	59.89	45.62	0.13	0.53	134.93	38.32	99.88
3	4.97	0.11	86.21	70.37	0.20	0.85	138.15	34.45	139.17
4	25.73	2.16	84.22	71.17	0.25	1.16	96.66	27.38	169.64
5	5.51	0.22	94.99	86.85	0.31	1.47	17.89	1.26	198.01

In Case 1 due to poor insulation the max heating load of 62.58 kW occurred on Day 360 and a very high peak load at 08:00am when the system started preheating. Max cooling load, one the other hand, was 114.72 kW on Day 235, not Day 265, when indoor solar gain was at its highest and solar altitude was used to size the overhangs. The highest cooling occurred in Zone 3, the west side rooms. Obviously the extra solar gain was the main reason for the cooling loads. The highest heating happened in Zone 4, the north rooms, which did not receive solar in winter.

The breakdown energy shows show better the effects of solar shading and improved glazing insulation (Table 5). The west zone (3) received much less solar penetration after shading, dropping from 138.15 to 34.45 $kWhm^{-2}$. Consequently, the cooling load dropped from 86.21 to 70.37 $kWhm^{-2}$. The south zone (2) also had a significant drop in cooling due to the external shading. Comparing with the west zone, the south zone had a high reduction, because the overhang shading had better shading effect to south facing facades than to a west facing ones, for which vertical fins would do better job.

Although with a smaller façade area comparing with other zones, the north zones (zone 4) had seen a fall in heating loads when single glazed windows were replaced completely by double glazed one.

Over a whole year operation (Fig 4), the biggest save was achieved during the summer cooling seasons from May until October. The saving in heating due to double glazing and other improvement in insulation was not significant comparing with the saving in cooling due to solar control.

The little saving in heating due to improved insulation could be the reason for some colleagues in China exclaiming that it is "useless" to insulate building envelope in the climate featured with cold winter and hot summer. Comparing with the effects in shading and cost to replace the glazing parts, it is not easy to pursuit building owns to use double glazed windows when external shading can make a dramatic difference. But the actual figure of heating saving was 18,119kWh for a $3000m^2$ building ($6kWhm^{-2}$). The saving due to double glazing would be much bigger for domestic buildings as those building would need heating during night time, when the temperature difference across the building envelope would be larger than that during the days.

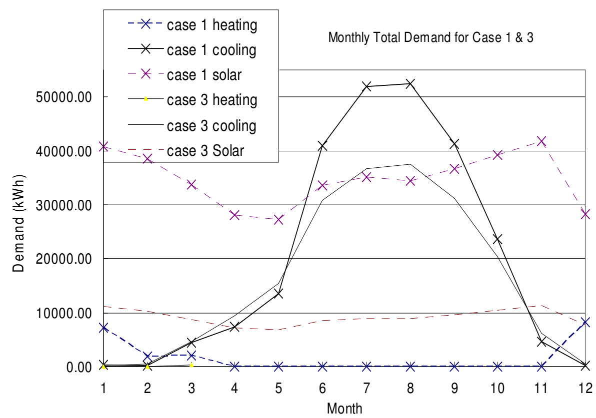

Figure 4 Annual total demands for case 1

It is interesting to note from Figure 4 that during the heating season, there was yet amount of cooling load. This was due to the solar gain and humidity, both of them could warm up the rooms particularly when ventilation was insufficient.

It was noted that the slates were modelled static in this exercise. They actually provide better shading than modelled. Therefore the saving could be even large. The proper control could also reduce electricity demand for lighting which was not considered. Overall the electricity saving for the heating and cooling was over 24%.

Effects of natural ventilation

The first column in Table shows the energy demands during the spring, summer and autumn when the building was completely sealed. The second column shows the same figure when windows were open during day time to allow natural ventilation to cool the building, whilst the third, night cooling was applied. It is clear that the ventilation during the mild seasons could save over 40% in spring and 25% in autumn. Even during the summer, the night cooling achieve 0ver 8% saving. Over the whole year the smart ventilation could save over 12% electricity.

Table 6 Energy demand ventilation solutions during a whole year

Periods	energy demand during the periods (kWh)		
	window closed	day ventilation	night ventilation
Day 66-143	17895.8	10574.5	10584.3
Day 144-265	186309.2	N.A.	170194.2
Day 266-340	36181	27084.4	27100.4

When natural ventilation was applied together with solar shading, the saving can be seen by Fig 5. About 39% energy was saved for heating and cooling annually. Assuming the main energy consumed, such as air conditioning and lighting all use electricity, this could cut down 32Kg CO_2 emissions each square meter of treated floor area, which could be a significant alleviation for this number one carbon emission country.

As explained earlier, the modelling of case 1 allowed firstly the starting/ending days for each of the five sections to be determined (Table 6). Secondly it allowed two ventilation solutions to be tested and energy saving results could be quantitatively compared.

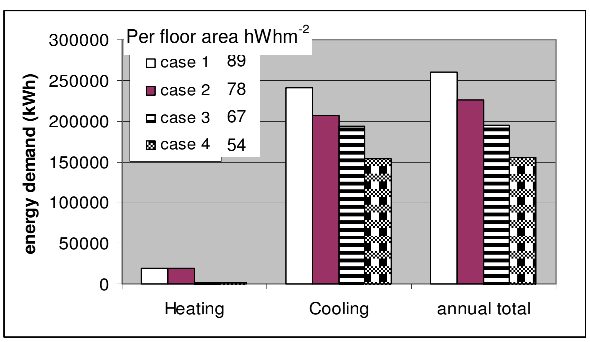

Figure 5 Comparison of the four cases on annual heating and cooling energy demands

It has to be pointed out that in TAS modelling there were times when windows were open and cooling could be also on during the two mild seasons when indoor temperature went over 26ºC. This resulted in energy wasted and would be avoided if a building manager or a Building Management System was in control. More reasonable modelling that avoids such waste would surely lead to a more accurate prediction on energy saving on cooling due to natural ventilation. This would require simulation of integrated control of cooling and window opening and could be examined in future studies.

Financial benefits

Initial costs

All the curtain walls including those operable windows panels were “Clear 6-12-6”, purchased locally at 235 Yuan/m^2. The total glazing area was 1929 m^2, which cost 453K yuan. The shading device was again a local product, and its total costs were 1,344K Yuan. Therefore, the total initial costs for these two improvements were 1,797K Yuan including installation.

Electric costs

Before the refurbishment, the consumptions were 19183.3 kWh for heating and 240842.4 kWh for cooling, and the figures have been reduced to 1493.7 kWh and 154076.1 kWh respectively after the refurbishment, which produced annual electricity saving of 104,455.9 kWh. Extra electricity used to operate the shading device was 63.1 kWh according to the supplier. Therefore the net energy saving:

$$Q - C - Z = 260{,}025.7 - 155569.8 - 63.1 = 103{,}391 \text{ (kWh per year)}$$

After series of calculation, the following profit table is obtained:

Year	Profit
10	-640k
20	1260k
30	4,69k
40	8,28k
50	14,53k

As shown above, the payback time of this project is less then 20 years. The actual payback should be quicker as the real energy demands with natural ventilation would be lower than what was calculated here, due to the inclusion of waste cooling. On the other hand, it would introduce another running cost if natural ventilation is to be used to its best, as this involves integrated control over operating windows and AC system, which could only be achieved by either a trained operator manually or a Building Management System (BMS) automatically operating the windows and the A/C system. Employing a building energy manager can be expensive over the full life-cycle and installation of BMS surely increases both initial and maintenance costs. Both could extend the return on investment. This could further examined in later studies.

It is noted that the energy calculated was not the primary energy actually consumed by the system, as no HVAC systems were modelled. The further study could target at this aspect and recalculate the pay back term. Moreover although this exercise examined a real building and the low energy measures were applied in the refurbishment, no data, such as break down electricity consumptions were available to validate our modelling prediction. This was due to the fact that the management system was not yet well established by the owner to manage the building operation.

CONCLUSION

There are following conclusions drawn from this study. Firstly, dynamic simulation when properly used could simulate many real operations, such as solar shading with horizontal slates and natural ventilation by schedule opening windows and doors. Controlled natural ventilation could be modelled more properly in future if control of cooling and window opening could be integrated and scheduled together. Then their effects in heating and cooling can be quantified more accurately. Even though the method represented here provides a good example for financial assessment on application of a new technology.

Secondly, for purely technical benefits, combining three low energy measures could save over 39% energy. This is equivalent 32Kg reduction in CO_2 emissions for each square meter of treated floor area if the heating and cooling both use electricity. Maximising natural ventilation, a simple operational solution, could save over 12%. Applying external shading, a very simple and widely used solution, together with double glazing could save over 24%. This was mainly achieved by the external shading, as the saving due to double glazing was mainly for winter heating, and this took a very little portion compared with cooling in Shanghai climate. Its financial implication could be examined and quantified in further studies.

Thirdly, the life cycle cost model worked well although with many assumed but reasonable data. When more data are systematically collected for public access, this assessment can surely provide reliable analysis for sound decision making.

Fourthly, this study also reveals some problems. One such problem is lack of statistical data, which are critical for accurate quantitative cost analysis. Uncertainty on future development on prices, costs, and policies are the main barrier to a quality prediction and comparison. In addition, inadequate management procedure was the main cause for the missing data from this real project.

Last but not the least, this assessment exercise together with the renovation project demonstrates how a state funded research project took the initiative in the green design campaign badly needed in the overheated estate market and encourages, hopefully, more developers and building owners to apply new but mature technologies in buildings, even their financial benefits are not seemingly certain or attractive.

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