Monitoring and Evaluation of Building and Heating System Energy Performance of Huaxiajindian Integrated Demonstration Subprojects

HEAT REFORM AND BUILDING ENERGY EFFICIENCY PROJECT

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Executive Summary

In the northern China regions, a large amount of energy is used for heating buildings in winter season. Traditional residential buildings are not well insulated and the heating charge is calculated based on the building area rather than the real usage. Heating consumption could be reduced through improved shell construction and responsible billing structure to eliminate wasteful behaviors. The Heat Reform and Building Energy Efficiency (HRBEE) Project financed by the Global Environment Facility (GEF) is a key part of the World Bank-led international assistance program to assist the Government of China implement its heat reform policies and promote more energy-efficient design and construction of residential buildings. The World Bank chooses Tianjin as the first city in this demonstration project with an integrated approach to reduce heating energy consumption. The integrated approach includes both building shell improvement and economics incentive such as metering the consumption for each unit.

Both the Huaxiajindian and Diliutianyuan demonstration subprojects are among the first residential developments which are designed and constructed according to Tianjin's new energy efficient design standards for residential buildings (DB 29-1-2004, effective since January 1, 2005), which could lead to heating energy savings of 65%, compared to residential buildings constructed in the early 1980s. All apartments in these two subprojects are connected to variable flow hot water heat supply systems and have individual heat meters as well as thermostatic temperature control valves.

With the assistants from Tianjin International Engineering Consulting Corporation, we monitored the heating energy usage and the indoor air temperature of apartments in Huaxiajindian from November 2007 to March 2008. We constructed simulation models to simulate the building and determine the energy savings from both the shell insulation and the occupants' behavior changes. We used that information to quantify the overall energy-saving effects of the integrated approach and assess the compliance/conformity of the completed buildings with Tianjin's 65% energy savings standards (DB 29-1-2004).

We found that the completed building almost met the energy savings standards. The apartment units at the top floor used 68% less than buildings built in 80s with no insulation. The units at the middle and bottom levels used 49% less than that of the traditional apartments. Overall, the nine floor building used 53% less than that of the conventional construction. In comparing the source energy, the Huaxiajindian was 66% more efficient than the standard because the distribution system was 5% and the boilers were 8% more efficient than before.

The expected behavior change from metering was small and barely noticeable. Occupants tended to open the windows in the early morning for natural ventilation and few of them choose to setback the temperature during night and unoccupied hours, even though they were charged upon the individual heating metering. We estimated the savings potential from occupants behavior changes and identified that window itself should be the focus of the future energy efficient improvements.

Introduction

The Heat Reform and Building Energy Efficiency (HRBEE) Project financed by the Global Environment Facility (GEF) is a key part of the World Bank-led international assistance program to assist the Government of China implement its heat reform policies and promote more energy-efficient design and construction of residential buildings. It adopts an integrated approach toward improving space heating energy efficiency in northern Chinese cities, stressing simultaneous application of measures to improve building envelope thermal integrity, demand-driven (variable flow) heat supply systems, heat metering and consumption-based billing.

Tianjin is the first city in this project to have completed demonstration projects with this integrated approach. Both the Huaxiajindian and Diliutianyuan demonstration subprojects are among the first residential developments which are designed and constructed according to Tianjin's new energy efficient design standards for residential buildings (DB 29-1-2004, effective since January 1, 2005), which could lead to heating energy savings of 65%, compared to residential buildings constructed in the early 1980s. All apartments in these two subprojects are connected to variable flow hot water heat supply systems and have individual heat meters as well as thermostatic temperature control valves.

The Huanxiajindian subproject includes multi-story and mid-rise apartment buildings. The apartment buildings and additional public buildings are served by one substation, which is a part of a large hot water district heating system supplied by a combined heat and power plant. The substation is equipped with variable speed circulation pumps and automatic temperature controls, as well as heat meters. The apartments are heated through radiators with thermostatic radiator valves. Each apartment has an ultrasonic heat meter. The centralized heating system does not provide domestic hot water service.

We monitored a nine-story apartment building in Huaxiajindian. Year 2007 is the first heating year of this newly built apartment complex. Although the apartments were all sold to the public before the heating season started, some of them are still unoccupied. By design, every unit has a heating meter that reports the accumulated heating energy consumption during the heating season. This accumulated heating consumption was used to calculate the bill.

Systematic monitoring and evaluation of the building to quantify heating system energy efficiency performance were conducted in the winter of 2007/2008 when most of the apartments are expected to be occupied. The main objectives of the monitoring and evaluation are to:

(i). Quantify the overall energy-saving effects of the integrated approach;
(ii). Assess the compliance/conformity of the completed buildings with Tianjin's 65% energy savings standards (DB 29-1-2004); and
(iii). Identify areas where the designs and constructions of building envelope could be improved.

To achieve the above objectives, we conducted detailed energy audits for a representative sample of apartments and buildings, and collected the building design drawings to build the simulation model. We selected unit 102, 402, and 902 in building No.4 as the representative units. We added the following sensors and measurements to these units.

(i). Measurement of ambient temperatures and other relevant weather data throughout the heating season;
(ii). Measurement of indoor air temperature for each individual room within the units.

(iii). Collection of design and construction information, including construction drawings and physical properties of materials and components used;
(iv). Sample survey of households regarding household size (number of people), major appliances and capacities (kW), and household routines which may affect heating energy consumption;
(v). Sample survey of household income, satisfaction of metering, overall satisfaction of heating system, behavior changes due to metering,
(vi). Sample survey of similar households in the region;

After collecting the information from the audits, we built a DOE2 model to calculate the heat load and specific energy consumption of each sample apartments. We compared the results with the baseline in the standard and determined whether the building was able to meet the project goal.

1.0 DOE2 model

1.1. Geometry and thermal zones

Figure 1 shows one level of the DO2 model we built for this project. The red surfaces are the exterior walls, the blues are the windows, and the pinks are the interior separations. The layout is same as the architecture drawings. We simulated one half of the building, because the other half of the building is geometrically identical to this half and the effect of switching the east facing window with the west is insignificant because of their small size. Since we monitored three apartment units separately instead of the whole buildings, we built the model level by level and calibrated the simulated results for each unit separately as well.

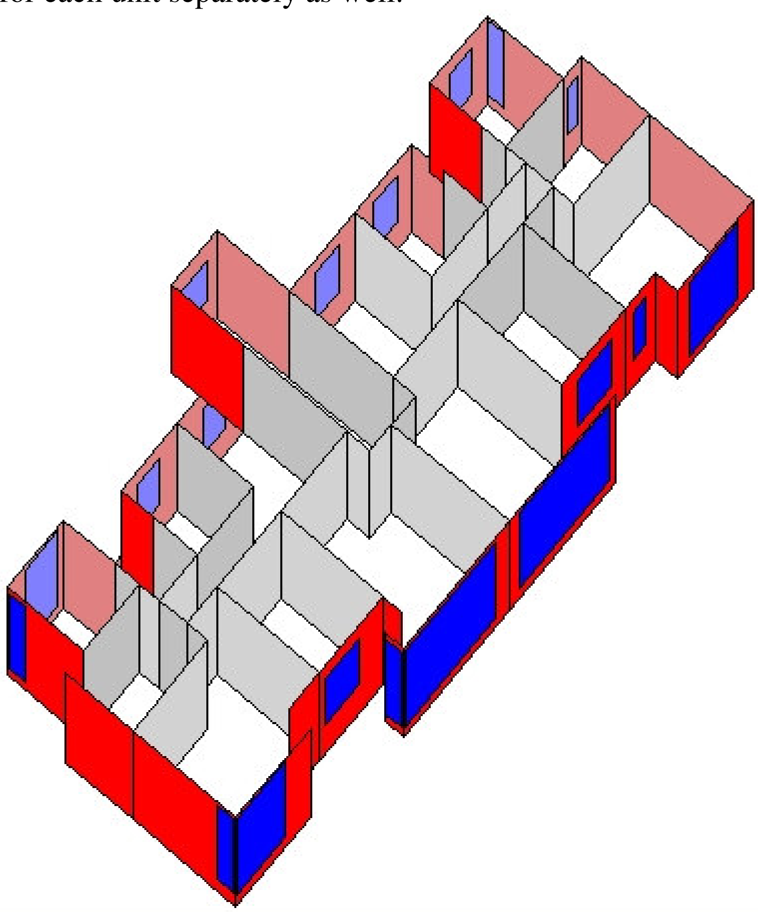

Figure 1 Geometry layout of the typical floor in DOE2 model

Each unit has three bedrooms, one master bedroom in south and two guest rooms facing south and north each. Each unit also has one living room, one dinning space, one kitchen. The south facing windows are relatively large, compared with northern facing windows. On the east side, there are only two small window strips extended from the large south and north facing windows. The architecture drawings show the balcony facing south as an unconditioned space. However, in the real usage, the balcony was sealed and the occupants seldom closed the door between the balcony and the living room. The balcony door is made in wood with no insulation. Therefore, we treated the balcony space as a conditioned space and it was part of the living room thermal zone.

The windows used in the model are double-pane clear glazing with a K value of 2.7 $W/m^2.K$. The exterior roof has a K value of 0.45 $W/m^2.K$. The roof is made of 120mm thick concrete with 110 mm thermal foam EPS (Expanded Polystyrene) insulation. The exterior wall has a K value of 0.53 $W/m^2.K$. It is made of 200mm thick concrete and 80 mm thermal foam EPS (Expanded Polystyrene) insulation on the exterior side.

1.2. Internal load and schedule

We used the measured electricity consumption to estimate the internal load during the heating season. During the design, typically the internal load was treated as zero in sizing the heating system in China. However, in comparing the real heating usage, it is important to measure the real internal load because of the increasing numbers of electronics used in homes in China. Measuring the internal load will also help us to understand the occupant's activity.

Figure 2 shows the electricity usage measured for one typical unit. The black line is the seasonal average value and the vertical gray lines are the ranges of the standard deviations for each hour. On a typical day, the occupants got up and started the light and home appliance around 7:00 am. After the breakfast, around 8:15 am, the occupants left the room. The morning load in average was higher than the afternoon, which indicates elevated activities in the morning period. Occupants came back and the dinner started around 7 pm and the internal load reached its peak from then till 11 pm.

To reduce the heating bill, the occupants should setback the temperature set point between 11 pm to 6 am, and between 8 am to 6 pm. However, the temperature measurement showed that the indoor air temperature was seldom below 18 ^{o}C. The heating system seemed to be on 24 hours a day and the temperatures swung between 18-21 ^{o}C. To match the measured temperatures, we set the room temperature set points at 19 ^{o}C in the simulation model, with a 3-degree dead band.

We also noticed that the 24 base electricity usage are quite high, which is about 1/3 of that during the peak period. Other than the usage for refrigeration, a large portion of the base load was standby power usage from unplugged home appliance. Occupants will be able to save a significant amount of it simply by unplugging the unused appliances or use advanced smart switch boards that will automatically switch off after a while.

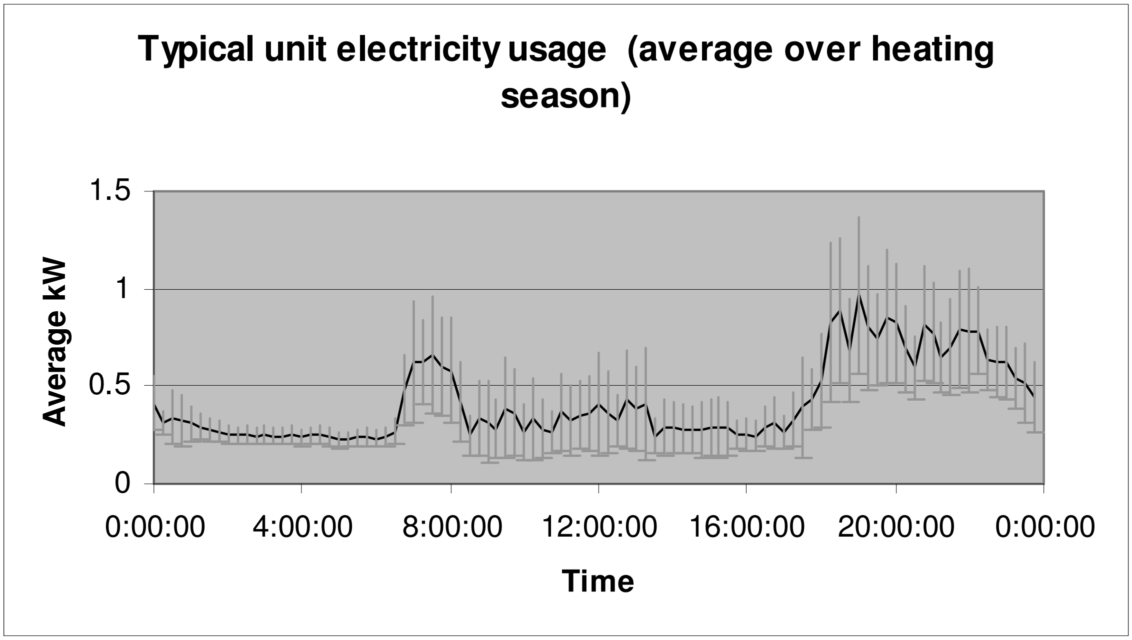

Figure 2 Electricity internal load measured

Table 1 shows the value and schedule of the internal load we used in the DOE2 model. The number is still relative small compared with the overall heating load.

Table 1 Electrical internal load schedule

	Lighting	Equipment	Total	Lighting per m^2	Equipment per m^2
	kW	kW	kW	W/m^2	W/m^2
0:00-7:00	0	0.26	0.26	0.0	2.0
7:00-8:15	0.18	0.44	0.62	1.4	3.5
8:15-18:15	0	0.32	0.32	0.0	2.5
18:15-24:00	0.23	0.49	0.72	1.8	3.9

2.0 DOE2 model calibration

We calibrated the DOE2 model against the measured heating data and use the calibrated model as a baseline for the parametric analysis. The measured data are the data we collected during the heating season from November 2007 to March 2007. These data include the hourly heating rate measurement for some units of a short period, the daily heating rate usage for two months, and the total seasonable heating usages for all three units.

2.1. Weather data

We use the real weather data in late 2007 and early 2008 in running the simulation, instead of using typical year weather files, such as TMY2. Tianjin has two weather stations, one is the Tianjin BinHai weather station and the other is the Tianjin Airport weather station. Tianjin airport is closer to the Huaxiajindian than the other one and we download the airport data and construct a weather file in simulation.

2.2. Missing data

The heating season started from 11/15/07 and ended on 3/15/08. Because of the delay in starting the project and a data loss, the available daily heating rate data were from 12/23/07-1/23/08. We also collected hourly heating rate for a short period from 12/20-1/4/08 for all three units. The seasonal accumulated heating consumptions are available for all three units.

We used a simple regression model and extrapolated the daily heating rate between 11/15/07 to 12/22/07 and 1/24/08 to 3/15/08 using hourly weather data from the following equation:

$$\text{Hourly Heating rate} = \text{Constant} \times (18.5\ ^{o}\text{C} - \text{Outdoor air temperature})$$

Table 2 shows the comparison of extrapolated seasonal heating consumption with the real seasonal heating consumption. The hourly heating degree extrapolation method we used here works fairly well and the heating consumption at the whole building level are within 1% to each other.

Table 2 Daily heating rate extrapolation results

Heating consumption (GJ)	Middle	Bottom	Top	Whole building
Daily measurement (real) + extrapolation	52.3 GJ	50.1 GJ	84.0 GJ	500 GJ (within +1% of real measurement)
Heating season meters (real)	49.5 GJ	56.9 GJ	93.3 GJ	496.1 GJ

Figure 3 shows the extrapolated daily heating rate data for the entire season. The daily heating rate peaked at around the end of the January, the coldest period in the heating season. The peak daily heating rate was about twice as large as the daily heating rate in mid November and March. The daily heating rate was used to calibrate the DOE2 simulation model.

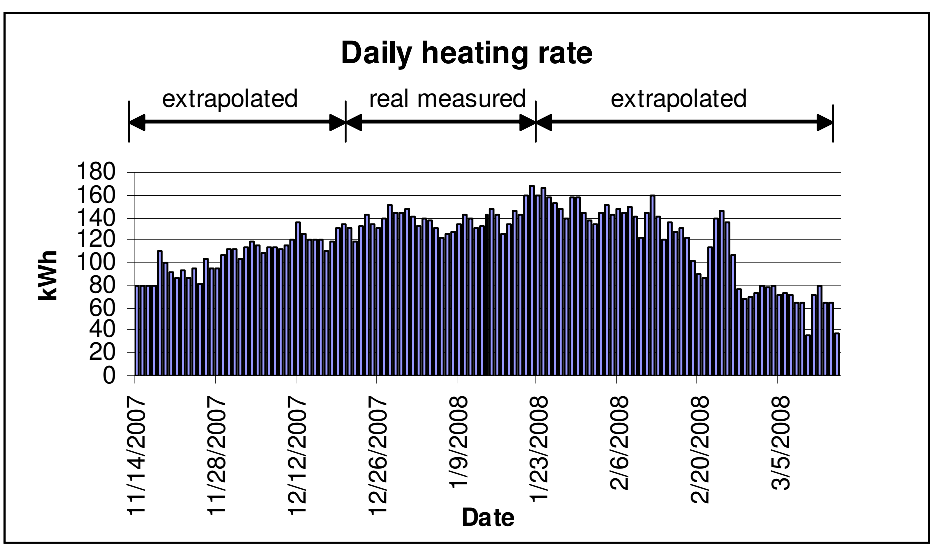

Figure 3 Measured daily heating rate consumption

2.3. Daily heating rate calibration

We ran the baseline model simulation and compared the simulated daily heating rate with the measured daily heating rate. The only parameter we adjusted to calibration the model is the infiltration rate. Building shell, internal load, and the temperature set points were all fixed. We used a calculated infiltration rate to model the heating loss through the window in early morning when occupants open windows for fresh air.

Figure 4, 5, 6 show the calibration results for all three floors, the top, the middle and the bottom units.

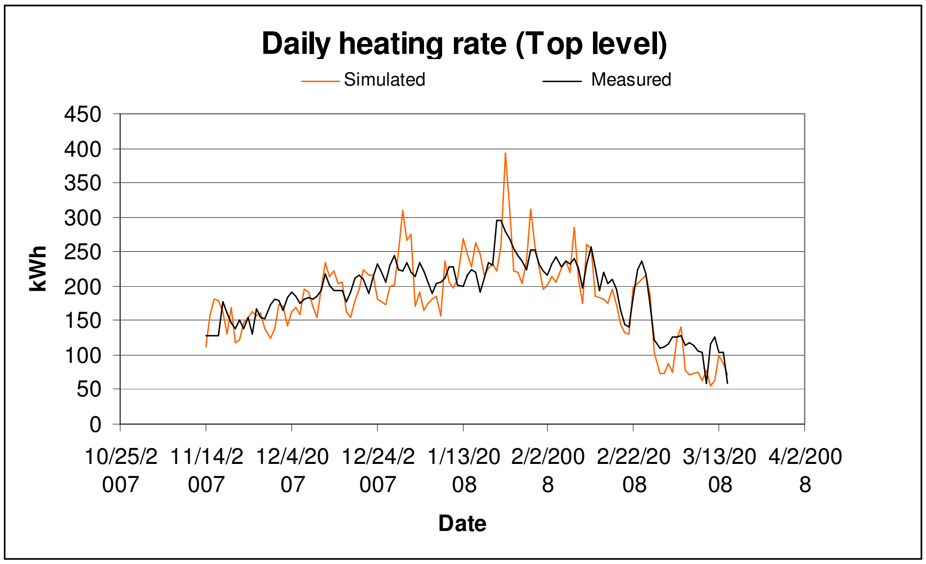

Figure 4 Model calibration daily heating rate (top level)

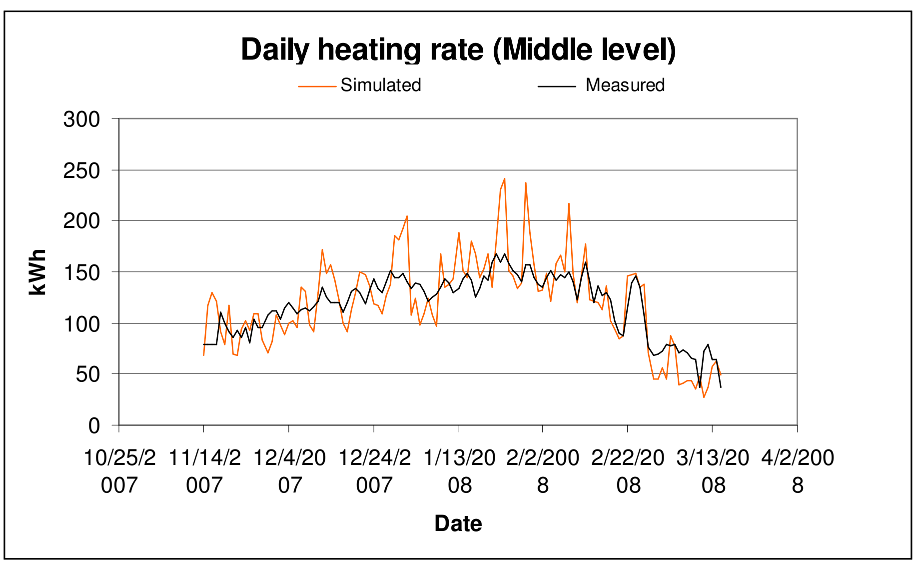

Figure 5 Model calibration daily heating rate (middle level)

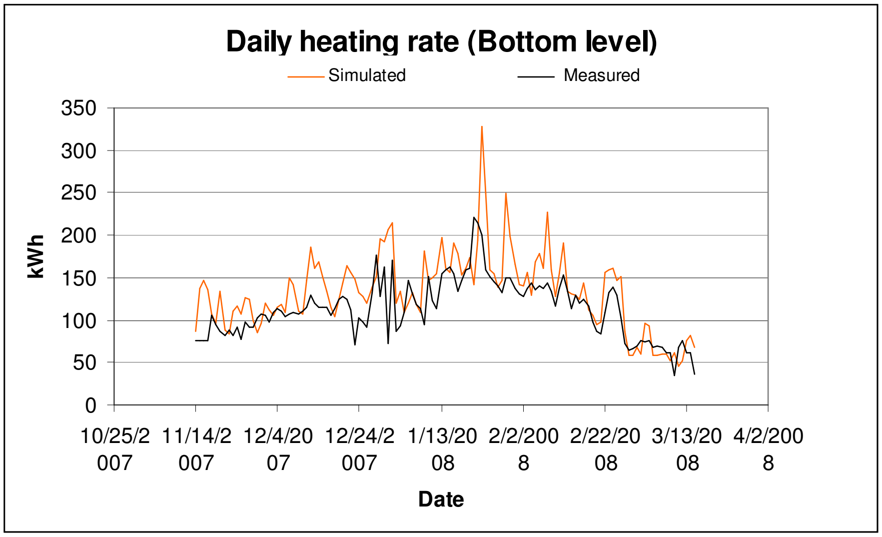

Figure 6 Model calibration daily heating rate (bottom level)

The simulation results of the top and middle units matches well with the measured data. Although the simulation results seem to be a bit more jumpy than what was measured, the overall daily consumptions were close to each other. The measured results of the bottom seem to be lower than the simulated results. In theory, the heating rate of the bottom unit should be higher than the middle units if everything else is equal because of the heat loss through ground. However, from the measurement, although for certain days the daily heating rate of 102 was higher than 402. Overall, the rate of 102 is lower. It may be due to the difference in usage instead of an error in modeling.

2.4. Seasonal heating rate calibration

To further test the accuracy of the baseline model, we compared with seasonal simulated heating rate with measured heating rate. The seasonal measured data are all real data from the measurement with no extrapolation. Figure 7 shows the comparison of the seasonal heating consumption of the three units. The measured and simulated data are matching with each other within 2% range..

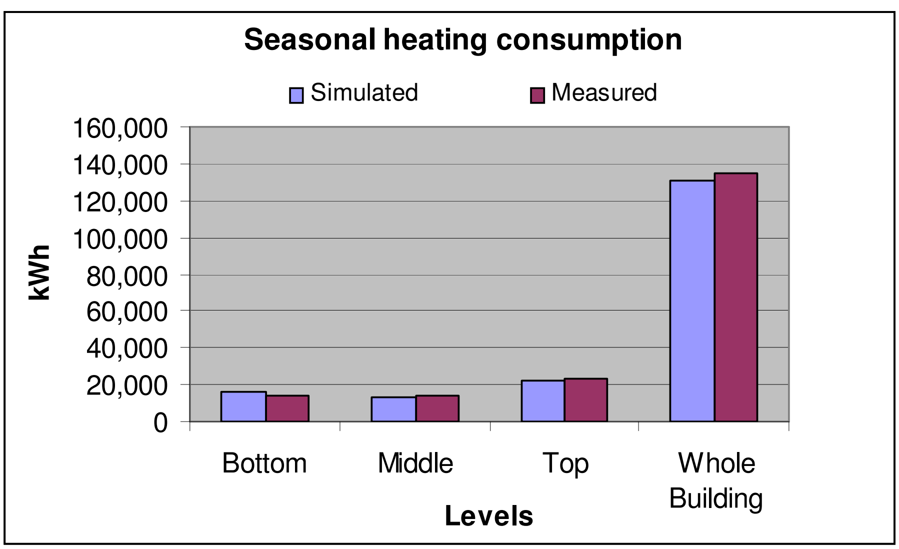

Figure 7 Model calibration seasonal heating consumption

2.5. Hourly heating rate

Figure 8 shows the hourly heating rate of one typical day for all three units. Surprisingly, the measured hourly heating rate was "flatter" than we anticipated. It seemed that the radiator was left on at full capacity all the time, and the heating rate was increased slightly only in the afternoon because the supply hot water temperature was slighter higher in the afternoon than the other period.

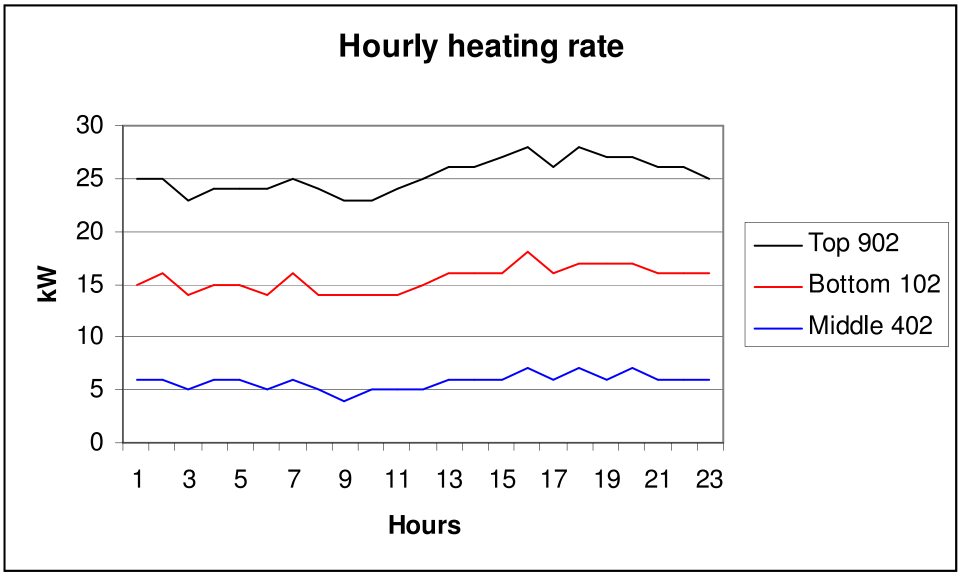

Figure 8 Hourly heating rate measured

Figure 9 show the comparison between the simulated hourly heating rates with the measured heating rates. Although the overall daily consumption was close to each other, in simulation, because the program need to maintain a constant air temperature throughout the day, the heating rate decreased more significantly in the afternoon period than that was measured.

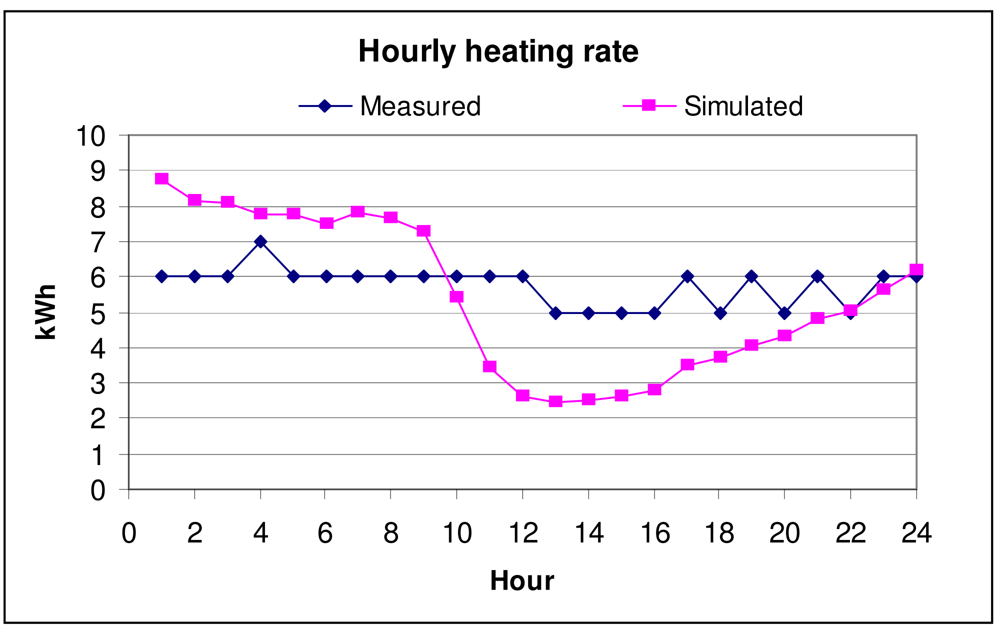

Figure 9 Hourly heating rate (measured and simulated)

One possible argument is that the thermal mass in the model is smaller than the real building. However, we did match the modeled thermal mass of concrete wall and floors with the real one. The more likely case is that in real building, the heating system was not controlled to maintain a constant temperature but to leave on at full capacity all the time. It is unclear the why the water flow was unchanged throughout the day. It may be caused by poor quality of radiator water control valves or because the temperature set points were too high and no one set them back.

3.0 Occupant behavior change

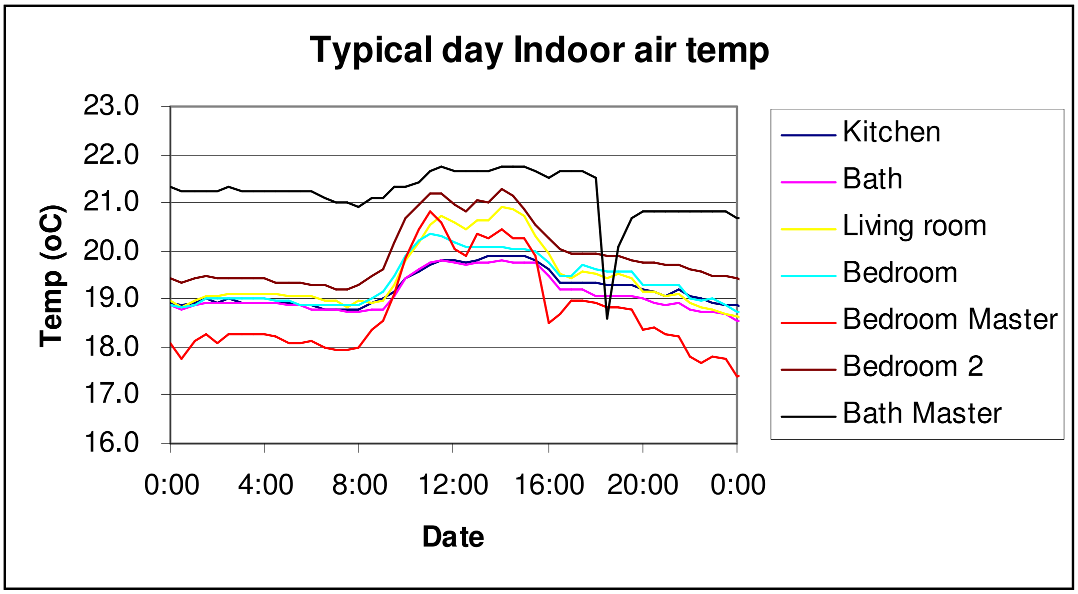

Figure 10 Typical day indoor air temperature

The goal of consumption basis billing is to encourage users to use their heating system more efficiently. More specifically, the occupants should avoid opening the window to cool the indoor air temperature when the indoor temperature is too high and setback the temperature during night and unoccupied hours. However, from the survey of 25 apartments, little behavior changes were observed.

We monitored the indoor air temperature to decide whether the users setback their temperatures. Figure 10 shows the typical day indoor air temperature for 24 hours. The temperature of each zone is different to each other. The internal zones, such as the master bath room were warmer than other zones. The master bedroom and living room temperature are generally low because of the large glazing area. It seemed that the indoor air temperature was not controlled to meet the set point. The temperature was always higher than 18 ^{o}C. During noon hours, the temperature was higher than 20 ^{o}C.

The problem gets worse for the top apartment units. Figure 11 shows the temperature of one top unit, 902. For many days, during the noon hours, the temperature was above 30 ^{o}C. In several extreme cases, for example, the maximum temperature was 44 ^{o}C. We talked with the local engineers and found out that the units change its heating system to floor heating. The heat exchange area increased significantly compared with radiator, but the supply hot water temperature was still very high. The apartment owner significantly oversized the heating system in 902. In general for all three units on the top that we recorded the temperature, the temperature seemed high. The heating system for the top unit may be oversized. Traditionally, design engineers in China typically size the heating system of top units much larger than the middle one because the units have poor insulated roofs. If the radiator was oversized, and occupant did not setback the set points, the indoor air temperature could be very high.

The survey confirmed the results of the temperature measurement. Out of the 25 occupant's survey, only one family claimed that they setback the temperatures; 23 occupants claimed they still use early morning ventilation. The behavior has no correlation with family income and size. The economic incentive does not seem to work in Huaxiajindian, even in poor families.

We investigated with the district heating company and occupants in the regions and summarize the following factors as the reasons why occupant did not change their behavior at all:

1) The incentive is not strong enough for the occupants in Huaxiajindian. Huaxiajindian is a high end apartment development. The average selling price is around RMB 15,000 per square meter or RMB 2,225,000 ($320,000) for a typical 150 m^2 unit. The heating charge is around RMB 20 per square meter for one heating season or RMB 3,000 per unit. The charge has a basic charge of RMB10/m^2 and the rest of the charge was calculated from the usage. Occupant typically pre-paid RMB 3,000 before the heating season starts and the district heating company will refund them back if they use less than the expected. The maximum saving is about RMB1,500 ($210) per season. The saving incentive is too little to make occupants change their behavior.
2) It is difficult to change behavior and reset the temperature. One typical unit has 5 radiators and 5 thermostat valve to reset. It is virtually impossible for occupants to change the setpoint value of all 5 of them three times a day. The only reset that some occupants used is to reset the set point for the entire heating season or shutting off the system when they leave the apartments for a long period of time. Daily reset is impossible.
3) The district heating company has developed lots of reach-out materials and was trying to educate the occupants on how to save heating energy. However, traditions were hard to break. Occupants like to open windows in the early morning and bring in fresh air.

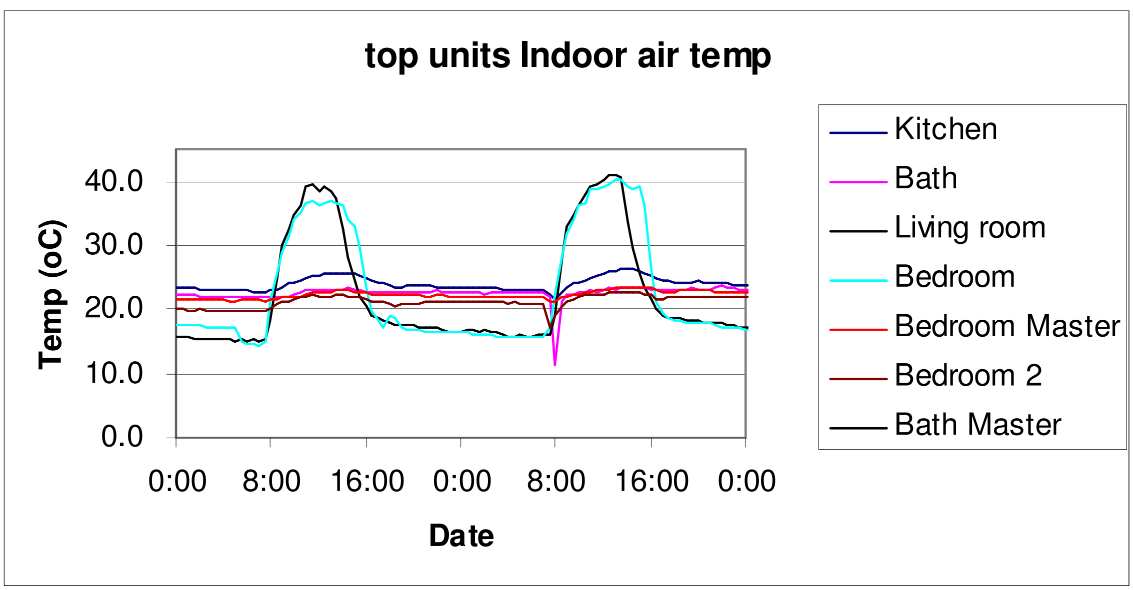

Figure 11 Indoor air temperature (top units)

4.0 Savings from integrated approach

After calibrating the baseline model of the current completed construction, we run the following scenarios to estimate the energy savings of the building:

- Case 0: Current construction
- Case 1: No insulation
- Case 2: Current design + No morning natural ventilation
- Case 3: Current design + Temperature setback at nights and unoccupied hours
- Case 4: Current design + No morning natural ventilation + Temperature setback at nights and unoccupied hours

Table 3 shows the results of the simulation runs of the different scenarios.

Table 3 Annual building heating energy consumptions

		Bottom units	Middle units	Top units	Whole building[1]
Case 0: Current	kWh	16,919	14,956	22,425	144,036
Case 1: No insulation	kWh	31,541	29,611	70,889	307,775
	% (Case1-current)/Case1	46%	49%	68%	53%
Case 2: No morning natural ventilation	kWh	16,521	14,375	21,496	138,642
	% lower than current (Case2-Current)/Current	3%	4%	4%	4%
Case 3: Temp setback at night and unoccupied hours	kWh	14,425	12,723	19,036	122,522
	% lower than current (Case3-Current)/Current	15%	15%	15%	15%
Case 4: Temp setback + no morning ventilation	kWh	13,885	12,235	18,478	118,008
	% lower than current (Case4-Current)/Current	18%	18%	18%	18%
	% lower than Case1 (Case4-Case1)/Case1	56%	59%	74%	62%

4.1. Current construction

In the current construction model, each unit has 1 m^2 window opening for one hour from 7:00 to 8:00 am. This information was from the occupant's survey. The current construction model has no temperature setback and this was consistent with the survey results. The top unit heating usage is about 50% higher than the middle and bottom unit. The annual heating rate of the whole building is 144,036 kWh, which transfers to 36 kWh per m^2.

4.2. No insulation

Building with no insulation is the baseline for 65% saving used in Tianjin's new energy efficient design standards for residential buildings (DB 29-1-2004). The baseline is a traditional brick building with no insulation in the walls and on the roof. Huaxinjindian is significantly better than the traditional building. Building as a whole is 53% more efficient than the traditional building. The savings from top units are larger than the other units because of the large insulation area on the roof.

[1] Whole building means 9 units in total, seven middle units, one top and one bottom units. Total occupied area is 1143 m^2.

4.3. No morning natural ventilation

One reason to add the heating meter to each individual unit is to avoid the wasteful behavior such as opening the window in the early morning to bring in fresh air. From thermal point of the view, morning is the worst time to natural ventilate a building because the low outdoor air temperature. If occupants stop opening windows, the saving will be around 4%, still small comparing with other improvement on shell.

4.4. Temperature setback at nights and unoccupied hours

Ideally, after installing the heating meter, the occupants should setback the temperature set points during night and unoccupied hours because of the economic incentives. However, we did not see that from the survey and it as confirmed from the temperature measurement. The simulation run showed that if the occupant was able to setback the temperature, the saving will be around 15%.

4.5. No morning natural ventilation + Temperature setback at nights and

This shows the combined effect of the behavior changes. Because of the metering of each individual unit, if the occupants were able to change both of these behaviors, the savings will be 18%. However, from the monitoring data and the survey results, Huaxiajindian failed to achieve this 18% savings.

5.0 Conclusions

Huaxiajindian is the first apartment complex we monitored in the pilot project. We conducted extensive monitoring and simulation work to figure out whether the integrated approach works. From the monitoring data, the survey and the building energy simulations, we draw the following conclusions:

- Compared with traditional buildings with no insulation, the baseline used in energy savings standards (DB 29-1-2004, the nine floor apartment building in Huaxiajindian reduced the heating consumption by 53%. The district heating company claimed that the distribution system was 5% more efficient than the old system and the boiler was 8% more efficient. In comparing the source energy, Huaxiajindian was 66% more efficient than the baseline in DB 29-1-2004.
- The effect of metering at each individual level is small. Little or no behavior changes were observed.
- With behavior changes, the savings could potential increase by another 18% from the current condition
- Heating loss through windows accounts for more than 50% of envelop heat loss. Future improvement should focus on balcony windows and reduce overall window K value

The building falls a bit short of meeting the 65% target for several reasons. The baseline heating consumption weighted too heavily toward wall and roof insulation and did not account for the heat loss through windows and infiltration as much as it should. In real usage, the main balcony facing south is not an unconditioned zone anymore and therefore the heat loss through balcony windows was much larger than what was expected in the standard. Second, the baseline in standard did not account for the natural ventilation heat loss in the early morning. Opening window alone increased the overall heat loss by 5%.

In the year 2008, we will start to work the evaluation of the second apartment district, Diliutianyuan. Early planning is extremely important for the success of the project. In the Huaxiajindian project, we lost some data because of the rushing to install the meter when heating season was approaching. The electricity meters and heating meters were installed after the heating seasons started in November. A secondary objective of this project is to analyze the impact of the improved building envelope thermal integrity (designed for enhancing space heating efficiency) on air conditioning requirements in the summer. We are planning to work with local consultants to collect monitoring data for the coming the summer cooling season and check whether the shell design improve the overall building energy usage and quantify the combined savings from heating and cooling.

We will conduct the following parametric simulation analysis to determine how to design and construct an energy efficient building in Tianjin.

- What is the best window to wall ratio in south? Direct solar gain increases with the window but conductance heating loss may increase as well with the window size. What is the trade off?
- What should the SC of south window be? What is the trade off between cooling and heating load
- How much will the building save with Low-E glass?
- How much more heating energy top units use more than the middle units? The information will be useful to define quota and fee structure.