A Retrofit Tool for Improving Energy Efficiency of Commercial Buildings

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ABSTRACT

Existing buildings will dominate energy use in commercial buildings in the United States for three decades or longer and even in China for the about two decades. Retrofitting these buildings to improve energy efficiency and reduce energy use is thus critical to achieving the target of reducing energy use in the buildings sector. However there are few evaluation tools that can quickly identify and evaluate energy savings and cost effectiveness of energy conservation measures (ECMs) for retrofits, especially for buildings in China. This paper discusses methods used to develop such a tool and demonstrates an application of the tool for a retrofit analysis. The tool builds on a building performance database with pre-calculated energy consumption of ECMs for selected commercial prototype buildings using the EnergyPlus program. The tool allows users to evaluate individual ECMs or a package of ECMs. It covers building envelope, lighting and daylighting, HVAC, plug loads, service hot water, and renewable energy. The prototype building can be customized to represent an actual building with some limitations. Energy consumption from utility bills can be entered into the tool to compare and calibrate the energy use of the prototype building. The tool currently can evaluate energy savings and payback of ECMs for shopping malls in China. We have used the tool to assess energy and cost savings for retrofit of the prototype shopping mall in Shanghai. Future work on the tool will simplify its use and expand it to cover other commercial building types and other countries.

Introduction

Globally, 35 percent of all energy used in buildings occurs in these two countries. The energy use in commercial buildings is predicted to increase by 0.9% and 2.7% per year from 2007 to 2035 for developed and developing countries, respectively (EIA, 2010). China has surpassed the US to become the world's largest energy consumer and GHG emitting country. Building energy efficiency has become an important policy for the Chinese government in order to meet its energy efficiency and GHG emission reduction target.

One of the building energy efficiency policies the Chinese central government developed is to support the retrofit of energy-intensive commercial buildings (or called "public buildings" in China). The central government has established a public building energy performance monitoring network to measure energy use of energy-intensive commercial buildings. The central government has also established incentive programs during the 11th Five-Year Plan (FYP) for retrofitting of energy intensive commercial buildings[1]. Commercial building retrofit has become one of the important building energy efficiency policies in China.

In the U.S., approximately 86% of current building construction expenditures are for the renovation of existing buildings and the remainder is for new construction. An estimated 14

[1] MoHURD provided 20 RMB/m2 with a total subsidy level of about 80 million RMB during China's 11th FYP (MoHURD, 2012). (6.3 RMBs equal 1 U.S. $.)

billion m^2 of existing buildings (approximately 50% of the entire building stock) will be renovated over the next 30 years (Zhai J., 2011; Holness, 2008).

Both countries pay great attention to commercial building retrofit programs. In order to better identify retrofit measures and evaluate potential energy savings and economics for existing commercial buildings, this study introduces a newly developed commercial building retrofit tool.

Methodology

To develop a retrofit tool for commercial buildings, we first developed a representative set of building characteristics (prototype). We performed energy simulations using EnergyPlus and cost data collected in the field are combined to obtain estimates of energy and cost savings of energy efficiency measures (ECMs). The simulations were performed for individual ECMs as well as for different a combination of ECMs. We have created a simple Graphical User Interface (GUI) for inputs. The GUI will assists in selecting ECMs before retrofit and calculating their value and after retrofit.

Prototype Building and Model Development

The prototype building energy model provides a baseline for the analysis of energy retrofits. Several studies have discussed developing prototypical buildings in US (Hale, et al., 2008; Field K., 2010; ORNL, 2007; InterEnergy Software, 2012). However, there is no existing research about commercial building prototype development in China. To develop a prototype retail building (shopping mall), we conducted a series of investigations and on-site surveys in the Shanghai area. The purpose of this investigation was to document the following features:

- Building general profiles (shape, floor area and operation hours etc.)
- Building envelope systems, including exterior walls, windows, roofs, door etc.
- Interior and exterior lighting systems
- Heating, Ventilation, Air-Conditioning and Refrigeration (HVAC&R) systems
- Internal equipment and plug load usage
- Building Management System (BMS) & Control System

Table 1. Summary of Characteristics of a Prototypical Retail Building

Item	Description
Function	Retail with restaurant on top floor
Floors	7 floors above grade, 2 floors underground (base: retail, sub-basement: parking)
Geometric contour	Rectangle
Area (m2) per floor	4000 (L*W = 40*100)
Operation Schedule	10:00-22:00
Building envelope	Ext-wall: U = 1.0 W/m2•K Roof: U = 0.7 W/m2•K
Fenestration	Window to wall ratio (WWR) = 0.2 Window: U = 4.7 W/m2•K (double clear pane) Shading: No
Lighting	Retail general lighting: 10 W/m2 Task lighting: 10 W/m2 Parking: 2.4 W/m2
Internal loads	Occupancy: 3 m2/person Equipment: 13 W/m2
Infiltration	0.63 ACH
External loads	Elevator and lift power: 4% of total electricity consumption Exterior lighting: 2.2 W per façade area (17:00-23:00)
HVAC air system	CAV Fresh air supply rate: 20 m3/(hr • person)
Cooling and heating source	Water-cooled centrifugal chillers (COP = 5.0) Gas boilers (efficiency = 0.8)
Pumps	Constant volume
Cooling tower	Constant speed fan
Room temperature set point	Cooling: 25℃; heating: 18℃
Supply air temperature set point	Cooling: 17℃; heating: 28℃
HVAC operation seasons	Summer season: 4/1 -- 10/31 Winter season: 1/1 -- 3/31, 11/1 -- 12/31

The Chinese building climate zone map is shown Figure 1. Based on the survey data, a retail building prototype was identified.

Table 1 gives a summary of retail prototype building systems in Hot Summer Cold Winter (Shanghai) climate zone. The building's floor plan and geometry are shown in Figure 2. The retail prototype building has seven above-grade floors and a two-story basement (B for retail and SB for parking lots), based on the survey results shown in Figure 3.

The prototype building's envelope system is developed in accordance with Chinese commercial building standard (MoHURD, 2005; Hong, 2009). According to our survey, the retail prototype building's lighting power intensity is slightly higher than the commercial building code. The internal plug load demand in a shopping mall mainly comes from sales equipment (including televisions). The HVAC system of the prototypical retail building in China is a constant air volume system. In some buildings, local fan coil units are used to supplement the constant volume outdoor air system. In large shopping malls, the typical central plant for cooling system is a centrifugal chiller and cooling towers. Natural gas fired boilers provide space heating for the building. In Northern China, district heating usually provides heating during winter heating season. Domestic hot water is not common in Chinese retail buildings.

Figure 1. Building Climate Zone in China

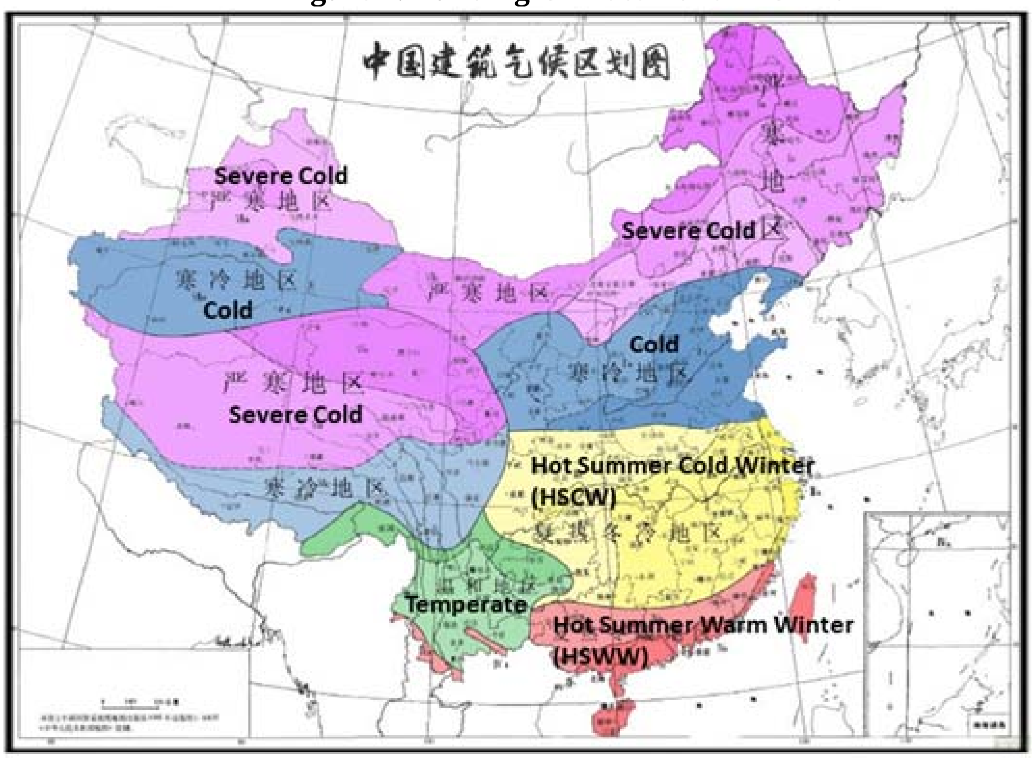


Figure 2. Floor Plan and Geometry of the Prototype Retail Building

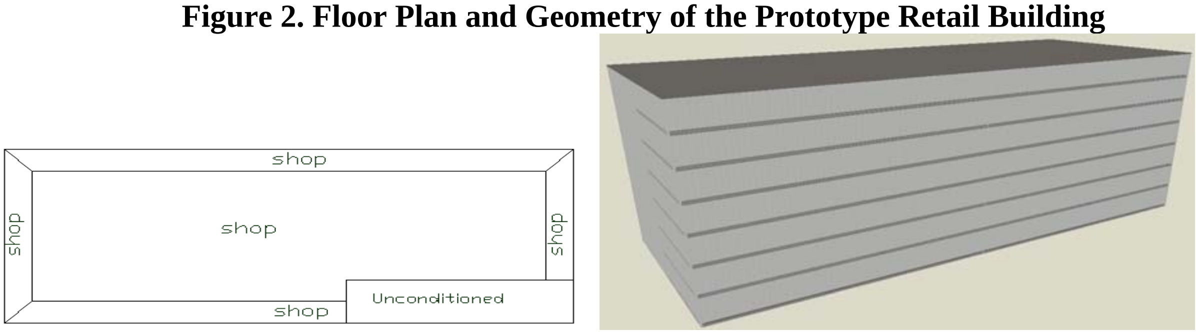
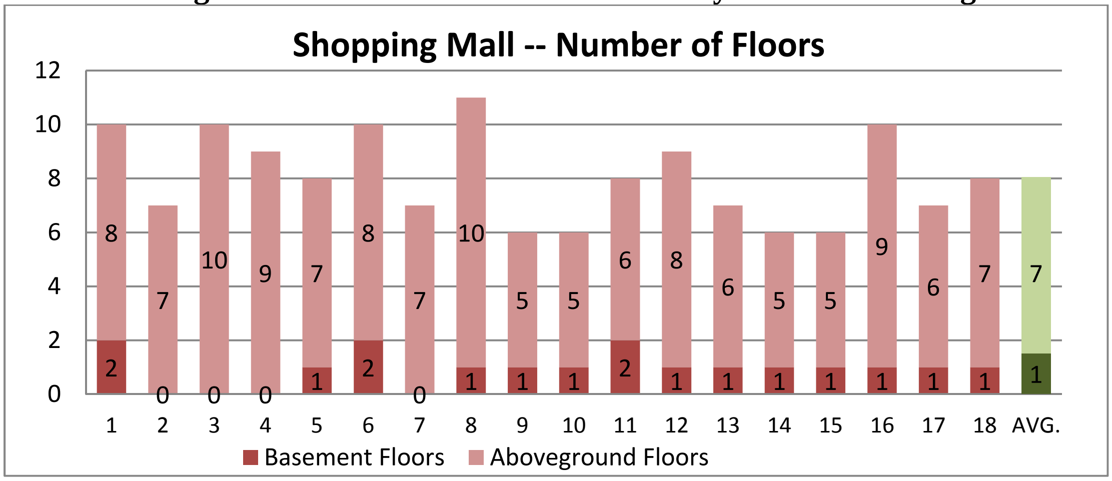


Figure 3. Number of Floors in the Surveyed Retail Buildings



Energy Conservation Measures for Retrofit

The retrofit tool groups ECMs into following categories:

- Building envelope
- Lighting system
- HVAC air-side and zone equipment
- HVAC plant system
- Refrigeration system
- Domestic hot water system
- Internal plug load
- Others

Over 90 measures are implemented in the tool. Some examples are:

- Color of exterior wall
- Insulation of exterior wall
- Measures to improve building air-tightness and reduce infiltration
- Color of roof
- Insulation of roof
- Window type (U value and SHGC)
- Window frame type
- Install internal shading
- Interior general lighting type (T12, T8, T15)
- Install reflective fixture
- Use efficient task lighting equipment
- Use efficient exterior lighting lamps, ballasts, and fixtures
- Install occupancy sensor
- Use BMS for lighting control and scheduling
- Boiler plant efficiency upgrade
- Heating supply water temperature control
- Chiller plant COP upgrade

- Chiller supply water temperature control
- Use BMS for chiller plant control, staging, sequencing, optimal start/stop
- Install VFD to control CHW, CWP and HW pumps
- Use energy efficiency pump motor
- Install VFD to control cooling tower fan
- Use water side economizer
- Install VFD on air handling unit fan
- Use BMS to control fan on/off, optimal start/stop
- Install outdoor air economizer
- Use proper room set point
- Air side supply air temperature control and reset
- Demand control ventilation
- Use energy efficient internal equipment
- Use VFD to control escalators
- Install energy recovery device for elevators
- Install PV device
- Use high-efficiency fans for refrigeration system's condenser side
- Reduce refrigeration display case lighting power

Sensitivity Simulation

There are basically two methods to develop the baseline for the analysis of ECMs. The first method starts from a prototype building (saved as a building energy simulation project template file--e.g. in EnergyPlus format). Following this approach, one can modify characteristics of such building elements as the envelope, lighting, HVAC system, geometry, etc. to create a new building model. This method permits the input of very detailed data describing the building. This approach requires considerable time and effort to analyze different combinations of multiple retrofit measures.

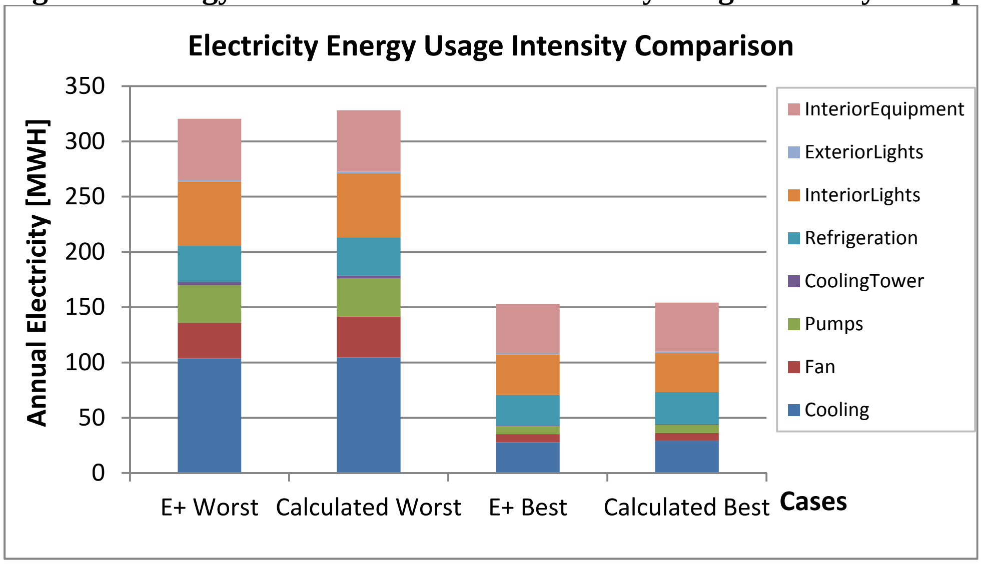
The second method also relies on using a prototype building energy model. A large number of ECMs are pre-simulated and the results built into a database. The pre-simulated results account for interactions among retrofit measures as well as user-defined building information. By accessing a stored database of energy savings of retrofit ECMs, time-consuming simulations (combined with high demands on the user to input descriptions of the ECMs.) are avoided.

In the second approach it is in principle necessary to conduct a very large number of sensitivity studies to encompass all options that the user might choose. Assuming that there are two options for each measure ("yes" and "no") and there are 30 energy conservation measures to choose from, one would need to simulate 2^30 (more than 1 billion) simulations to capture the whole spectrum of interactions. Even with existing computer capacity and sophisticated database management systems, this is not practical.

We have chosen the second approach (pre-simulated results) but with an important simplification to greatly reduce the needed number of simulations. We pre-simulate combinations of interacting measures (such as envelope, lighting, internal equipment etc.) If this set consists of two values for each of these measures and a total of 10 measures that interact with one another, then only $2^{10} \sim 1000$ simulations are needed. To estimate the HVAC energy use of the prototype building. In actual fact, a few tens of thousands of simulations were performed. The results of these simulations were used to extrapolate to new sets of measures.

The strongest test of this approach is to compare simulated and extrapolated energy use for the extreme cases of a very inefficient building (labeled "worst" in Figure 5) and a very efficient building (labeled "best.")

Figure 4. EnergyPlus and Calculated Electricity Usage Intensity Comparison



The "worst" case, for example, includes low R-value of insulation, high lighting power density and internal plug loads, low HVAC equipment efficiency, no VFD control, no advanced temperature control, no economizers etc., all set to be within the range of common experience.. The "best" case, conversely, has all measures that can be found in high performance buildings. Figure 5 makes clear that the extrapolation results are very close to results of EnergyPlus simulations. The difference between the two sets is mainly caused by the assumption that the change in HVAC energy use is linearly proportional to the change in building load. In fact, the equipment performance curves in EnergyPlus are generally non-linear and written in polynomial expression.

Retrofit Cost Data

Retrofit measure cost data are needed for economic analysis of the ECMs. Three types of cost data -- equipment/material capital cost, retrofit labor cost, and operation and maintenance (O&M) cost – are needed for each measure. The lifetime of the equipment and measures is not considered in this study but if available would improve the accuracy of the economic analysis. For the United States, a comprehensive cost database for retrofit measures is available (R.S. Means Co., 2011; Enkvist, Naucler, & Rosander, 2007). Since China construction material and labor cost is significantly different from the United States, we assembled a China-specific cost data set for this retrofit application.

Assume the total cost for retrofit measure *i* is C_i, the total annual cost savings are *X*, the input discount rate is *D* and the evaluation period is n. Then, the net present value savings for retrofit can be expressed as:

$$NPV_{savings} = [X + X/(1+D) + \ldots + X/(1+D)^{n-1}] - \sum C_i$$
$$\sim X[1 + D]/D \text{ for large n}$$

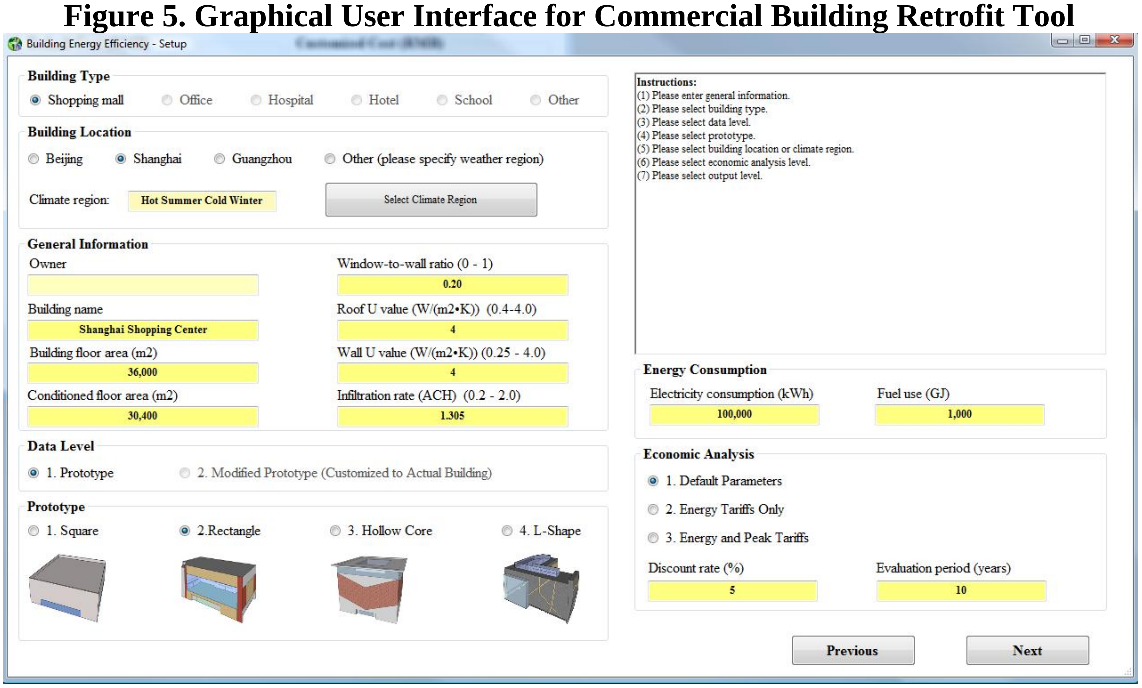
The annual energy cost savings data are used in this way to estimate benefits of building energy efficiency retrofit.

Graphical User Interface

The model has a bi-lingual (English and Chinese) graphical user interface (GUI). Input data include building type, climate region, and some building characteristics as well as measured energy use data for electricity and fuel (Figure 5). The model results will display the actual and simulated energy use (or an indicator of the magnitude of the difference between these energy values).

Operation and control conditions are used to tune simulation results for consistency between simulated measured energy. The user identifies starting conditions (base case building) for each of the ECMs (e.g., black roof) and the condition after retrofit (e.g., white roof) for all of the measures. The model provides estimates of costs and savings for each measure to guide the user. After analysis, the program reports the total energy savings, cost and payback period for the set of ECMs chosen (as compared with the base case building). Should users want to browse individual measures' energy savings and economic benefit, the GUI allows users to sort measures' results based on "net benefit", "payback period", and "saved energy".

Figure 5. Graphical User Interface for Commercial Building Retrofit Tool



Results

Figure 6. Retail Prototype Building Energy Usage Intensity in China Climate Zones

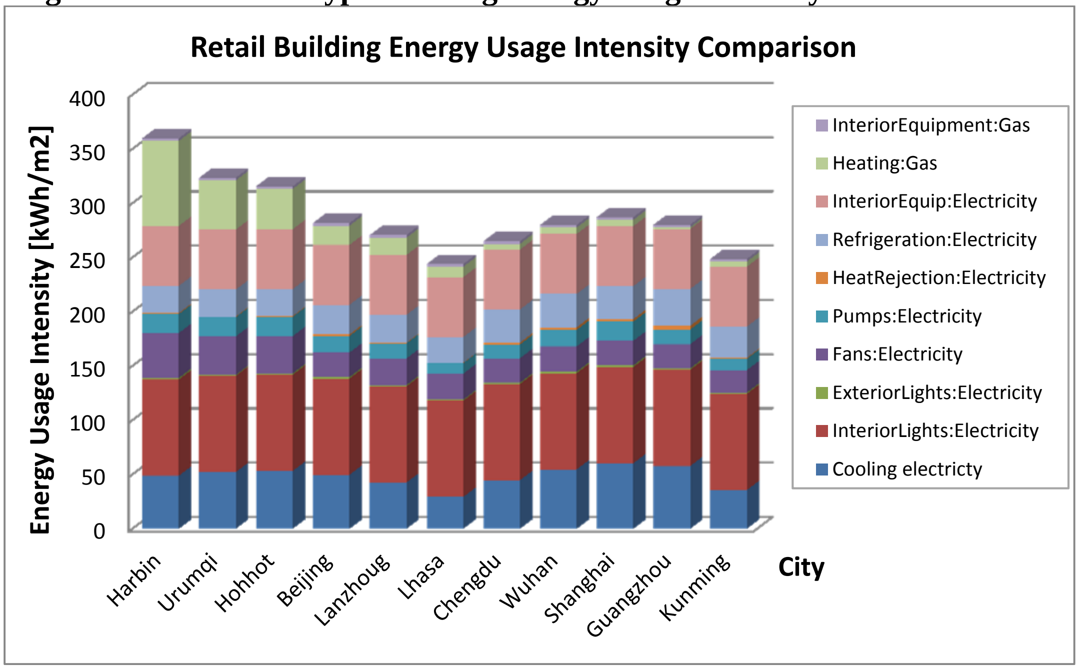
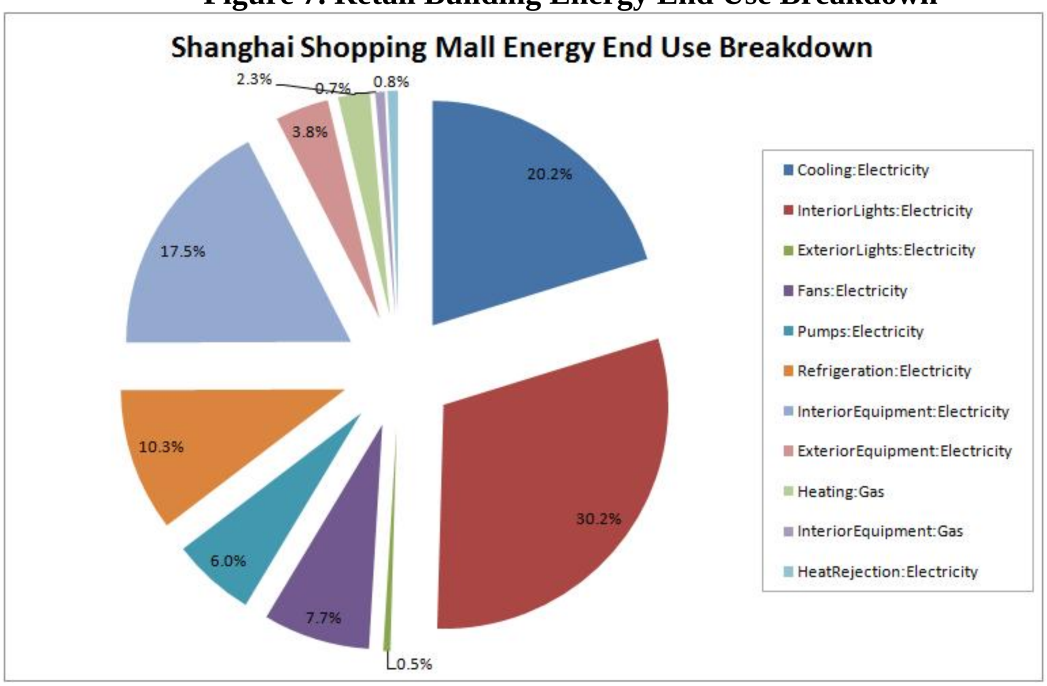


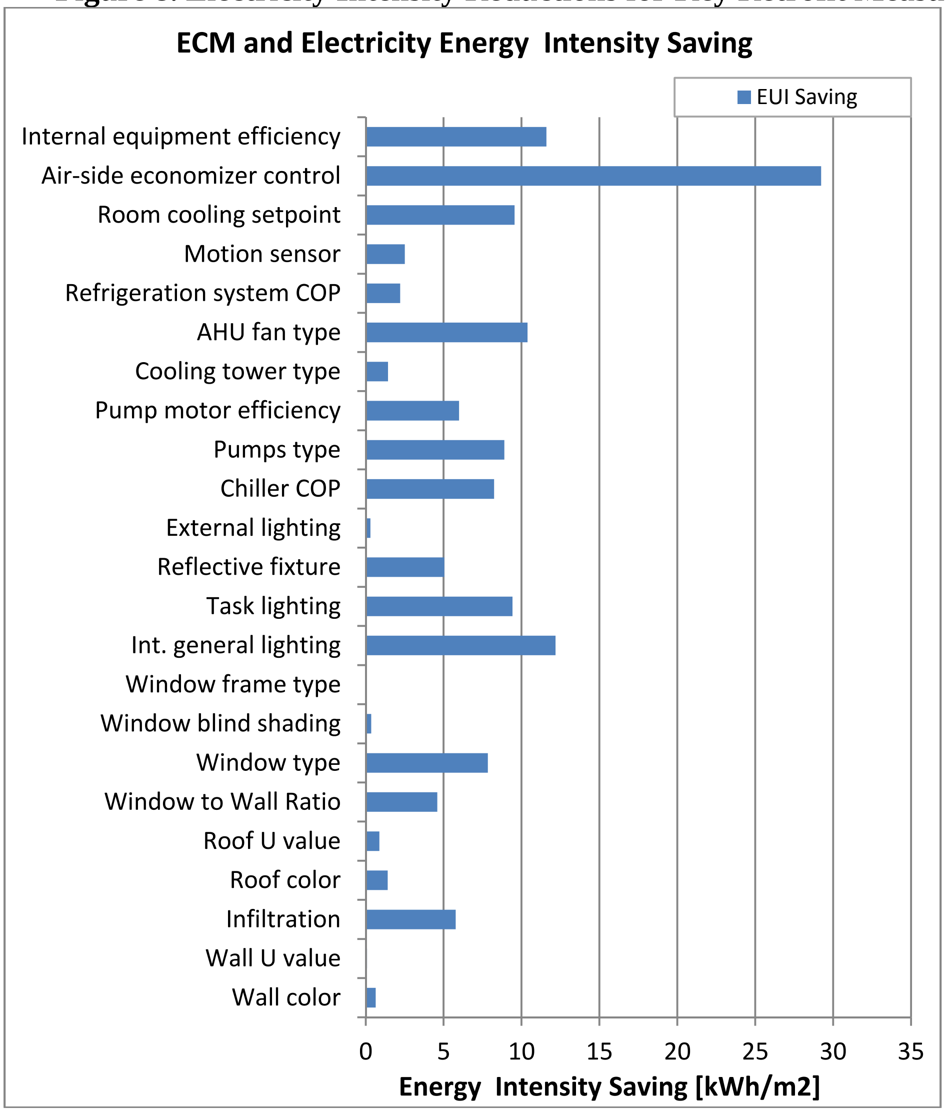
Figure 7. Retail Building Energy End Use Breakdown



The prototype building energy performance is simulated in major Chinese cities representing all five climate zones. Results are shown in Figure 6. Energy consumption is dominated by internal loads (lighting, plug loads, occupants). Cooling energy in shopping malls is mainly used to compensate for these large internal heat gains. As a result, the prototype shopping mall is only mildly sensitive to climate conditions, evident in the results in Figure 7. Figure 8 provides the breakdown of energy use by end use for the Shanghai (Hot Summer Cold Winter – HSCW) climate zone.

To evaluate the energy savings from retrofit measures, we use initial conditions as described in Table 1. Figure 8 shows energy savings for key retrofit measures in a typical shopping mall in Shanghai, as estimated by our computer model.

Figure 8. Electricity Intensity Reductions for Key Retrofit Measures



The air-side economizer produces the energy largest savings in the retail prototype building. The large internal heat generation results in a nearly constant cooling energy demand even in shoulder seasons and winter. This air-side economizer is thus able to provide free cooling for many hours of the year. Retrofit measures related to lighting and internal plug loads are generally large. The most cost-effective energy efficiency improvements through retrofits of HVAC systems are often improving pump performance and installing or repairing variable speed control for fans. In this study, the baseline case chiller reference COP value is already set at 5.0; this does not offer much cost-effective potential for chiller performance upgrade. Also, because the baseline building before retrofit already complies with Chinese commercial building energy efficiency code, and because the buildings are internal load rather than shell dominant, the measures applied to building envelope system generally do not produce much savings. However, if the target building is, for example, built in the 1980's and poorly insulated, the potential of building envelope retrofit is still significant.

Conclusions

This study demonstrates methodologies to develop a commercial building retrofit tool, and reports the energy savings results. The program uses a sensitivity run approach to quantify ECMs energy saving. The calculated energy savings are combined with cost data to estimate economic impacts of different retrofit strategies. Finally, the program provides a simple graphical user interface to help users define their building and retrofit measures.

The energy use of a baseline shopping mall is simulated. The computer model analyzes energy savings for this building for individual ECMs and for groups of ECMs.

Future research will focus on simplifying the computer tool for ease of use, adding building types, and refining the retrofit measure cost data.

Acknowledgment

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