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Investigating the Performance and Energy Saving Potential of Chinese Commercial Building Benchmark Models for the Hot Humid and Severe Cold Climate Regions

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INVESTIGATING THE PERFORMANCE AND ENERGY SAVING POTENTIAL OF CHINESE COMMERCIAL BUILDING BENCHMARK MODELS FOR THE HOT HUMID AND SEVERE COLD CLIMATE REGIONS

By

LESLEY ANNE HERRMANN

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The final copy of this thesis has been examined by the signatories, and we
find that both the content and the form meet acceptable presentation standards
of scholarly work in the above mentioned discipline.

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Investigating the Performance and Energy Saving Potential of Chinese Commercial Building Benchmark Models in the Hot Humid and Severe Cold Climate Regions

Thesis directed by Associate Professor John Zhai

The demand for energy in China is growing at an alarming rate. Buildings have become a significant component of the energy-demand mix accounting for nearly one-quarter of the country's total primary energy consumption. This study compares the building code standards for office and hotel buildings in the hot humid and severe cold climate regions of China and the United States. Benchmark office and hotel building models have been developed for Guangzhou and Harbin, China that meets China's minimum national and regional building energy codes with the integration of common design and construction practices for each region. These models are compared to the ASHRAE standard based US reference building models for Houston, Texas and Duluth, Minnesota which have similar climate conditions. The research further uses a building energy optimization tool to optimize the Chinese benchmarks using existing US products to identify the primary areas for potential energy savings. In the case of the Harbin models, an economic analysis has also been performed to determine the economic feasibility of alternative building designs. The most significant energy-saving options are then presented as recommendations for potential improvements to current China building energy codes.

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Chapter 1: Literature Review and Introduction

1.1 Introduction

China is one of the fastest developing countries in the world and as a result, energy consumption is increasing at an alarming rate. The China Sustainable Energy Project stated that, "The torrid pace of China's building construction is the largest and fastest in human history," (2008). In addition, the EIA reports that China is the largest producer and consumer of coal in the world and the second-largest consumer of oil (behind the U.S.) (EIA, 2009). What is particularly daunting is that the majority of China's electricity is generated from burning coal and many of the country's large coal reserves are yet to be developed. In addition, buildings have become a significant component of the energy-demand mix accounting for nearly one-quarter of the country's total primary energy consumption. This figure is expected to increase to 35 percent by 2030 (Zhou, et al., 2007). Currently, approximately 25 percent of the nation's green house gas emissions are attributed to the building sector (18 percent from commercial buildings along) (Hong, et al., 2008). Curbing the rate of energy consumption in China is urgent and improving the level of energy efficiency in buildings is one necessary measure that must be addressed.

Research at Laurence Berkeley National Laboratory has estimated the breakdown of primary energy consumption in the commercial building sector (also referred to in China as the public building sector), which makes up roughly 20 percent of the built environment in China (Hong, et al., 2008). As shown in Figure 1, coal accounts for roughly 89 percent of the total primary commercial building energy consumption, which is used indirectly for electricity generation or directly for space heating and hot water (Zhou, et al., 2007). Natural gas is estimated to make up only two percent of the energy mix for commercial buildings. There is obviously a great dependence on fossil fuel energy which will persist as the country continues its economic growth. The need for improving energy efficiency in buildings is more important than ever before.

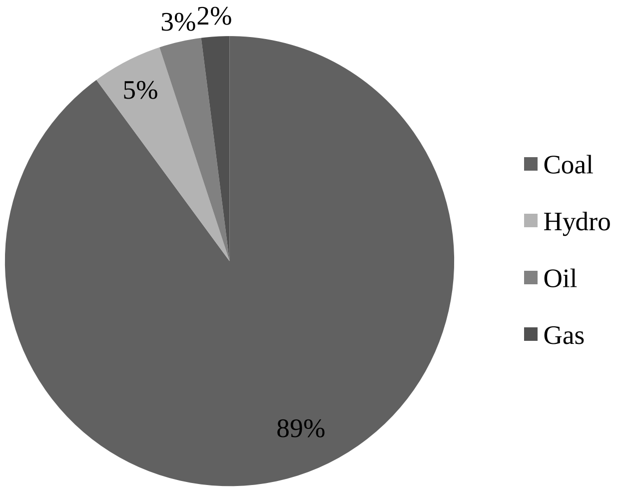

Figure 1: Commercial building total primary energy consumption in 2000 (Zhou, et al., 2007).

The commercial building sector includes a combination of building types including offices, hotels, education and religious facilities, retail stores, warehouses, and hospitals to name a few. Figure 2 shows the floor area distribution breakdown by subcategory in 2000 starting with offices making up 33 percent of the mix and continuing clockwise.

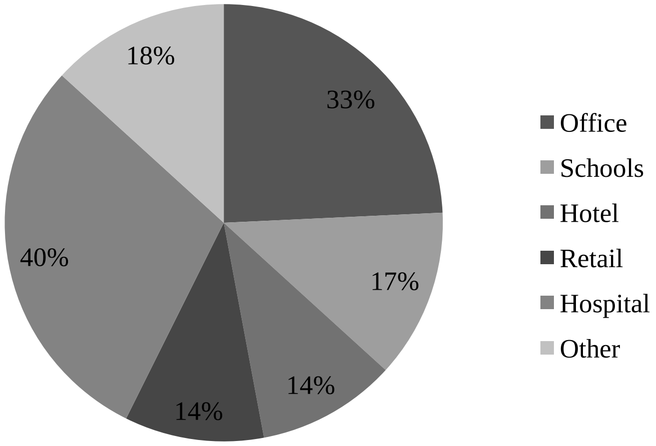

Figure 2: Floor area distribution in commercial buildings (Zhou, et al., 2007).

Trends in building energy consumption depend on the building design (including construction materials and heating, ventilation, and air-conditioning (HVAC) systems), and the functionality of the building. The major end-use energy categories in commercial buildings include sources of heating and cooling and all associated HVAC components such as fans and pumps, water heating, and electric lighting and equipment. The end-use energy breakdown of commercial buildings is shown in Figure 3 (Zhou, et al., 2007). Common methods of heating in China include coal, oil, and gas boilers, electric resistance, central combined heat and power (CHP) systems, air-source heat pumps, and geothermal heating systems. Common air-conditioning systems include electric powered central cooling systems, central gas systems, ground-source heat pumps (GSHP), and air-source heat pumps (Chmutina, 2010).

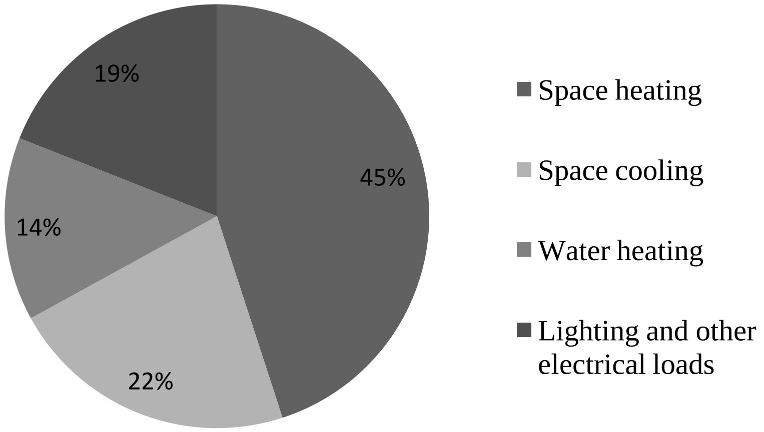

Figure 3: Commercial building end-use energy consumption (Zhou, et al., 2007).

1.2 Trends in Building Energy Consumption

Tianzhen Hong, from the Lawrence Berkeley National Laboratory, identifies some trends and establishes predictions associated with commercial building energy consumption in China in the article, *A close look at the China Design Standard for Energy Efficiency of Public Buildings.* He makes a clear point that building energy consumption has increased rapidly in relation to the country's economic growth. Furthermore, China seeks to quadruple its gross domestic product (GDP) between 2000 and

2020 while doubling energy consumption. In the past 35 years, energy consumption in commercial buildings rose from 10 percent of the nation's total primary energy in the late 1970's to more than 25 percent in 2006 (Hong, 2008). This fraction is expected to increase to 35 percent by the end of the next century.

This article also points out specific trends in energy consumption in Chinese commercial buildings. First, heating energy tends to be quite high in the northern regions where cold weather accounts for much of the year. This is due to inefficient or improperly sized heating distribution systems, poor HVAC system controls and management, poor building envelope design and construction, and relatively low heating prices. N. Zhou (et al., 2007) suggest that space heating alone accounted for about 45 percent of total end-use energy consumption in 2000, as shown in Figure 3 above. However, Chinese experts anticipate heating energy intensity to decline as construction circumstances improve and the price of energy increases (Hong, 2008). In contrast, cooling energy is expected to increase as comfort levels in buildings improve with the use of mechanical air conditioning. Lighting energy is expected to increase most dramatically as lighting levels in buildings improve. This may be offset with the use of new lighting systems that are much more efficient. Electrical equipment is also expected to increase with the use of more office equipment. The increase in internal electrical loads could then lead to increase cooling requirements and hence an increase in cooling energy. Hong estimates that the primary energy consumption in commercial buildings was five quadrillion BTUs in 2005, 50 to 60 percent of which corresponded to HVAC systems and 20 to 30 percent corresponded to lighting. The researchers project primary energy consumption will increase to about 13 quadrillion BTUs by 2020 (Hong, 2008).

Given the fact that China has recently surpassed the US as the world's largest emitter of CO_2, environmental impacts could be are very detrimental and even catastrophic if a strategic action plan is not carried out quickly! The Chinese government is aware of the immense consumption of energy in buildings and of the risks involved with heading down the "business-as-usual" path. As a result, significant efforts have been given to building energy efficiency, including the development of a national building energy code.

1.3 The Chinese Building Energy Code Standard

In response to the concern over increasing energy consumption rates, the Chinese government has developed a national building code standard which aims to achieve a 50 percent energy savings over typical buildings built in the 1980's. (Xu, et al., 2009) Some local governments have also developed regional building code standards that set more stringent conservation measures. The national building code is relatively new compared to the history of building codes in the United States.

The first building code standard was developed for residential buildings in heating dominated climates in 1986. This standard set the goal of achieving 30 percent energy savings over pre-existing construction built in the early 1980's. It was revised in 1995 to achieve 50 percent savings from again this early 1980's reference point (Xu, et al., 2009). In 1993, a standard for hotels was formulated over concerns regarding the growing energy demand in "Western-style" hotels. This was followed by other residential building standards for the hot-summer, cold-winter climate region and the hot-summer, warm-winter climate region in 2001 and 2003, respectively. It wasn't until 2005 that a national energy efficient design standard for public buildings was adopted. Today, this standard is known as *National Design Standard for Energy Efficiency of Public Buildings* (GB 50189-2005) and is often referred to as *the Standard*.

The Standard was developed by the Department of Science and Technology, was introduced and is led by the Ministry of Housing and Urban/Rural Development (MOHURD, formally the Ministry of Construction, MOC), and are implemented by local governments. In addition, the China Academy of Building Research provides technical support. The enforcement of the standard is generally better in large cities compared to smaller cities and towns. Recently, there have been efforts to go beyond the building standards; building performance ratings and green building rating systems, such as LEED ® in the United States, have been developed in addition to other programs including the Green Olympic Building Assessment System and the Evaluation Standard for Green Buildings. However, these programs are not widely used and are still under development.

The strategy used to develop the Standard is simple. Baseline building models for common archetypes were developed based on the characteristics of the typical public buildings constructed during this time period. The lighting power density of the models was set to comply with the national lighting standard (GB50034-2004). The models were then simulated with proposed building envelope properties and HVAC system efficiencies until the model achieved an annual energy savings of 50 percent. The resulting envelope and HVAC efficiency measures were then taken as the minimum requirements for the Standard. This approach was applied in four of the five climate zones to create a region-specific national standard; these climate zones include the Sever Cold Region, Cold Region, Hot-Summer Cold-Winter Region, and the Hot-Summer Warm-Winter Region. There are no specific codes for the Temperate (Mild) Region, but buildings must comply with codes from the climate region with the most similar climate (Hong, 2008). These regions are shown in figure 4 (Hong, 2008). The Standard is divided into two categories, one for the building envelope and the other for HVAC system efficiencies. The Standard also refers to three existing national standards for lighting and HVAC equipment efficiencies, namely the 2004 standard for lighting (GB50034-2007), the 2004 chiller rating system (GB19577-2004), and the 2004 packaged air-conditioning unit rating system (GB1956-2004).

Figure 4: Climate Zones of China.

The standard lists mandatory requirements for the building envelope, HVAC systems, lighting power densities, shape, and window and skylight areas as was mentioned previously. These include maximum U-values for exterior walls, roofs, and floors, minimum thermal resistance values for slab-on-grade floors, and below-grade walls, and maximum shading coefficients and U-values for glazings. The Standard also specifies a required percentage of operable window area for some regions, making natural ventilation a practical option. It is important to point out that outdoor-air requirements, infiltration rates, and temperature set points are recommended but *not* mandatory. Specific details regarding wall properties, window materials, lighting and equipment power densities, and HVAC specifications will be presented within the context of this thesis in the appropriate sections. Currently, the Standard does not include a performance path option for compliance.

1.4 Lack of Compliance

Many of the reviewed articles point out that compliance with the national and local codes are weak. For example, Hong (2008) suggests that only four percent of all building perform according to the Standard; L. Yang (et al., 2008) determined that the overall thermal transfer value (OTTV) of building envelopes is on average 30 greater than a building that complies with the Standard (OTTV is a measurement of heat transfer through the exterior envelope from outside to inside); Liang (et al., 2007) determined that of the 411 new buildings surveyed in their research of public buildings in China, only 20 percent complied with the Standard. Once more, according to a government survey carried out by the Ministry of Construction in 2000, only 2.1 percent of new construction in the surveyed areas complied with the Standard (Yao, et al., 2005). A disappointing trend is fairly obvious.

Chmutina points out in a discussion paper that the thermal performance of building envelope construction in China is less than that in developed countries with similar climate conditions. Yang (et al., 2008) suggests this as well in a report that highlights the findings of an in-depth study on building envelope performance. Here, the thermal properties of commercial building envelopes (exterior walls, roofs, and windows) were compared to local Chinese codes and to AHSRAE Standards for four climate regions, namely the severe cold, cold, hot summer cold winter, and hot summer warm winter regions. The results show a few important points. First, in most cases, the surveyed buildings do not meet the local codes for envelope thermal performance. This suggests that potential energy savings can be achieved by simply implementing stricter compliance mechanisms of existing building codes. Second, the report suggests that the in some instances, local Chinese codes have higher standards than those stated by ASHRAE for similar climate regions but in general, ASHRAE is better in most cases. The results of Yang's (et al., 2008) study are summarized in Table **1**.

There are a number of suggested reasons why building codes are not well implemented in China which are described in the following section.

Table 1: Summary of Building Envelope Design U-values [W/m^{2}K] (Yang et al., 2008)

		Average Surveyed	Local Code	ASHRAE Standard	Local Code better than ASHRAE	Surveyed buildings better than Local Code
Severe Cold	Exterior Walls	0.50	0.40	0.51	Yes	No
	Windows	2.57	2.20	2.61	Yes	No
	Roof	0.37	0.30	0.36	Yes	No
Cold	Exterior Walls	1.05	0.50	0.86	Yes	No
	Windows	2.89	2.30	3.24	No	No
	Roof	0.74	0.45	0.36	No	No
Hot Summer, Cold Winter	Exterior Walls	1.51	1.00	0.86	No	No
	Windows	3.37	3.00	3.24	Yes	No
	Roof	0.61	0.70	0.36	No	Yes
Hot Summer, Warm Winter	Exterior Walls	1.7	2.01	3.29	Yes	Yes
	Windows	5.24	-	6.93	-	-
	Roof	0.48	0.54	0.36	No	Yes

1.5 Barriers to Building Energy Efficiency Implementation

As mentioned previously, building standards have only recently been developed and unfortunately, implementation and compliance is rather pathetic. Yao, (et al., 2005) points out a few key barriers that slow the implementation of these building energy codes including the lack of 1) markets, 2) political will, 3) education, and 4) supporting resources.

Markets: Building codes, including the Standard, were developed based on energy savings alone and did consider the corresponding economic impacts. It is a common perception that energy efficient buildings have a higher capital cost but can be shown to have long term economic benefits. Therefore, it is important to consider the *total lifecycle cost* of energy efficiency improvements. The higher capital cost of efficient building designs has been enough to obstruct the implementation of the Standard. Yao, et al., 2005 also suggests that unbalanced local economic levels lead to uneven implementation of building codes, as it is evident that code enforcement and compliance is much less prevalent in smaller cities and towns than in larger cities. Since design decisions are typically based on economic motives, it is essential that energy efficient buildings prove themselves as marketable, affordable and a good long-term investment for the building owner!

Political will: Another barrier relating to this point is the fact that building codes in China do not address customized jurisdictions or innovations for specific *local* regions. In addition, there is little legislation to enforce the standard.

Education: Many Chinese building designers and builders are unfamiliar with the content and requirements pertaining to building codes. In addition, many of the construction workers lack the skills and motivation to build a building according to specifications.

Supporting Resources: There is a lack of detailed guidelines and other necessary tools available for building designers. Additionally, building materials are not always accessible in every region of the country. Energy efficiency cannot improve without proper tools!

1.6 Recommendations for Improving Implementation and Enforcement

In response to these barriers, lists of recommendations have been established by Yao (et al., 2005) that may improve the compliance of building codes. The first recommendation is to introduce stricter legislation by local governments. Government officials should be knowledgeable about the content of the code and the definition and benefits of compliance. There should be an easy mechanism for conformity that allows for quick processing and approval. The second is to create an incentive policy (or policies) to encourage efficient building design. These could be a set of divers mechanisms that target both the building and energy economy. Thirdly, a more detailed set of building specifications and guidelines should be made accessible to builders. This could include online literature resources, energy modeling tools, and other documentation sets made widely available at the designer’s and builder’s disposal. Fourthly, necessary building materials must be widely available! Materials, such as insulation, fenestration products, and HVAC equipments, must be made easily accessible in all regions of the country as it is impossible to comply with building codes without the necessary products. These materials/products should also be promoted in some way, perhaps through special advertisements, tax incentives, and or government rebates. The fifth recommendation involves commissioning. For a building design to meet a prescriptive list of code standards is one thing, but to assure the building is built *and operates* according to that design is another important consideration that must not be overlooked! A performance assessment requirement should most definitely be incorporated into the requirements for code compliance. This is may be another avenue for job creation. Lastly, international cooperation should be highly encouraged and prompted to accelerate the technology transfer of materials and building design. Note that the use of imported building materials may have a higher lifecycle carbon footprint due the embedded energy consumption associated with transportation. However, some manufacturing methods may be more energy efficient in countries other than China. It would be ideal if all of these factors All of these factors should be considered when selecting building products. (Note, this should *not* be mistaken with the promotion of increased use of imported building materials, as imported produces may have a higher carbon foot print[1] than those that are manufactured locally. On the other hand, some manufacturing methods may be less energy intensive in countries other than China. Although embedded energy costs and greenhouse gas emissions are very difficult to track they should not be overlooked. Consideration should also be given to how using local materials could benefit local economies.) Developing countries like China can benefit from the “leap-frog effect, ”that is, by moving to a higher level of energy efficiency at a much faster pace than other countries by implementing technologies and strategies that have been developed, tested, and proven effective in other parts of the world. The atmosphere has no borders; every additional gram of green house gas emitted, whether emitted from a coal-fired power plant in China, a wood-burning stove in Guatemala, or from a plow-tractor in a corn field in Iowa, has an effect on the entire global population!

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[1] A carbon footprint is a term that often refers to the amount of carbon dioxide equivalent (CO_2e) or greenhouse gas emissions associated with the production, transport, and use of a particular product. It can also refer to an event, organization or lifestyle.

In an article titled *Energy Efficiency in China: Accomplishments and Challenges* (Stinton, et al., 1998), other barriers to code implementation are addressed. One of the major barriers includes the structure of the energy market. Historically, energy prices in China were strictly planned by the central government. It wasn't until 1980 that the government began the first stages of deregulating the energy market. Pricing mechanisms have been shown in many countries to be an important factor in energy efficiency improvements as market-based economies induce price signals that have a critical impact on energy use. Although China has come a long way in the reforming process, progress has been "tortuous and slow," and multi-track pricing systems remain in effect for electricity in some areas. Needless to say, problems still persist. For example, although coal prices are now market-based and relatively stable, they do not include any of the negative externalities associated with the production and burning of this fossil fuel, nor are they predicted to in the near future.

Indeed energy prices are important in the promotion of energy efficiency, but Sinton, et al. suggests that the cost of energy will not be enough to promote efficiency and curb consumption. This is due to the fact that major driving forces in investment decisions spawn from the desire to meet market demand as quickly and as cheaply as possible. As stated previously, efficient building designs tend to correspond with higher up-front costs. This is where government-developed incentives can be helpful. Although the energy market reform has helped create a moderate pricing scheme for energy, it has unfortunately weakened, or in some cases eliminated, existing energy efficiency incentives and have degraded China's technical energy management apparatus. For example, tax rate reductions and tax holidays in place before the reform were abolished upon the creation of new simplified tax codes; energy conservation services centers have lost a significant amount of government funding; and the government-controlled areas of decision making are far less than a short period ago. Sinton, et al. state that there is a definite lack of national incentive programs causing a major gap in the countries efforts to encourage efficiency. In addition, banks far less likely to subsidize low-interest loans for efficiency projects and are less willing to lend their money for these projects. They often consider energy efficiency projects risky due to the stability of energy prices incurred by the development of low-cost coal fired power plants.

Sinton, et al. also provides recommendations pertaining to these obstacles. First, it is suggested that organizational institutes that focus on energy efficiency and conservation be transformed in ways that will sustain their existence under the new energy market. This will be far more productive than rebuilding these organizations in the future. Second, the government must conduct focused energy efficiency policy research that will prove to be valuable and robust against many future uncertainties. International cooperation is also suggested. Thirdly, it is suggested to quickly redesign and strengthen the data-gathering methodologies at the firm and national level which will assist with the policy development. Lastly, funding should continue to support efficiency investments; how these funding mechanisms will be structured and to what areas deserve attention should be thought out critically. This article concludes by saying that China's leaders have previously proven themselves to be concerned about and committed to the implementation of energy efficiency and that this is a sign of optimism.

The implementation of building code standards could lead to an entire realm of new jobs for the Chinese economy. As mentioned above, these jobs could come from the development of resources and tools, the distribution of education, and on-site inspection and commissioning associated with compliance.

1.7 Chinese Commercial Building Benchmark Development

Benchmark buildings for the Chinese office and hotel buildings have recently been developed for the hot summer warm winter climate region and the severe cold climate region. The representative cities are Guangzhou and Harbin, respectively. Research continues on models of these building types for the hot summer cold winter and cold climate regions, represented by Nanjing and Shanghai, respectively. Office buildings and hotels are selected for a few reasons. First, these two building types make up a large percentage of the energy consumption associated with Chinese commercial buildings. Secondly, architects and design professionals predict a large growth in office and hotel construction in the near future (Zhai, Chen, 2009). Lastly, the occupancy and operation schedules of these building types are more regular and easier to predict than other building types (such as hospitals and retail stores) which leads to a better estimation of building energy consumption.

Developing these models requires critical input data including building construction, internal loads, and HVAC efficiencies. In most instances, this information is taken from the national or regional standards, in which the most stringent values are used. However, some input parameters including but not limited to building aspect ratio, orientation, number of floors, and window to wall ratios, are not explicitly stated in either the national or regional code and are therefore based on assumptions. These assumptions are made based on industrial experience, design practice, or the analysis of existing building patterns (Zhai, Chen, 2009).

The Chinese benchmark models used in this research document typical building design practice and use patterns of public buildings in four climate regions of China. In addition, these models will serve as starting points for energy efficiency research and other energy modeling simulations. The benchmarking research for China is an assignment under the Asia-Pacific Partnership (APP) agreement through the National Renewable Energy Laboratory (NREL). As a joint proposal among seven partner countries, the APP aims to accelerate the development and implementation of clean energy technologies and energy efficiency. Furthermore, the Department of Energy’s Office of Energy Efficiency and Renewable Energy is working with its Chinese partners to improve the energy efficiency of China’s rapidly growing commercial building sector. By using building simulation tools developed by NREL, the APP will formulate recommendations that can help Chinese authorities form future commercial building energy codes (Zhai, Chen, 2009).

1.8 Chinese Benchmark Building Model Energy Consumption Validation

In an article titled *Survey of Commercial Building Energy Use in Six Cities in South China,* Joe Huang presents the findings of over 400 building surveys carried out in six cities across Southern China. These six cities include Shanghai, Wuhan, Chongqing and Chengdu, representative of the Hot Summer Cold Winter region and Fuzhou and Shenzhen, representative of the Hot Summer Warm Winter region. The types of buildings surveyed include government offices, public offices, hotels, shopping mall and small offices, college buildings, hospitals, food stores, multi-function buildings, air port terminals, libraries, and stadiums. During the survey, information pertaining to the size and function of the buildings, their annual energy consumption, and some detailed HVAC specifications. Unfortunately, utility data for many of the buildings was not available so the information was collected from reports published b the SECSC of Shanghai.

It should be noted that all fuel-use values are conventionally reported in kWh in China. Huang states that “this implicitly neglects a source multiplier of electricity [so it is] misleading to compare heating and cooling energy consumption without recognizing these values are site energies of natural gas for heating and electricity for cooling.” (Huang, 2010)

The average, minimum, and maximum EUI (kWh/m^2) for office and hotel buildings built in the last decade are compared to the Chinese benchmark values to gage the relevant accuracy of the electrical energy consumption in the benchmark models. The average and extreme EUI values in Figure 5are taken directly from Huang’s article and the EUI values for Beijing in Figure 6 Figure 7 are taken from the “Large scale commercial building energy efficiency” database from Tsinghua University (T.U., 2010) . Recall that the EUI values listed in the survey have been converted to kWh equivalents and represent site energy consumption values. The comparison shown in Figure 6 and Figure 7 divide the electricity end use energy into categories including electrical equipment, lighting, and specific HVAC equipment. Heating energy is not included in this comparison because the database did not include EUI data for this end use category. It should also be mentioned that the reference data used for this validation is not ideal given the difference in climate regions but are the extent of the literature search findings. The comparison of the Guangzhou benchmark models to the surveyed data in Figure 5 can be confidently validated while those for Harbin may be less comparable given the difference in climate. The EUI breakdown in Figure 6 and Figure 7 provide a confident comparison for lights and equipment power densities for both models but the HVAC energy intensity values should be loosely interpreted.

Figure 5 shows that the electricity EUI for most of the benchmark building models are near the average of the surveyed buildings. The vertical lines represent the range of EUI values of the surveyed buildings and the black diamonds represent the average.

Table 2 lists the corresponding EUI values and the percent difference between the average surveyed building and the benchmark models. As mentioned above, it may not be fair to compare the EUI values for the Harbin case to the survey data due to the fact that the surveyed buildings are located in the southern region of China and have different heating and cooling patterns but the results do verify that the benchmark model's consumption values for this climate region are not outrageous.

Consumption data from the "*Large scale commercial building energy efficiency database*" provides a breakdown of end use EUI values which is helpful in verifying the EUI of particular end use categories including lighting, electrical equipment, and components of HVAC energy. Figure 6 and Figure 7 show a number of interesting points. First, the average electricity EUI for office electrical equipment shown in Figure 6 is 125 percent greater in the benchmark models compared to the value in the database. This difference may be related to an over estimate of occupancy density (that is, if equipment power density is derived based on the average equipment use per person). Second, lighting energy consumption in the office benchmark models is within ten percent of the database values, as is the auxiliary HVAC energy for the case of Guangzhou. Lastly, cooling energy associated with the chiller in the Guangzhou model is greater than that of the database which is to be expected, as Guangzhou is located in a much hotter climate region than Beijing. However, this difference may also be due to an over estimate of internal gains. Heating energy has not been compared due to the lack of available data presented in the database from Beijing.

As shown in Figure 7 hotel equipment power density is about 40 percent greater in the benchmark models compared to the database while the lighting power density is 125 percent greater. Energy associated with the chiller in the Guangzhou hotel model is greater than that of the database; the same justification applies to this model as with the Guangzhou office model. Cooling energy is lower in the Harbin model compared to the database which is again expected given that Harbin is located in a colder climate region than Beijing. The fan energy in both models is significantly less in the benchmark models compared to the database. This may be due to the low pressure drop which is used in the models (40 Pa) and may also need to be reconsidered. Values corresponding to Figure 6 Figure 7are listed in Table 3.

In general, the benchmark building models' annual EUI falls within acceptable ranges when compared to the overall EUI of the surveyed buildings. There are a few concerns regarding the office models' equipment power density and the lighting, fan, and equipment power density in the hotel models. The high equipment power density in the office may be associated with the high occupancy assumption. It is recommended that the pressure drop of the fans be confirmed. It is also recommended that LPDs and EPDs surveys be conducted in actual buildings in Guangzhou and Harbin to confirm or improve the values used in the models.

Table 2: Benchmark EUI Comparison to Surveyed Buildings [kWh/m^2]

	Benchmark EUI	Survey Max EUI	Survey Min EUI	Survey Average EUI	Benchmark Percent Diff from Survey Average
Harbin Office	118.3	342.2	5.1	99.6	15.8%
Guangzhou Office	127.9	342.2	5.1	99.6	22.1%
Harbin Hotel	184.8	388.8	51.4	172.6	6.6%
Guangzhou Hotel	121	388.8	51.4	172.6	-42.6%

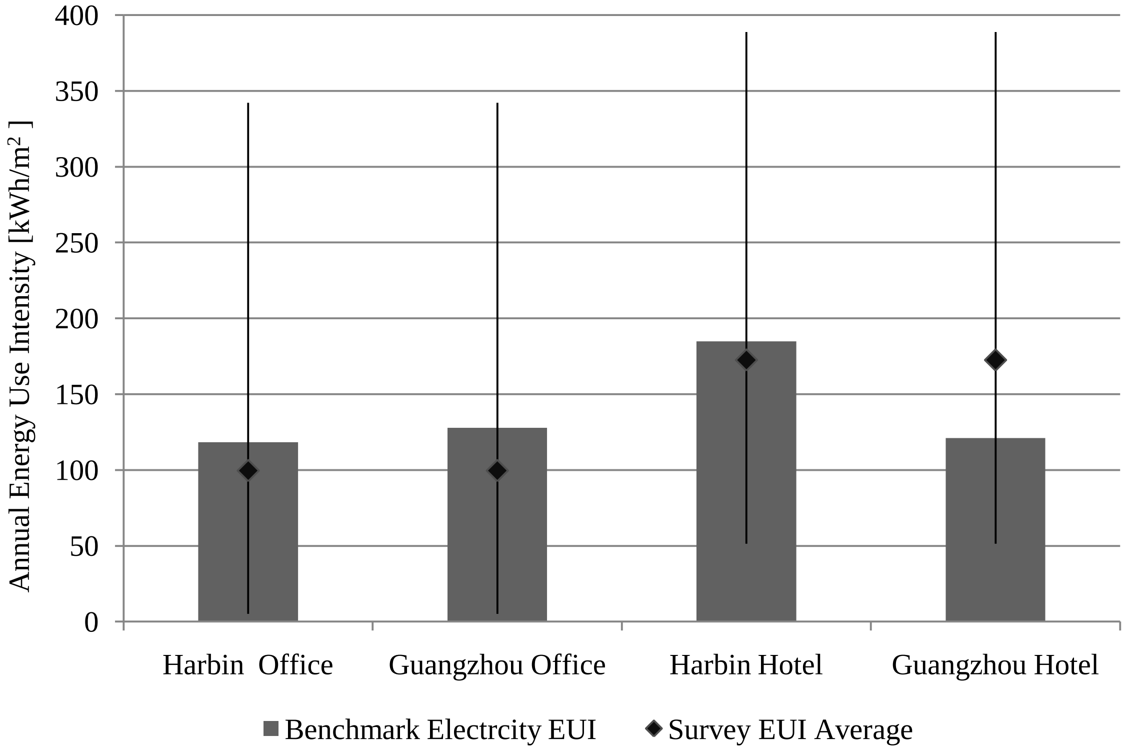

Figure 5: Benchmark EUI values compared to surveyed buildings.

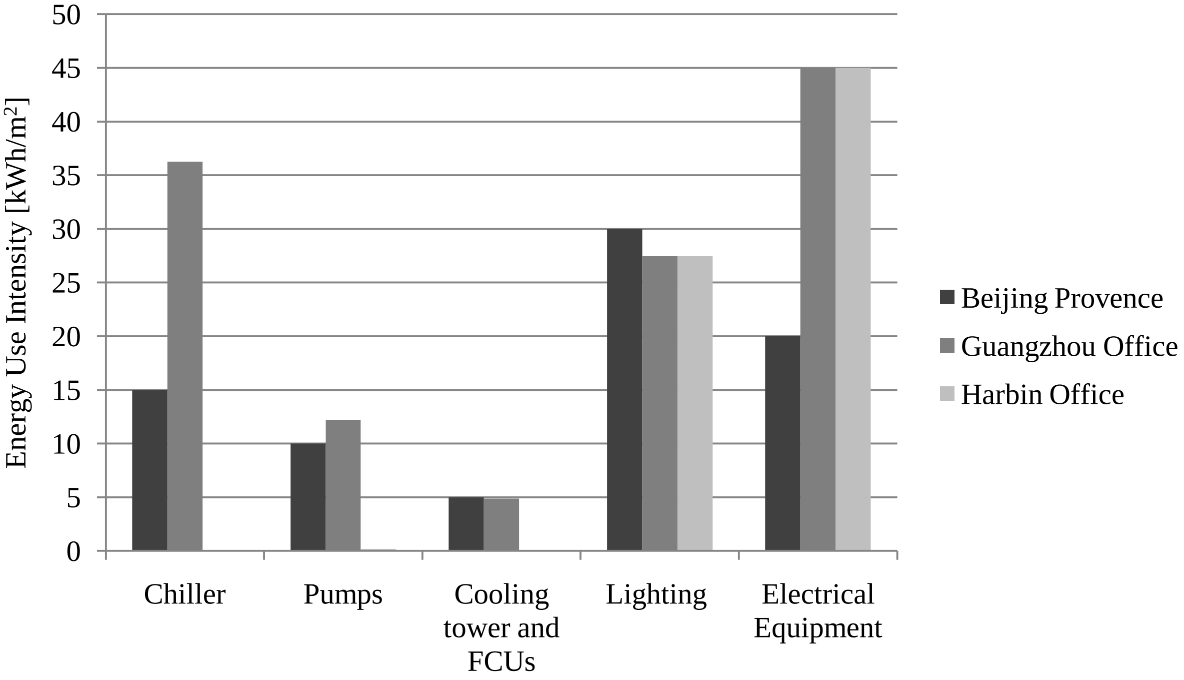

Figure 6: EUI breakdown comparison between Beijing database and benchmark office models.

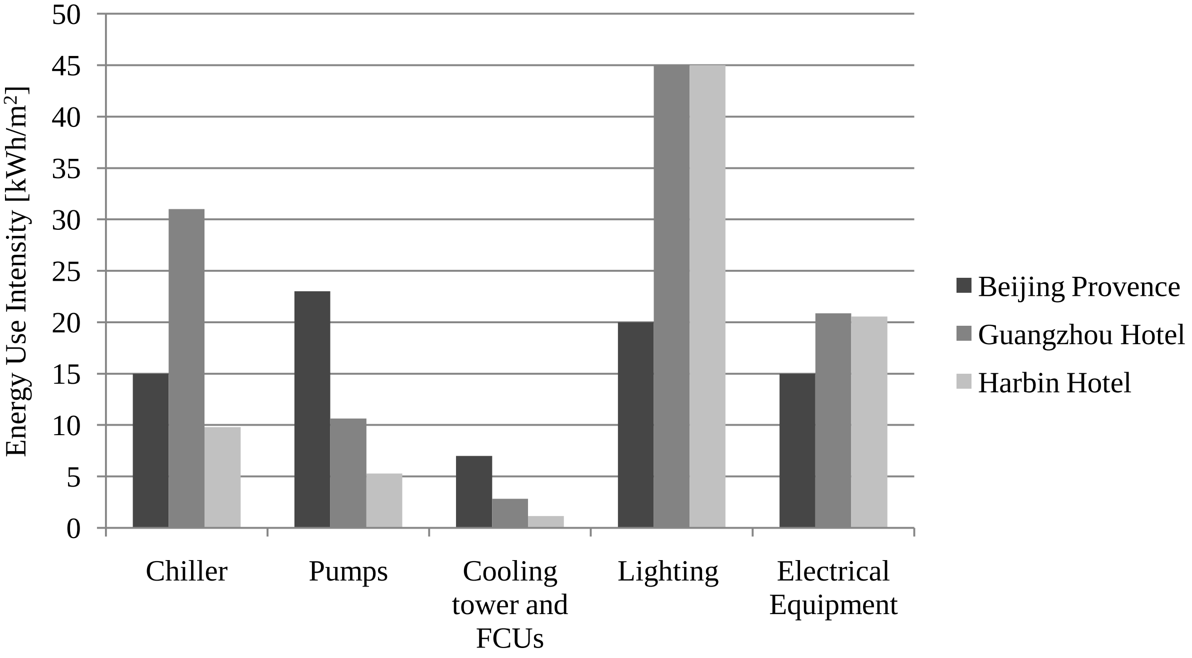

Figure 7: EIU breakdown comparison between Beijing database and benchmark hotel models.

Table 3: Benchmark Comparison with Beijing Database [kWh/m^2]

	Office			Hotel		
	Beijing Provence	Guangzhou (% Diff)	Harbin (% Diff)	Beijing Provence	Guangzhou (% Diff)	Harbin (% Diff)
Chiller	15.0	36.3 (142%)	0.0	15.0	26.0 (73%)	9.8 (35%)
Pumps	10.0	12.2 (22%)	0.2 (98%)	23.0	8.8 (62%)	5.3 (77%)
Cooling tower & FCUs	5.0	4.9 (-2.2%)	0.0	7.0	2.3 (67%)	1.1 (83%)
Lighting	30.0	27.5 (-8.4%)	27.5 (8.4%)	20.0	45 (125%)	45 (125%)
Electrical equipment (including elevators for hotels)	25.0	45.0 (125%)	45.0 (125%)	15.0	17.2 (15%)	20.5 (37%)

1.9 Purpose of the Study

This thesis aims to quantify the annual potential energy savings of code-compliant public building benchmark models in China through the application of common energy efficiency measures while provided recommendations for improvements to existing building code standards. Specifically, the research focuses on the office and hotel benchmark buildings in the Hot Summer Warm Winter climate region and the Severe Cold Climate region. In addition, this research also:

1. Compares the performance of code compliant buildings in China and the US and identifies the impact of the impact of different components on end use energy consumption (including schedules, set points, envelope construction types and HVAC systems)
2. Develops a general strategy for identifying potential energy savings using the building simulation tools EnergyPlus and Opt-E-Plus (DOE, 2010)
3. Develops a general strategy for performing an energy-economic optimization using Opt-E-Plus.
4. Identifies important economic parameters that must be defined for accurate economic analyses

1.10 Data Limitations

The limitations associated with this research pertain to the lack of a complete Chinese material and cost database as well as with uncertainties in economic data. The exact value of the discount rate used in the economic optimization is unknown as is the type of discount rate (nominal versus real). Therefore, an economic sensitivity analysis has been carried out. To account for the lack of a complete Chinese database of materials and costs, a US database of materials has been used for all optimizations. Material and operation and maintenance cost multipliers have been applied in the economic optimizations based on appropriate assumptions to account for the lack of true Chinese costs.

1.11 Arrangement of the Thesis

First, chapter two presents a detailed design and energy performance comparison between the Chinese office and hotel benchmark models and the ASHRAE based US reference building models to compare the relevant differences between building energy code standards and common practice. Next, chapter three presents the recommendations for improved building energy codes for the Guangzhou climate region which are derived based the energy design measures leading to maximum energy saving potential. The methodology for this process is also presented. Then, recommendations for improved building energy codes for the Harbin climate region, which have been derived based an economic optimizations, are presented in chapter four. The economic input parameters as well as cost multiplier assumptions are also discussed in detail. Chapter five summarizes the conclusions and lists intended and recommended future research. Finally, the appendices provide figures of the building schedules, full results tables of the optimization outputs from Opt-E-Plus, and peak electricity demand figures for the China/ US building performance comparison.

Chapter 2: Chinese Benchmark and US Reference Building Model Comparison

A comparison of the Chinese benchmark models and the US reference building models has been carried out to identify key differences in design and operation. The envelope and HVAC system parameters as well as the building loads are summarized. In addition, a detailed energy performance comparison has been carried out to identify key reasons for consumption differences. The goal is to answer two main questions: first, which building is more energy efficient and second, what effects do operation schemes such as schedules, loads, and set points have on the energy consumption differences. To answer these questions, each building model is modeled in the opposite country's location with the opposite building's operation schemes. To clarify, consider the following example. First imagine moving the empty US office building model from a particular climate region to a similar climate region in China and allowing the Chinese people to operate the building according to their standard practice (i.e. using Chinese building loads, temperature set points, schedules, and other HVAC operation settings). The question to ask is: Does the US building perform better or worse that the Chinese building? Similarly, what happens when a Chinese model from a particular climate region is moved to a similar climate region in the US and operated according to US practice? Again, does the Chinese building perform better or worse? This comparison seeks to determine the primary factors leading to the energy consumption differences.

In the comparison, GZ will be used to abbreviate Guangzhou and HB will be used to abbreviate Harbin. When simulating a building in the opposite country's location, the corresponding location-dependent data sets are also used including ground temperatures, weather data, design days and site to source energy conversion factors.

Reference buildings for the United States have been developed in previous work by the Department of Energy in conjunction with three national laboratories (DOE, 2009). Like the Chinese benchmarks, the US reference buildings are designed to represent new building constriction that comply with national and regional building code standards described by ANSI/ASHRAE/IESNA Standard 90.1-2004 (DOE, 2010). These models are also in the form on EnergyPlus IDF files and include sixteen building types for each of the sixteen US climate regions. These models represent nearly 70 percent of the US building stock mix (Torcellini, et al., 2008).

Building performance is compared based on two normalized metrics: energy consumption per unit floor area as well as energy per occupant hour. Occupant-hours are calculated by multiplying the maximum number of people in a particular space-type by the fraction of people in the space for each hour of the day, then multiplying by the number of days in a year. This is done for each space type. Then, the occupant hours for each space type are summed to attain a total building occupancy-hour value. This metric gives the reader some idea of how heavily the building is used and the associated energy footprint of each occupant.

2.1 Selecting US Reference Models for Comparison

2.1.1 Selecting the Appropriate US Model for Comparison

The US reference building models include three office models (small, medium, and large) and two hotel models (small and large). For this comparison, the medium office model and the small hotel model are selected as counterparts to the Chinese office and hotel benchmarks, respectively, based on similar floor area, facilities, and use. It should be noted that the US small hotel reference model includes a number of specific facilities that are not included in the Chinese design including a laundry facility, exercise facility, meeting room, employee lounge, and front office; the differences in space-types are shown below. The laundry and exercise facilities have been deleted from the US models to eliminate excess electrical loads and water use that are otherwise not included in the Chinese model. This helps create a more fair comparison between the models. It should also be noted that the Chinese hotel model includes two unique facilities including a canteen and a shop.

Table 4: Hotel Zone Types

Zone Type	Houston	Guangzhou
Stairs	✓	✓
Storage	✓	✓
Corridor	✓	✓
Front Lounge	✓	
Front Office	✓	
Public Restroom	✓	
Meeting Room	✓	
Mechanic Room	✓	✓
Employee Lounge	✓	
Elevator	✓	✓
Guestrooms	✓	✓
VIP Rooms		✓

2.1.2 Location and Climate Comparison

The location of the US reference building is selected based on similar climate and solar radiation patterns compared to the respected Chinese cities. To do this, the climate zone descriptions are matched as best as possible based on ASHRAE classification as well as Koppen classification. In addition, an analysis of the monthly daily average outdoor drybulb temperature, relative humidity, monthly average wind speed, and diffuse and global solar radiation patterns are compared. All climate data are taken from the TMY-3 statistical files available through the EnegyPlus website (DOE, 2010). The comparison shows that Houston, Texas and Duluth, Minnesota are the best matches for comparison with Guangzhou and Harbin, respectively. Recall, Guangzhou and Houston represent hot summer warm winter regions while Duluth and Harbin represent the opposite extreme, that is, the severe cold climate region. A comparison of the weather and solar radiation characteristics are shown in Figure 8 through Figure 15. Table 5 lists the ASHRAE and Koopen climate classifications. Table 6 and Table 7 list the seasonal average and extreme temperatures for Guangzhou and Harbin, respectfully.

Table 5: Climate Region Classification

	Hot summer, warm winter (Guangzhou climate region)		Severe cold (Harbin climate region)	
	Guangzhou, China	Houston, Texas	Harbin, China	Duluth, Minnesota
ASHRAE	2A	2A	7	7
Koppen	Csa	Cfa	Dwa	Dfb

Table 6: Guangzhou Seasonal Average and Extreme Temperatures

	Summer	Winter	Autumn	Spring
Seasonal Duration	June – August	December – February	September – November	March – May
Average Temperatures (Deviation) - ^{o}C	27.95 (0.014)	16.32 (0.064)	23.7 (0.358)	22.7 (0.781)
Seasonal Extreme Temperatures (Deviation) - ^{o}C	35.8 (6.70)	7.40 (4.718)	-	-

Table 7: Harbin Seasonal Average and Extreme Temperatures

	Summer	Winter	Autumn	Spring
Seasonal Duration	June – August	December – February	September – November	March – May
Average Temperatures (Deviation) - ^{o}C	21.29 (0.288)	-16.08 (0.663)	4.43 (0.909)	6.42 (0.275)
Seasonal Extreme Temperatures (Deviation) - ^{o}C	32.8 (7.230)	-28.68 (7.538)	-	-

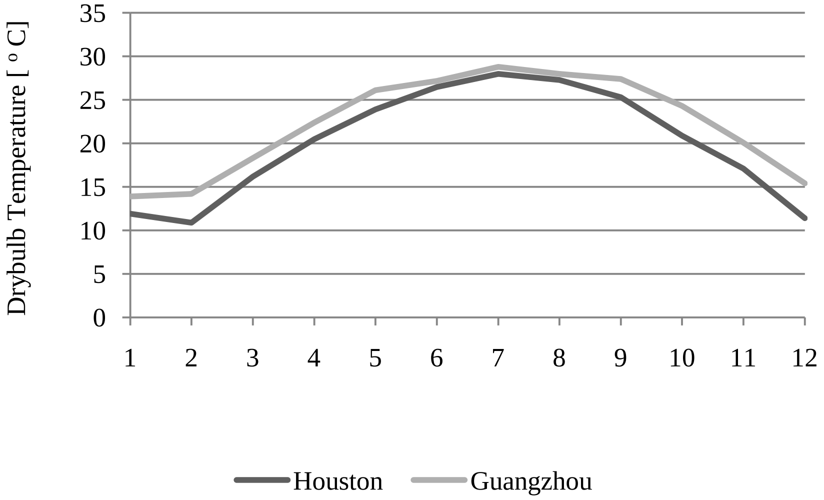

Figure 8: Monthly drybulb temperature.

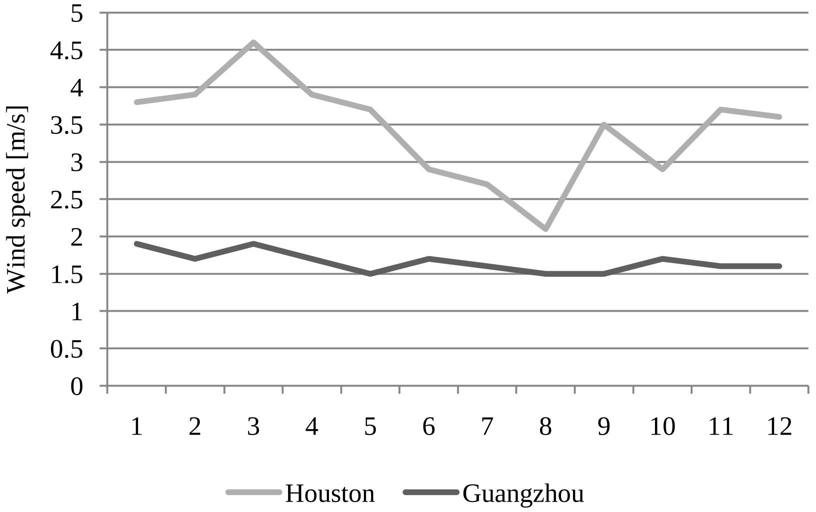

Figure 9: Monthly wind speed.

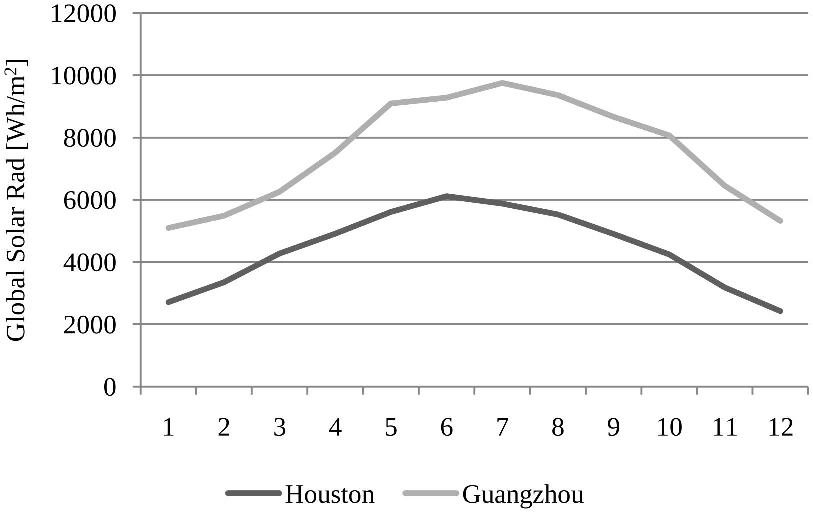

Figure 10: Global solar average radiation.

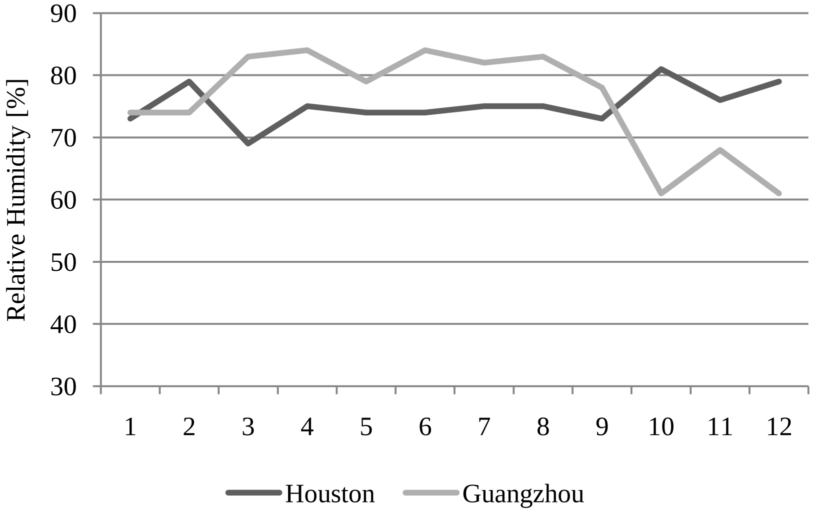

Figure 11: Monthly relative humidity.

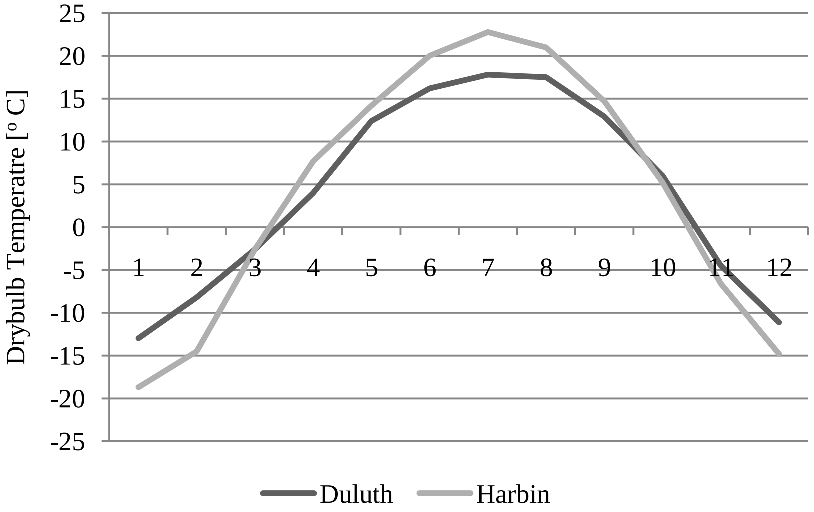

Figure 12: Monthly drybulb temperature.

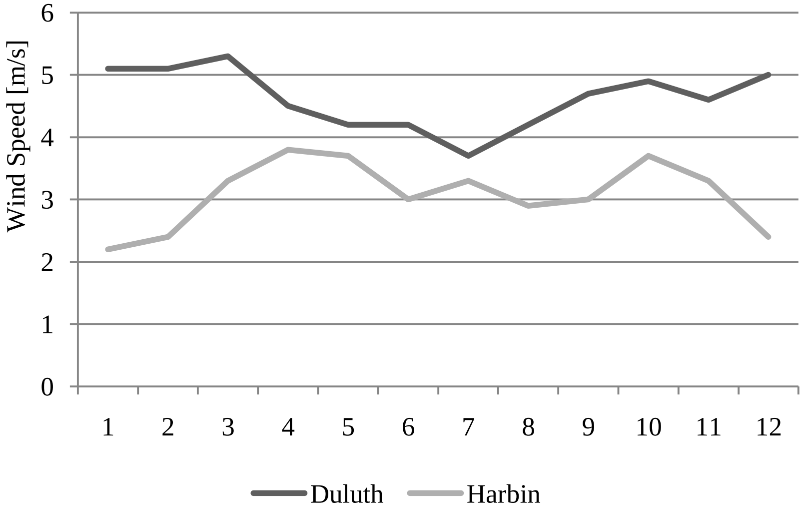

Figure 13: Monthly wind speed.

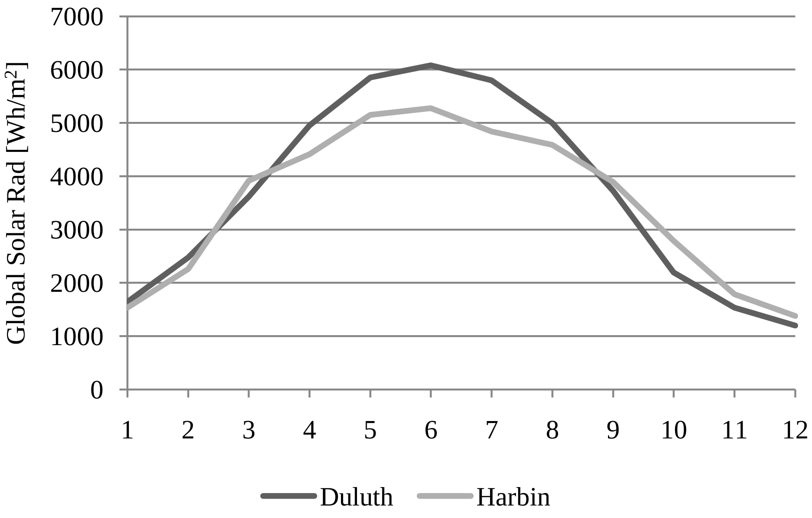

Figure 14: Global solar average radiation.

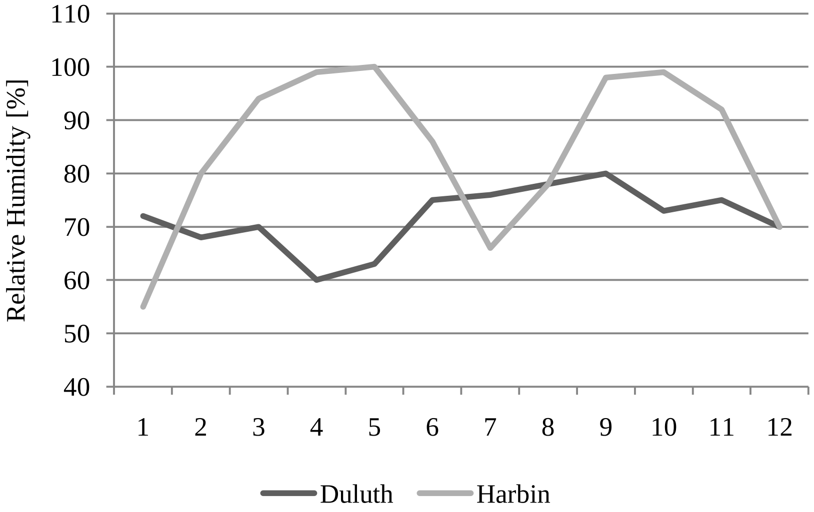

Figure 15: Monthly relative humidity.

2.2 Office Comparison

The office benchmark models for the Hot Summer Warm Winter (Guangzhou) climate region and the Severe Cold (Harbin) climate regions are compared to note the differences in building design across climate regions. The benchmark models are also compared to their equivalent US counterparts for each climate region. Details on this methodology will be provided in the appropriate sections.

2.2.1 Office Building Design Comparison by Climate Region

Major differences between the US and Chinese models are the construction materials, HVAC system designs, and building load densities (see Table 9 through Table 14). The three-dimensional renditions of the office models are shown in Figure 16 through Figure 18. The China office benchmark model is nearly twice the square footage of the US reference building (8,400 m^2 compared to 4,891 m^2). The construction of the China model includes concrete exterior walls and an insulated concrete roof. The US office is constructed of insulated steel-framed exterior walls and an insulated metal decking roof. All models use a five zone HVAC design layout with four perimeter zones and one core zone but the HVAC equipment differs between the Chinese and US models. The input parameters for each building are listed in Table 8 through Table 14. There are a few major differences in the HVAC design as well which include system equipments, outdoor air flow rates, pump types, system efficiencies, and supply air temperatures. Details are listed in Table 11 and Table 12.

The most significant difference may be the type of HVAC equipment used in each model. The Guangzhou model includes a four-pipe fan coil system while the Harbin model includes hydroid radiant baseboard heating (details are provided in Table 11 and Table **12**, and Table **13** and Table **14**, respectively). The Harbin model does not include any mechanical cooling or ventilation equipment; instead, cooling and outdoor air are provided by natural ventilation from operable windows. There are envelope differences as well; the insulation level in the exterior walls of the Harbin model is 32 percent less than that in the Guangzhou model. This seems inappropriate given that Harbin is located a heating dominated climate. On the other hand, the roof insulation levels are higher and the window U-values are lower in the Harbin model (see Table 9 and Table 10 for details).

Schedules for lighting, equipment and occupancy density as well as heating and cooling temperature set points are show in graphically in Figure 97 - Figure 103 in Appendix A: Schedules Occupancy density in the Chinese models is nearly four and a half times greater than the US models. The accuracy of this figure is unknown; it may be realistic for the working space but may not be an accurate estimation for whole-building occupancy density. It is questionable whether this value accounts for lower occupancy densities in corridors, stair cases, and other common areas. Secondly, the Chinese model has zero lighting and equipment power densities during unoccupied hours, which is another uncertain assumption, as it is very uncommon for all electrical devices to be turned completely off each night in the US. But without a firsthand look at the actual situation, the author must take her advisors word as valid. Precise measurement of occupant and electricity loads would improve the author's confidence in the Chinese models as these components have a significant impact on energy consumption. Another major difference between the Chinese and US models is hours of operation. The Chinese office model is occupied and operates five days a week from 7am to 7 pm; the US model is occupied and operates six days a week, including Saturdays from 6 am to 7 pm. The US office building also takes into account a nighttime custodial crew by modeling a non-zero occupancy from 7 pm to 12 am during all days of operation. The other major differences include lower heating and higher cooling set points, lower equipment power densities per person, and lower insulation levels in the Chinese building model.

During this comparison, a few questions arise regarding a few of the input parameters in the Chinese models. First, the fan pressure drop is significantly lower in the Guangzhou benchmark (40 Pa) compared to the US reference building (500 Pa) for this climate region; this may be appropriate for the given HVAC system used in the model, but this figure should be reevaluated for accuracy. Second, the EnergyPlus input parameter "*Chilled Water Outlet Node Name"* in the Chinese model references the chiller outlet node which is not what the Opt-E-Plus preprocessor suggests is correct; the predefined code that is added to the IDF file by Opt-E-Plus sets this reference point to "*Outside Air*." Comparing the annual energy consumption shows a dramatic difference in cooling and pump energy when the reference node is set to outside air. Further investigation is necessary to identify which node set point is most appropriate for the Chinese models.

It is also important to note that the original Harbin model lacked any outdoor air supply (mechanical or natural ventilation) and did not include infiltration. Natural ventilation has been added to the model by simulating operable windows during times when temperatures are above 12.7 degrees C. Also, infiltration has been added to this model in the perimeter zones during all hours of the day at a rate of 0.3 ACH. This value references the US model for an appropriate comparison but could be greater given the based on the assumption that Chinese construction quality is under par compared to the US or could be greater given construction is primarily concrete. From this investigation, it is suggested that future research evaluates the indoor air quality of the Chinese buildings given that the high occupancy density. This information is aimed directly toward the development team of EnergyPlus and of the Chinese building models.

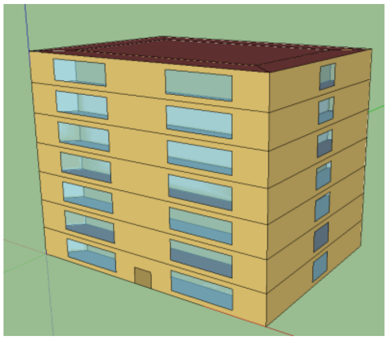

Figure 16: Guangzhou office benchmark model.

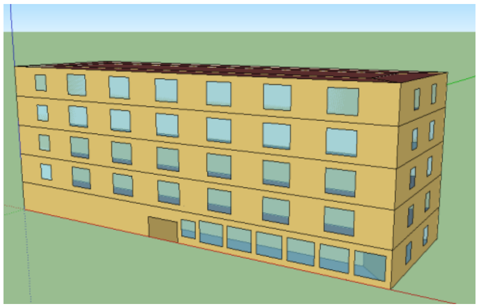

Figure 17: Harbin office benchmark model.

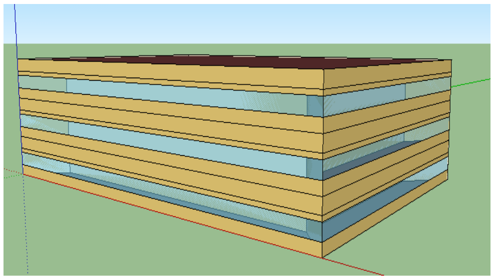

Figure 18: US office reference building.

Table 8: General Office Building Information

	Guangzhou Climate Region		Harbin Climate Region	
General Information	Guangzhou	Houston	Harbin	Duluth
Total floor area	8,400 m^2	4,982 m^2	5,978 m^2	4,982 m^2
Number of floors	7	3	5	3
Aspect ratio	1.33	1.50	3.00	1.50
Orientation	East/West	East/West	East/West	East/West
Wall Construction	Concrete	Steel frame	Concrete	Steel frame
Roof Construction	Concrete	Metal decking	Concrete	Metal decking
Zoning	five-zone perimeter/core	five-zone perimeter/core	five-zone perimeter/core	five-zone perimeter/core

Table 9: Office Envelope Construction – Guangzhou Climate Region

Envelope Construction	Units	Guangzhou	Houston
Exterior wall R-value	m^2K/W	1.31	1.42
Roof R-value	m^2K/W	1.55	2.80
Ground floor R-value	m^2K/W	0.558	0.537
Window U-value	W/m^2K	North: 5.06 South: 4.74 East/West: 5.77	6.49
Window solar heat gain coefficient	Fraction	North: 0.476 South: 0.425 East/West: 0.718	North: 0.610 South: 0.250 East/West: 0.250
Window visual transmittance	Fraction	North: 0.400 South: 0.400 East/West: 0.610	North: 0.610 South: 0.250 East/West: 0.250
Window - to- wall ratios	Fraction	North: 28% South: 33% East/West: 10%	All facades: 47.7%

Table 10: Office Envelope Construction – Harbin Climate Region

Envelope Construction	Units	Harbin	Duluth
Exterior wall R-value	m^2K/W	0.750	2.75
Roof R-value	m^2K/W	2.76	2.79
Ground floor R-value	m^2K/W	1.27	0.537
Window U-value	W/m^2K	3.06	3.24
Window solar heat gain coefficient	Fraction	0.700	0.487
Window visual transmittance	Fraction	0.781	0.409
Window - to- wall ratios	Fraction	North: 25% South: 25% East: 10% West: 21.5%	All facades: 47.7%

Table 11: Office HVAC Equipments – Guangzhou Climate Region

HVAC Component Standards	Guangzhou	Houston
Zone equipment type	Four-pipe fan coil units	Packaged multi-zone VAV units
Chiller type (COP)	Electric (4.70)	None
Air conditioners (COP)	None	Electric (3.14)
Boiler type (thermal efficiency)	Electric (0.90)	Natural gas (0.75)
Heating sys. pump type (head)	Constant speed (180000 Pa)	Variable speed (179352 Pa)
Heating sys. pump motor efficiency	0.9	0.85
Cooling sys. pump type (head)	Constant speed (180000 Pa)	None
Cooling sys. pump efficiency	0.90	-
Cooling tower pump type (head)	Constant speed (179352 Pa)	None
Cooling tower pump efficiency	0.87	-
Fan efficiency	0.70	0.60
Fan pressure drop	40 Pa	500 Pa
Outdoor air flow rate (m^3/s/person)	0.0083	0.01

Table 12: Office HVAC Equipments – Harbin Climate Region

HVAC Component Standards	Harbin	Duluth
Zone equipment type	Radiant hot water baseboard heaters	Single duct VAV with reheat
Reheat coil efficiency	None	0.80
Radiant baseboard heaters: Fraction radiant	0.30	None
Boiler type (thermal efficiency)	District Heating	Natural gas (0.75)
Unitary air conditioner type (coil COP)	None	Electric (3.1)
Fan efficiency	None	0.445
Heating sys. pump type (head)	Constant speed (180000 Pa)	Variable speed (179352 Pa)
Heating sys. pump motor efficiency	0.9	0.85
Fan pressure drop (Pascals)	None	500
Outdoor air flow rate (m^3/s/person)	0.0083	0.01
Infiltration (ACH)	0.3	0.26

Table 13: Office Building Loads and Set Points – Guangzhou Climate Region

		Occupied Hours		Unoccupied Hours	
Building Loads and Set Points	Units	Guangzhou	Houston	Guangzhou	Houston
Occupant density	Occupants/ 100 m^2	25	5.38	0	0
Lighting density	W/m^2	11	10.8	0	0.5
Equipment density	W/m^2	20	8.1	0	2.85
Cooling supply air temp	^{o}C	7	14	7	14
Heating supply air temp	^{o}C	60	40	60	40
Cooling set point temp	^{o}C	26	24	37	30
Heating set point temp	^{o}C	20	21	12	15.6

Table 14: Office Building Loads and Set Points – Harbin Climate Region

		Occupied Hours		Unoccupied Hours	
Building Loads and Set Points	Units	Harbin	Duluth	Harbin	Duluth
Occupant density	Occupants/100 m^2	25	5.38	0	0
Lighting density	W/m^2	11	10.8	0	0.5
Equipment density	W/m^2	20	8.1	0	3.2
Cooling supply air temp	^{o}C	NA	14	NA	14
Heating supply air temperature	^{o}C	NA	40	NA	40
Cooling set point temperature	^{o}C	NA	24	NA	30
Heating set point temperature	^{o}C	20	21	12	15.6

2.2.2 Office Energy Performance Comparison – Hot Summer Warm Winter Climate Region

The first comparison looks at the effects of simulating the Guangzhou office in Houston, Texas (including all appropriate location-dependent data sets). Here, both models in this comparison operate under the same operating conditions (US schedules, loads, and set points). Figure 19 figure shows that the Chinese building outperforms the US building under these operating schemes. The primary energy consumption differences are related to heating and cooling energy. The reasons are twofold. First, the US building model utilizes HVAC equipments with lower efficiencies and COP values compared to the Chinese model. The Houston model incorporates packaged multi-zone VAV units with heating provided by a natural gas boiler (with an efficiency of 0.75) and cooling provided by electric air conditioners (with

COP values of approximately 3.14). The Guangzhou model includes a four-pipe fan coil system with heating provided by an electric boiler (with an efficiency of 0.90) and cooling provided by an electric chiller (with a COP of 4.7). Refer to Table 11in the thesis for office equipment specifications. Second, envelope differences also contribute to greater heating and cooling energy in the Houston building model. The Houston office has larger window to wall ratios and a larger window U-value. These factors lead to greater solar heat gains in the summer greater heat loss in the winter.

In Figure 21, the US building is simulated in Guangzhou and uses the Chinese operation schemes. The results show similar trends in energy performance differences when the opposite situation was modeled above. Reasons for this are the same: the US cooling system operates with lower COP values and the WWR are greater for the Houston model. Specifically, the south façade WWR is 31% greater for the US building.

To verify these conclusions, the Chinese model is modified to incorporate the US cooling COP and window to wall ratios. The results in Figure 20 show that indeed the WWR ratios and cooling COP values have a noticeable effect on heating and cooling energy. It is obvious that higher COP values benefit energy savings in any situation but Figure 20 also emphasizes that the window sizes in the Guangzhou model are a more efficient design option compared to those in Houston model.

In addition to this comparison, which highlights differences in envelope and HVAC properties, a more detailed analysis has also been carried out to identify the individual effects of adopting US schedules, loads, and set points in the Guangzhou office model. The most dramatic effects appear when the US schedules and set points are incorporated into the Chinese model; heating energy, cooling energy, and electrical equipment energy increase significantly. Electrical equipment schedules in the US building are modeled to operate for six days a week and are assumed to draw some amount of power during unoccupied hours whereas the Chinese schedules assume all electrical equipment is powered down during unoccupied hours (see Figure 97 through Figure 101 in Appendix A: Schedules

Appendix A1: Office Schedules). The US set points also bring in more outdoor air per person which also adds to the heating and cooling load.

To summarize, the following conclusions can be made:

1. Although the opaque constructions of the Houston office have higher R-values compared to the Guangzhou office, the overall envelope performance of the Houston model is less efficient compared to the Chinese envelope. This is a result of larger window to wall ratios and lower window U-values in the US building.
2. Typical Chinese building loads, including electrical equipment and occupancy densities, are far more energy intensive than those in the US.
3. The US office schedules are more energy intensive than those in China due to the fact that US building operates six days a week and assumes a certain lighting and equipment power draw during unoccupied hours.
4. US set points are more energy intensive than those in China. This is a result of slightly higher heating and cooling set points and greater outdoor air flow rates per person.
5. The occupant energy intensity is dramatically higher in the original US reference building model due to the fact that the occupancy density is nearly one-fifth that of the Chinese benchmark building model. The Chinese schedules and set points are shown to be less energy intensive than those of the US. When also including the Chinese building loads, occupant energy decrease even more significantly. This shows two things: one, US occupancy density could be reduced if Chinese schedules and set points were incorporated into US operation schemes and two, the Chinese occupancy density could be reduced if US building and HVAC designs were adopted.

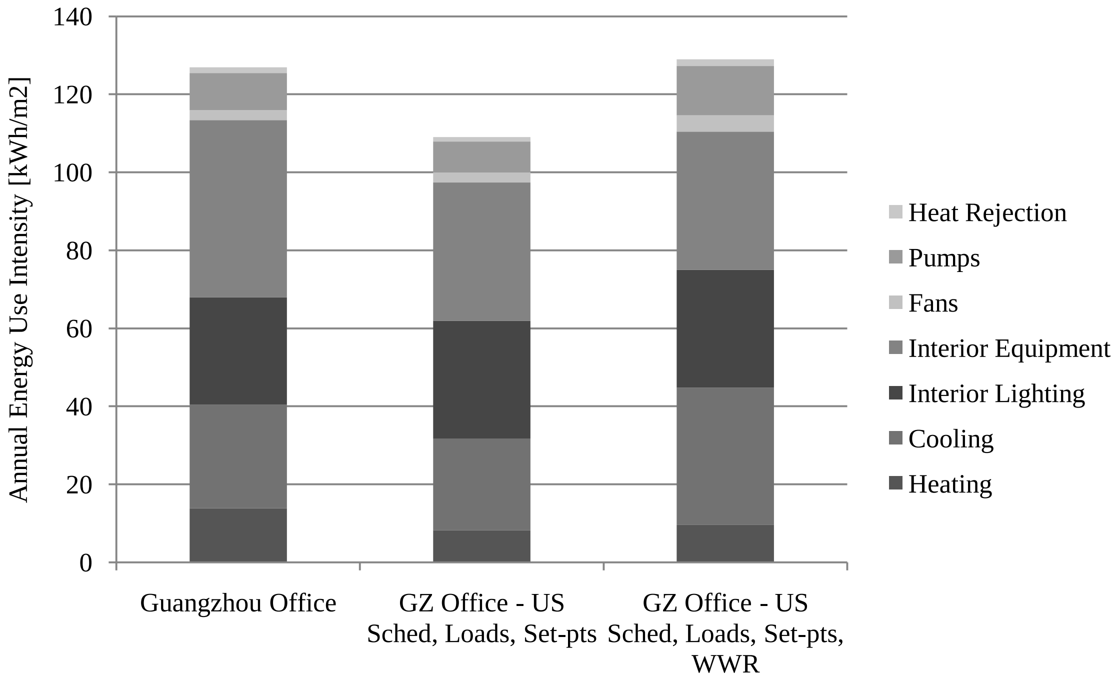

Figure 19: Guangzhou Office in Houston, TX with US operating schemes.

Table 15: Annual EUI [kWh/m^2] of Office Building Models in Houston, TX

	Guangzhou Office	GZ Office – US Sched., Loads, Set-pts	Houston Office
Heating	13.9	8.2	18.3
Cooling	26.6	23.5	39.3
Interior Lighting	27.5	30.2	30.2
Interior Equipment	45.5	35.4	35.4
Fans	2.5	2.6	2.4
Pumps	9.5	7.9	0.1
Heat Rejection	1.5	1.2	0.0
Total	126.9	109.0	125.7

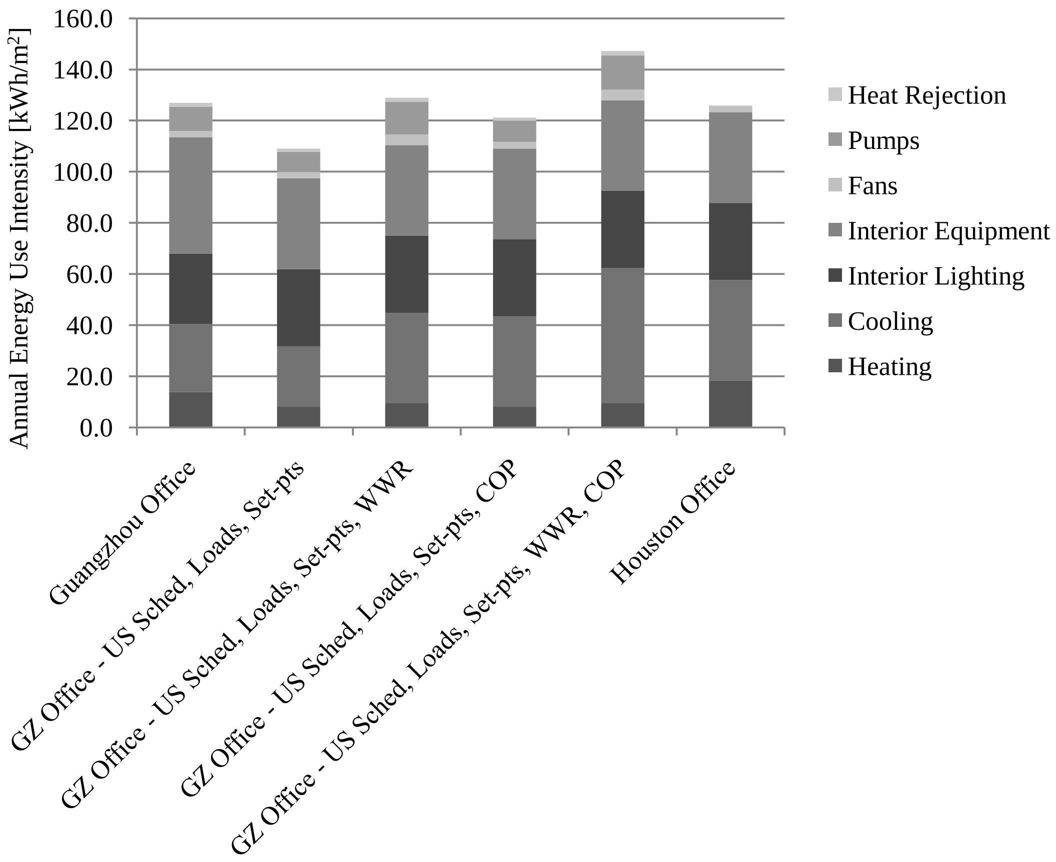

Figure 20: Effects of WWRs and COP values on the Guangzhou office.

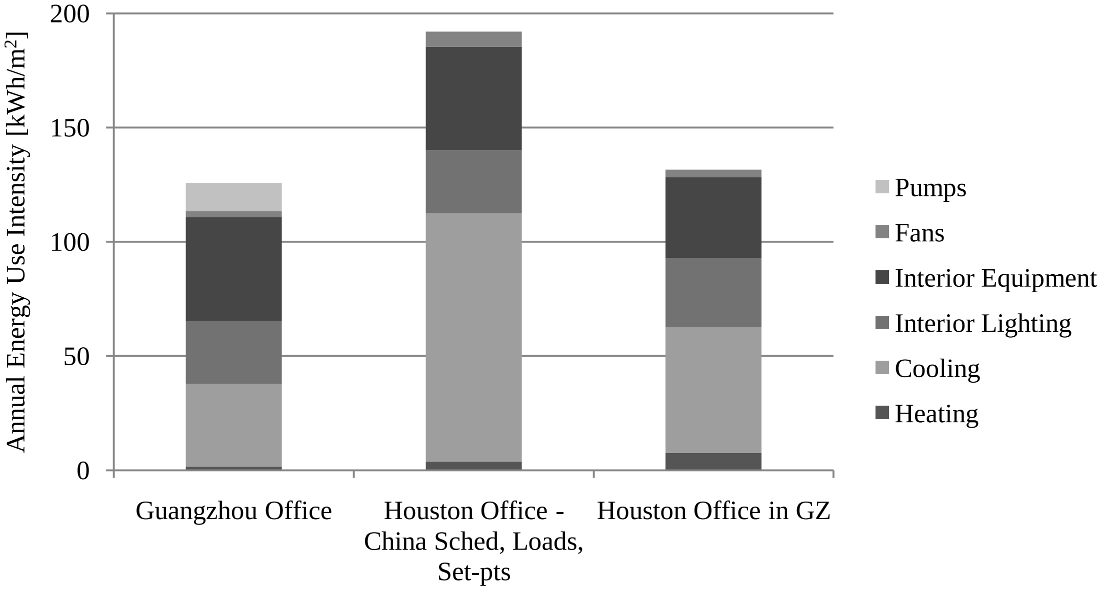

Figure 21: Houston office in Guangzhou with Chinese operating schemes.

Table 16: Annual EUI [kWh/m^2] of Office Building Models in Guangzhou China

	Guangzhou Office	Houston Office - China Sched, Loads, Set-pts	Houston
Heating	1.6	3.8	7.4
Cooling	36.3	108.7	55.2
Interior Lighting	27.5	27.5	30.2
Interior Equipment	45.5	45.5	35.4
Fans	2.7	6.6	3.2
Pumps	12.2	0.0	0.0
Heat Rejection	2.2	0.0	0.0
Total End Uses	127.9	192.0	131.5

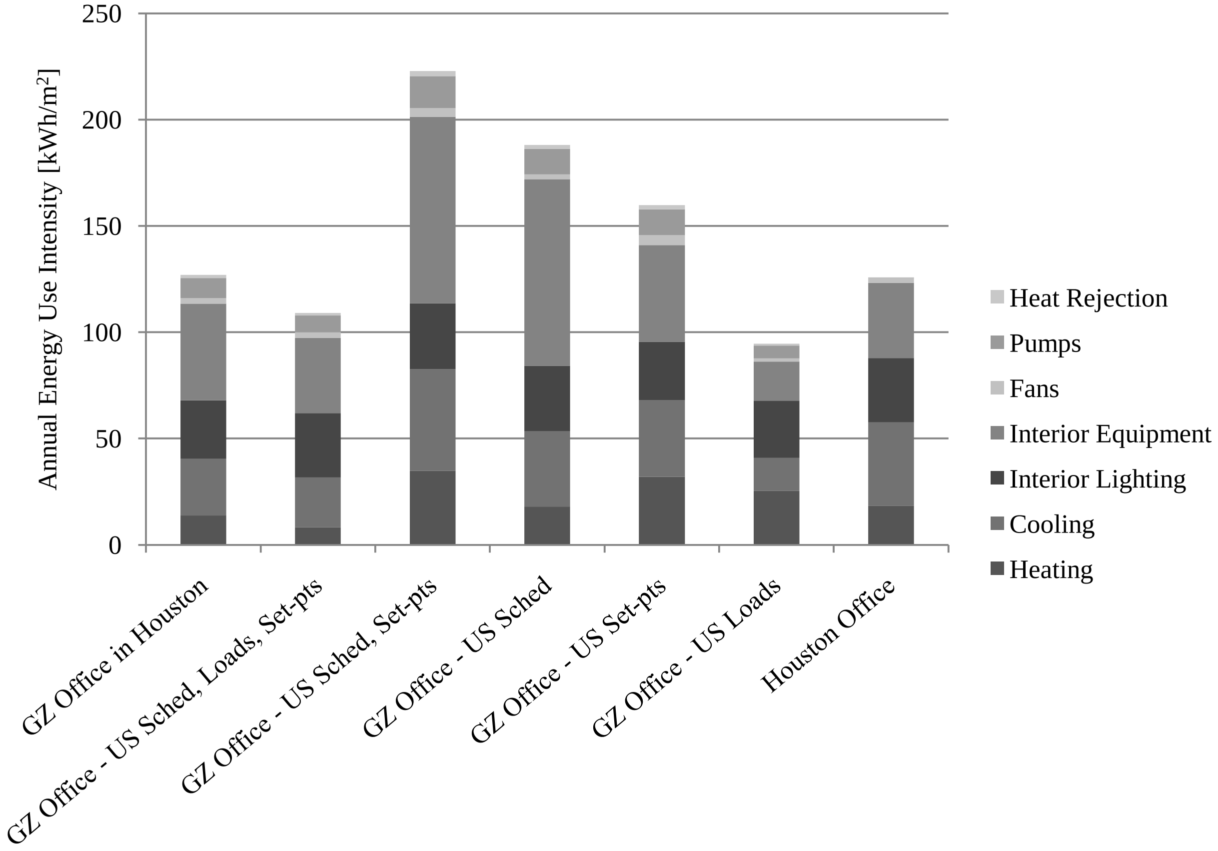

Figure 22: Effect of US operating schemes on Guangzhou office energy consumption.

Table 17: Effects of US Operating Schemes on Guangzhou Office EUI [kWh/m^2]

	GZ Office in Houston	GZ Office - US Sched, Loads, Set-pts	GZ Office - US Sched, Set-pts	GZ Office - US Sched	GZ Office - US Set-pts	GZ Office - US Loads	Houston Office
Heating	13.9	8.2	34.8	18.1	32.0	25.3	18.3
Cooling	26.6	23.5	47.8	35.2	36.0	15.6	39.3
Interior Lighting	27.5	30.2	30.9	30.9	27.5	26.9	30.2
Interior Equipment	45.5	35.4	87.8	87.8	45.5	18.4	35.4
Fans	2.5	2.6	4.1	2.2	4.7	1.5	2.4
Pumps	9.5	7.9	15.0	12.1	12.2	6.1	0.1
Heat Rejection	1.5	1.2	2.5	1.9	1.9	0.9	0.0
Total	126.9	109.0	222.9	188.1	159.8	94.7	125.7

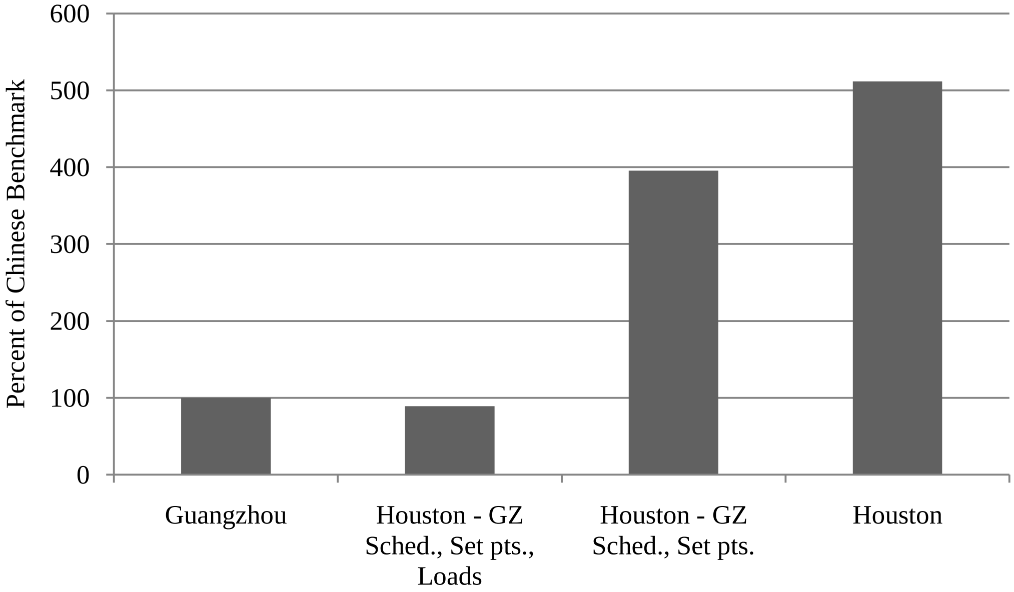

Figure 23: Energy consumption per occupant hour as a percent of the Chinese benchmark – Guangzhou climate region.

Table 18: Occupant Energy Intensity – Guangzhou Climate Region

	Guangzhou	Houston – GZ Sched., Set pts., Loads	Houston – GZ Sched., Set pts.	Houston
Energy consumption per occupant hour [kWh/occupant-hour]	0.19	0.17	0.76	0.99

2.2.3 Office Energy Performance Comparison – Severe Cold Climate Region

The same comparison is done for the severe cold climate of Harbin as was done above for the Guangzhou climate region above. The fist comparison looks at the effects of simulating the Harbin office model in Duluth, Minnesota and using the US schedules, building loads and set points. The results, show in Figure 24, indicate that the Chinese building is more efficient than the US building under the same operating practices. These differences are primarily a result of three major dissimilarities between the HVAC systems of the two models. First, the Duluth model includes a single duct VAV reheat system with heating provided by a75 percent efficient natural gas boiler. Heating in the Harbin model is provided by a radiant baseboard system with hot water provided by district heating. The efficiency of this system is assumed to be 100 percent. Second, the Duluth model provides outdoor air through the mechanical ventilation system at a flow rate of 0.01 m3/s/person whereas the Harbin model does not include any mechanical ventilation. Outdoor air in the Harbin model is supplied through operable windows so there is no energy consumption associated with conditioning frigid ambient air. Lastly, the Harbin model does not include any kind of mechanical cooling system.

There are also envelope differences that contribute to an increase in energy consumption for the Duluth model in Figure 24. First, the window specifications of the US building have significant differences; the WWR of the Duluth model is 47 percent larger on the north and south facades compared to the Harbin model. Also, the SHGC is 30 percent less for the US building compared to the Chinese building. Smaller windows and higher solar heat gain coefficients in the Chinese model lesson the thermal heat transfer through the envelope while allowing more solar heat gains in through the window glass. The results show this is apparently a better design tactic for this particular climate region. The roof R-values are comparable between models but the exterior wall R-value of the Duluth model is superior to the Chinese model.

Similar trends are observed when the Duluth office model is simulated in Harbin and operated according to Chinese practice. Again, the Harbin office outperforms the Duluth model. The results show that if the Chinese borrow the US building and operate it according to their typical operation schemes, they would consume more energy for heating due to lower system efficiencies and the addition of auxiliary HVAC equipment (including that of fans and pumps). Additional heating is also associated with the conditioning of ventilation air. One might expect heating energy to decrease a greater amount due to the fact that the Chinese equipment power density is over twice that modeled in the US building but there is now more ventilation air being supplied to the space as a result of the increase in the number of occupants in each zone. Recall that the standard outdoor airflow rates per person in China are slightly less than what is required in the US (refer to Table 12of Section 2.2.1). However, the Chinese occupancy density is over five times greater than that in the US so overall, the HVAC system must condition much more ventilation air. Using the US building may results in more comfortable working conditions but this comes with a significant energy cost. The quality of the ventilation air must also be taken into consideration in China. It may be the case that the supply outdoor air has a greater concentration of contaminants than the air in the zone. Air filters may be necessary. If air filters are added to the model, energy consumption may increase due to additional pressure drop that the supply fans must overcome.

Figure 26 shows the effects of replacing Chinese building parameters with those of the US including schedules, building loads, and set points. The US occupancy and equipment power densities are much less energy intensive than those in China. As a result, heating energy increase over 50 percent, which suggests the Chinese building loads help meet the heating requirement. The US schedules are more energy intensive compared to China. Recall that the US office model assumes 30 percent of the equipment and five percent of the lighting power is on during unoccupied hours in addition to operation on Saturdays whereas all equipment and lighting are assumed to go to zero in China during unoccupied hours. This additional operation time in combination with the high electrical equipment loads in China result in a major increase in electrical equipment. This model shows little reduction in heating energy because the HVAC system does not operate during hours with significant differences in equipment and lighting loads. In addition, the heating set points in both models are similar and do not result in a significant difference in heating energy consumption.

From this comparison, the following conclusions can be made:

1. HVAC type differences are the primary cause of energy consumption differences when both the Harbin and Duluth models are operated under the same operation schemes. One major difference is the fact that the US building supplies each zone with conditioned ventilation air as well as space cooling.
2. The most significant envelope differences are associated with window properties. The Duluth model has 47 percent more window area on the north and south facades along with lower SHGC. This combination leads to more heat loss through the window glass and blocks more of the beneficial solar heat gains from heating the space.
3. The US building loads, including occupancy and equipment power densities, are much less energy intensive than those in China.
4. The US operating schedules are much more energy intensive than those in China due in part to equipment and lighting operation during unoccupied hours and operation on Saturdays.
5. Thermostat set points are similar as shown in Figure 102 and Figure 103 of Appendix A: Schedules
6. Appendix A1: Office Schedules and do not lead to significant energy consumption differences.
7. The occupancy energy intensity related to the US reference building is significantly greater than that related to the Chinese office benchmark due to the fact that the US office occupancy density is about one-fifth of what is typical for China. The results of this comparison show two things: one, the US occupants could reduce their energy intensity by incorporating Chinese schedules and set points without sacrificing the amount of area per person and two, the Chinese benchmark

building would not benefit from the adoption of US building designs or operation practice as this model has the lowest occupant energy intensity in the comparison.

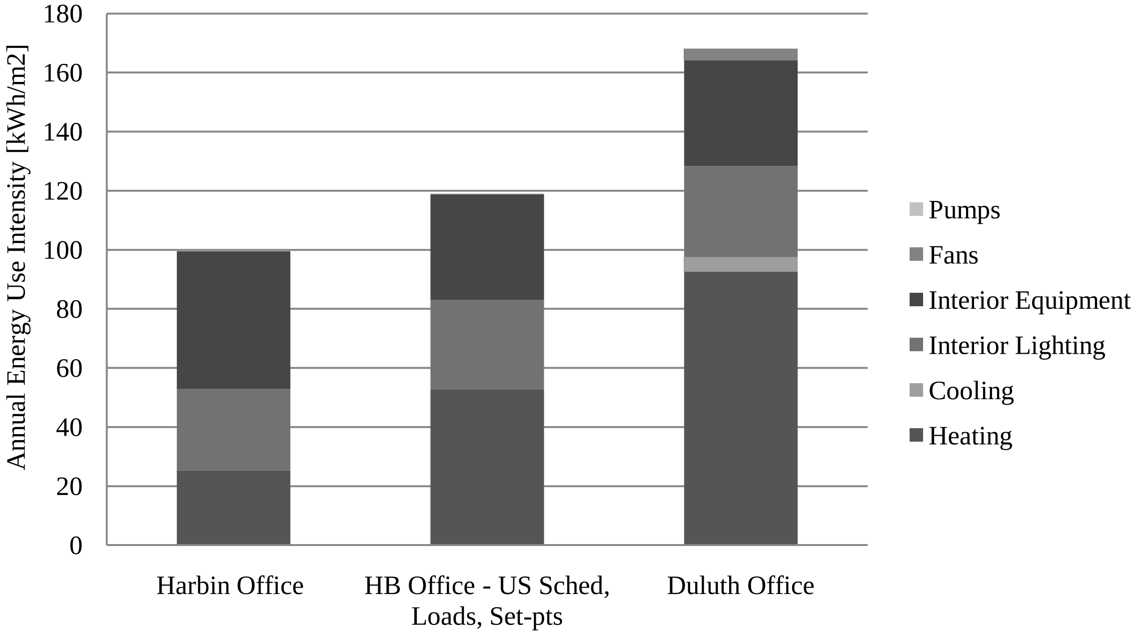

Figure 24: Harbin Office in Duluth, MN with US operating schemes.

Table 19: Annual EUI [kWh/m^2] of Office Building Models in Duluth, MN

	Harbin Office	HB Office – US Sched, Loads, Set-pts	Duluth Office
Heating	25.3	52.9	92.6
Cooling	0.0	0.0	5.0
Interior Lighting	27.6	30.2	30.8
Interior Equipment	46.6	35.8	35.8
Fans	0.0	0.0	3.9
Pumps	0.1	0.2	0.1
Total	99.6	119.1	168.2

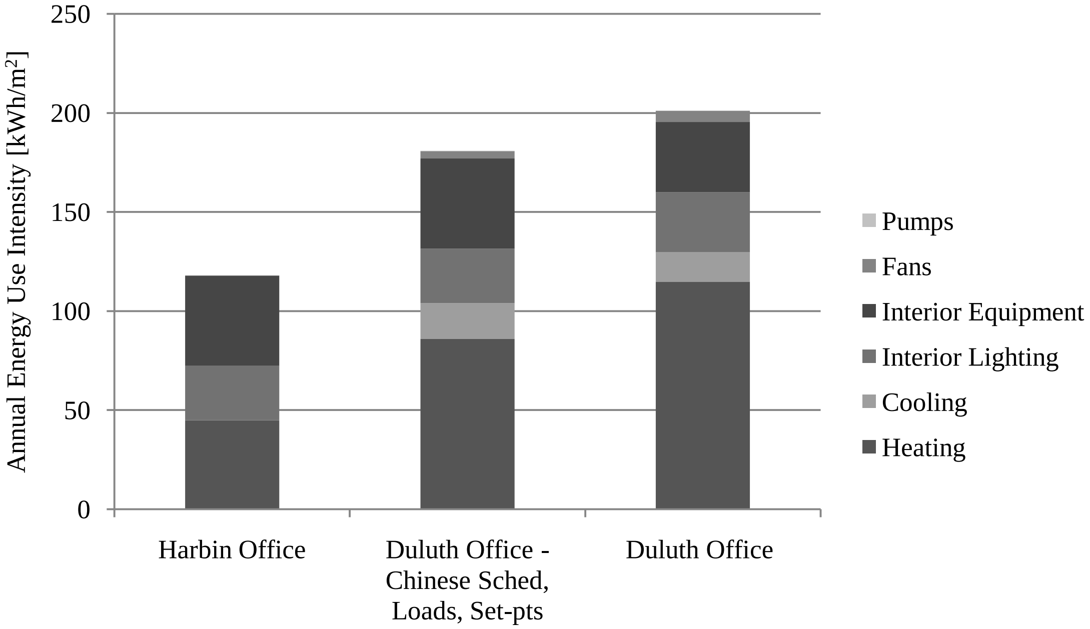

Figure 25: Duluth office in Harbin with Chinese operating schemes.

Table 20: Annual EUI [kWh/m^2] of Office Building Models in Harbin China

	Harbin Office	Duluth Office - Chinese Sched, Loads, Set-pts	Duluth Office
Heating	45.0	85.9	114.8
Cooling	0.0	18.1	14.9
Interior Lighting	27.5	27.5	30.2
Interior Equipment	45.5	45.5	35.4
Fans	0.0	3.8	5.7
Pumps	0.2	0.1	0.1
Total End Uses	118.1	180.9	201.2

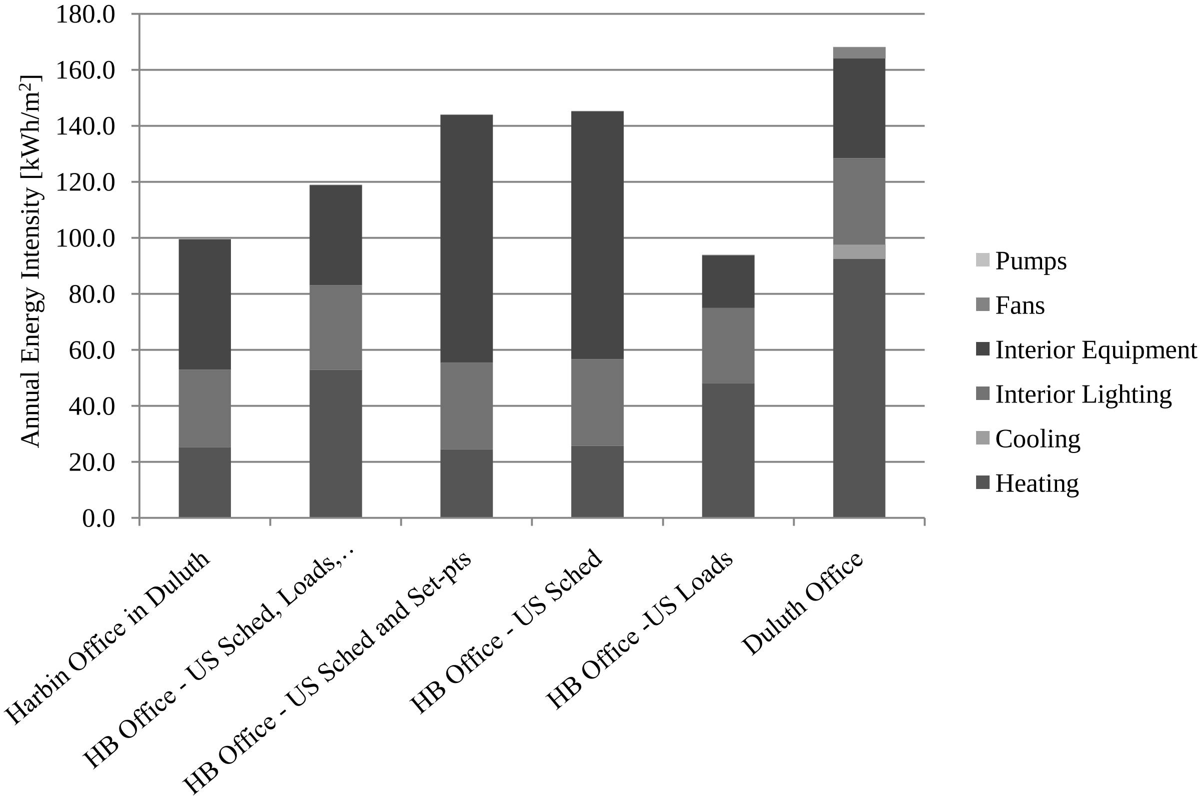

Figure 26: Effect of US operating schemes on Harbin office energy consumption.

Table 21: Effects of US Operating Schemes on Harbin Office EUI [kWh/m^2]

	Harbin Office in Duluth	HB Office - US Sched, Loads, Set-pts	HB Office - US Sched Set-pts	HB Office - US Sched	HB Office - US Loads	Duluth Office
Heating	25.3	52.9	24.5	25.7	48.0	92.6
Cooling	0.0	0.0	0.0	0.0	0.0	5.0
Interior Lighting	27.6	30.2	30.9	30.9	27.0	30.8
Interior Equipment	46.6	35.8	88.6	88.6	18.8	35.8
Fans	0.0	0.0	0.0	0.0	0.0	3.9
Pumps	0.1	0.2	0.1	0.1	0.2	0.1
Total	99.6	119.1	144.1	145.4	94.0	168.2

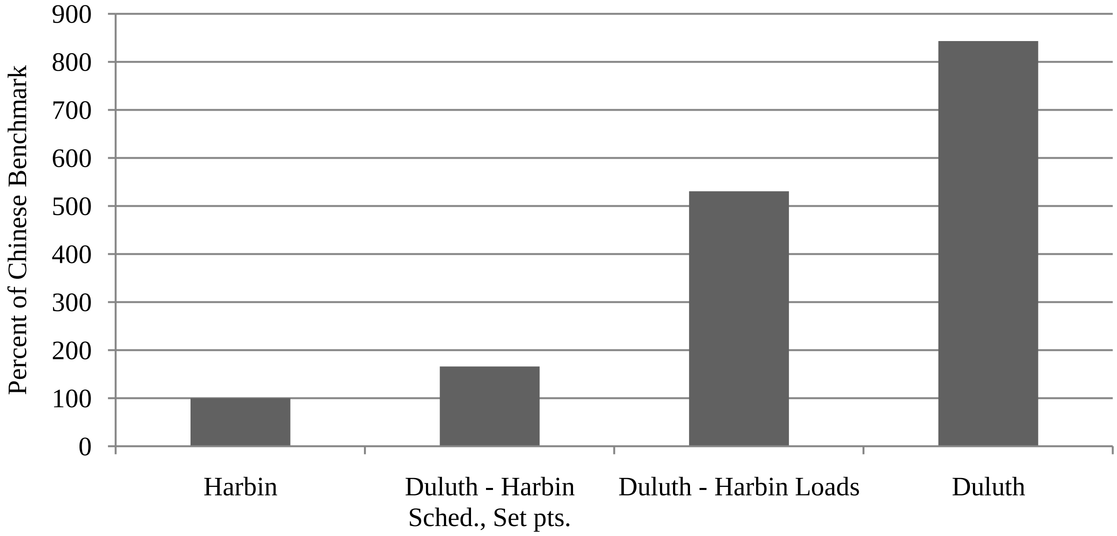

Figure 27: Energy consumption per occupant hour as a percent of the Chinese benchmark – Harbin climate region.

Table 22: Occupant Energy Intensity - Harbin Climate Region

	Harbin	Duluth – HB Sched., Set pts., Loads	Duluth – HB Sched., Set pts.	Duluth
Energy consumption per occupant hour [kWh/occupant-hour]	0.18	0.30	0.95	1.5

2.3 Hotel Comparison

This section outlines the different components of the Chinese benchmark hotel benchmark models and describes the design difference between the Chinese benchmark models and the US reference building models. In addition, the effects of schedules, loads, and set points on annual energy consumption and analyzed to identify the causes of energy consumption differences between the Chinese and US models.

2.3.1 Hotel Building Design Comparison by Climate Region

The Chinese building modes are fairly similar as far as functionality but the specifics, such as size, insulation levels and window to wall rations, are different. The Guangzhou hotel model has a total of 18,750 square meters and includes 15 stores while the Harbin hotel model has 9,288 square meters and three stories. Both buildings have the same space-types including those listed in Table 4. The building envelope properties, load densities, set points, outdoor air flow rates, and domestic hot water systems are the same for both models as shown in Table 24 and Table 32, respectively. The Harbin model has higher insulation levels in the roof and walls and lower window U-values which is appropriate for the colder climate. Another significant envelope difference is the window to wall rations; the Guangzhou model has an average north/south WWR of 53.5 percent while the Harbin model has an average WWR of 27.5 percent.

Both models use a four pipe fan coil system to deliver conditioned air to the guestrooms, the shop and the canteen. Cooling is provided by an electric chiller in both models but heating is provided by an electric boiler in the Guangzhou model and a natural gas boiler in the Harbin model. HVAC system details are listed in Table 26 and Table 27. The temperature set point schedules differ between the Guangzhou and Harbin models as well; Guangzhou implements a cooling setup schedule in the shop and canteen while Harbin implements a heating setback schedule for these spaces (see Table 29 and Table 30).

Generally speaking, the Chinese models are larger than the US models as shown in Table 23. Also, the Chinese models have lower insulation levels compared to their US counterparts but more efficient windows. Window to wall ratios are larger in the Chinese models compared to the US models. The average north/south WWR of the Guangzhou model is about 76 percent greater than that of the Houston model and the average north/south WWR of the Harbin model is about 55 percent greater than that of the Duluth model.

The US hotel reference building models for Houston and Duluth are for the most part, very similar. The only major differences are related to envelope and fenestration properties. These models use the same type of HVAC equipment for space heating and cooling (see Table 26 and Table 27). Unlike the Chinese models, the US models condition every space within the building; heating and cooling is provided by packaged systems rather than central boilers and chillers. The heating and cooling set points in the US models are comparable to those in the Chinese models for the guestrooms; however, the US model does not implement a setup/setback temperature schedule for any type of space.

There are a number of significant differences between the Chinese and US hotel models related to the geometry, envelope, HVAC systems, schedules, and building loads. Each of these will be discussed below. The first difference between the Chinese and US hotel models is the geometry. Three-dimensional renditions of these models are shown in Figure 28 through Figure 30 below. The total building area of the Chinese model is 18,750 m^2 (15 stories) for Guangzhou and 9,288 m^2 (four stories) for Harbin compared to 3,883 m^2 (four stories) for the US building. As far as construction goes, the Chinese model is concrete construction where as the US model is steel framed construction. Other differences related to construction, HVAC systems, building loads, and outdoor air flow rates are listed in

Table **24** through Table 31.

There are a few significant envelope differences that should be pointed out. First, the US model has over twice the insulation level in the roof compared to the Chinese model. Second, the window to wall ratio of the Chinese model is significantly higher than that of the US model.

Also, the Chinese implement a cooling setup temperature for the shop and canteen during unoccupied hours whereas the US model uses a constant temperature setting for all hours. The heating and cooling temperature set points for the guestrooms are comparable for the two models but the heating temperature set point in the shop and canteen in the Chinese model is 14 degrees Celsius cooler that common spaces in the US model. However, the building loads are much higher in these spaces so meeting the heating set point is most likely not a problem. Other significant differences are related to the type of HVAC equipments used in each model. Table 26 and Table 27 list the differences. Schedules for lighting, equipment and occupancy density as well as heating and cooling temperature set points are show in graphically in Figure 104 through Figure 110 in Appendix A2: Hotel Schedules.

The building load densities in the US models are the same for Houston and Duluth and are generally less compared to the Chinese models. The LPD and EPD are about 1.3 and 1.4 times greater, respectively, in the Chinese model compared to the US models. The occupancy density in the Chinese models is also about 1.5 times greater in the standard guestrooms but about 75 percent less in the VIP rooms compared to the US models. The LPD is less in stair cases and storage and mechanical rooms in the Chinese models. The Chinese LPD and EPDs in common areas are comparable to those in the US model; however, common spaces account for a greater percent of the total building area in the US model compared to the Chinese building.

The occupancy schedules in the Chinese guestrooms assume a higher number of occupants at all times compared to the US guestrooms. On the other hand the common spaces in the Chinese model (the shop and canteen) are occupied for fewer hours than the common spaces in the US model (including the front lounge and meeting room). It should also be mentioned that the front office is occupied at all hours of the day in the US model. It is also important to note that the US model assumes less people during the weekdays compared to weekends whereas the Chinese model assumes weekdays and weekend schedules are equivalent. There are also differences in the lighting and equipment schedules for the US building for weekdays and weekends (including differences between Saturdays and Sundays). The Chinese equipment schedule assumes all equipment is powered down for about 70 percent of the day 17 hours) on both weekdays and weekends for the guestrooms. According to the schedules for the shop and canteen, the equipment and lights are powered off in these spaces during non-business hours as well. The lighting schedule in the guestrooms however, shows that some lights are on at all hour of the day. These are not the best assumptions, especially since the occupancy schedule for the guestrooms shows that these spaces are never less than 50 percent occupied at all times of the day while equipment power densities are zero for the majority of the time. It is recommended that the lighting, equipment, and occupancy schedules be reevaluated for the Chinese models to improve the accuracy of the model; adjusting these schedules could potentially lead to an increase in annual energy consumption.

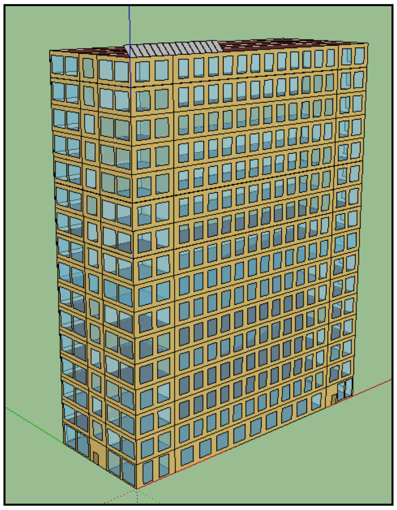

Figure 28: Guangzhou hotel benchmark model.

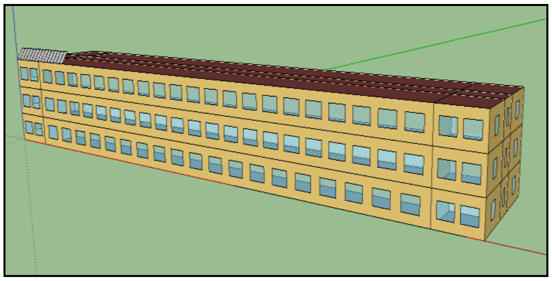

Figure 29: Harbin hotel benchmark model.

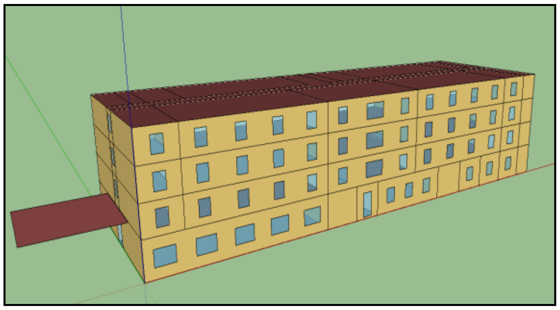

Figure 30: US hotel reference building.

Table 23: General Hotel Building Information

	Guangzhou Climate Region		Harbin Climate Region	
General Information	Guangzhou	Houston	Harbin	Duluth
Total floor area	18,750m^2	3,883 m^2	9,288 m^2	3,883 m^2
Number of floors	15	4	3	4
Aspect ratio	2.59	3.00	5.38	3.00
Orientation	East/West	East/West	East/West	East/West
Wall Construction	Concrete	Steel frame	Concrete	Steel frame
Roof Construction	Concrete	Metal decking	Concrete	Metal decking

Table 24: Hotel Envelope Construction Design - Guangzhou Climate Region

Envelope Construction	Units	Guangzhou	Houston
Exterior wall R-value	m^2K/W	1.17	1.42
Roof R-value	m^2K/W	1.23	2.80
Ground floor R-value	m^2K/W	0.557	0.537
Window U-value	W/m^2K	North: 5.36 South: 5.36 East: 5.89 West: 5.36	6.49
Window solar heat gain coefficient	Fraction	North: 0.448 South: 0.417 East: 0.610 West: 0.43	North: 0.610 South: 0.391 East/West: 0.391
Window visual transmittance	Fraction	North: 0.680 South: 0.410 East: 0.610 West: 0.230	North: 0.610 South: 0.390 East/West: 0.390
Window - to- wall ratios	Fraction	North: 65% South: 42% East: 10% West: 51%	All facades: 12.5%

Table 25: Hotel Envelope Construction Design - Harbin Climate Region

Envelope Construction Standards	Units	Harbin	Duluth
Exterior wall R-value	m^2K/W	2.08	2.74
Roof R-value	m^2K/W	2.77	2.80
Ground floor R-value	m^2K/W	1.27	0.537
Window U-value	W/m^2K	2.67	3.176
Window solar heat gain coefficient	Fraction	0.703	North: 0.651 South: 0.501 East/West: 0.501
Window visual transmittance	Fraction	0.781	North: 0.640 South: 0.490 East/West: 0.490
Window - to- wall ratios	Fraction	North: 25% South: 30% East: 10% West: 10%	All facades: 12.5%

Table 26: Hotel HVAC Design - Guangzhou Climate Region

Houston Hotel			
Guest Rooms	Packaged terminal air conditioners (PTAC)	Single speed DX cooling coil	$COP_{average} = 3.25$
		Supply air flow rate	AUTOSIZED
		Outdoor air flow rate	AUTOZISED
		Fan efficiency	0.25
		Fan motor efficiency	0.85
Common Areas/ Corridor	Packaged single-zone air conditioners (PSZ-AC)	Single speed DX cooling coil	$COP_{average} = 3.60$
		Gas heating coil	Efficiency = 0.79
Stairs/Storage Areas	Unit heaters	Electric heating coil	Efficiency = 1
		Supply air flow rate	AUTOSIZED
		Fan efficiency	0.25
		Fan motor efficiency	0.85
Guangzhou Hotel			
Shop, Canteen, All Guestrooms	Four-pipe fan coil	Cooling coil design set point	7 deg C
		Heating coil design set point	60 deg C
		Outdoor air flow rate	0.00833 m^3/s/person
		Supply fan efficiency	0.7
		Supply fan motor efficiency	0.9
		Max air flow rates	AUTOSIZED
		Max water flow rates	AUTOSIZED
	Chiller	Electric, water cooled, centrifugal	COP = 4.7
	Boiler	Electric Gas	Efficiency = 0.9
	Cooling Tower	Single speed	AUTOSIZED

Table 27: Hotel HVAC Design - Harbin Climate Region

Duluth Hotel			
Guest Rooms	Packaged terminal air conditioners (PTAC)	Single speed DX cooling coil	COP$_{average}$ = 3.1
		Electric heating coil	Efficiency = 1
		Supply air flow rate	AUTOSIZED
		Outdoor air flow rate	AUTOZISED
		Fan efficiency	0.25
		Fan motor efficiency	0.85
Common Areas/ Corridors	Packaged single-zone air conditioners (PSZ-AC)	Single speed DX cooling coil	COP<=3.14
		Gas heating coil	Efficiency = 0.9
Stairs/Storage Areas	Unit heaters	Electric heating coil	Efficiency = 1
		Supply air flow rate	AUTOSIZED
		Fan efficiency	0.25
		Fan motor efficiency	0.85
Harbin Hotel			
Shop, Canteen, All Guestrooms	Four-pipe fan coil	Cooling coil design set-point	7 ^{o} C
		Heating coil design set-point	60 ^{o} C
		Supply fan efficiency	0.7
		Supply fan motor efficiency	0.9
		Max air flow rates	AUTOSIZED
		Max water flow rates	AUTOSIZED
	Chiller	Electric, water cooled, centrifugal	COP = 4.7
	Natural gas boiler	Natural gas	Efficiency = 0.9
	Single speed cooling tower	Single speed	AUTOSIZED

Table 28: Hotel Building Load Densities - Guangzhou and Harbin Climate Regions

	Lighting Densities (W/m^2)		Equipment Densities (W/m^2)		People ($people/100m^2$)	
Zones	US	China	US	China	US	China
Standard Guest Rooms	11.84	15	14.3	20	4.5	6.67
VIP Guest Rooms		15	-	20	-	3.33
Corridor	5.38	5	-	-	-	-
Front Office	11.84	-	12.9	-	7.67	-
Shop	-	19	-	13	-	33.3
Canteen	-	13	-	13	-	5
Mechanical	16.2	5	-	-	-	5
Storage	13.7	5	-	5	-	5
Stairs	6.46	5	-	-	-	-
Employee Lounge	12.9	-	77.16	-	33.7	-
Meeting Room	14	-	12.9	-	53	-
Front Lounge	11.84	-	15.43	-	32.5	-
Rest Room	9.7	-	10.76	-	3.1	-

Table 29: Hotel Set Points - Guangzhou Climate Region

	Cooling Set Points [^oC]		Heating Set Points [^oC]	
Zones	Guangzhou (Hours)	US (Hours)	Guangzhou (Hours)	US (Hours)
Standard Guest Rooms	25 - All hours	24 - All hours	22 - All hours	21 - All hours
VIP Guest Rooms	25 - All hours		22 - All hours	
Corridor	-	24 - All hours	-	21 - All hours
Shop	37- until 8am 28 - until 9am 25 - until 9pm 37 - until 12am	-	10 - All hours	-
Canteen	37 - until 8am 28 - until 9am 25 - until 9pm 37 - until 12am	-	10 - All hours	-
Mechanical	-	24 - All hours	-	21 - All hours
Storage/Stairs	-	40 - All hours	-	15.6 - All hours
Employee Lounge/ Meeting Room / Front Lounge/ Restroom/ Front Office	-	24 - All hours	-	21 - All hours

Table 30: Hotel Set Points - Harbin Climate Region

	Cooling Set Points [^oC]		Heating Set Points [^oC]	
Zones	Harbin (Hours)	Duluth (Hours)	Harbin (Hours)	Duluth (Hours)
Standard Guest Rooms	25 - All hours	24 - All hours	22 - All hours	21 - All hours
VIP Guest Rooms	25 - All hours	-	22 - All hours	-
Corridor	-	24 - All hours	-	21 - All hours
Shop	25 - All hours	-	12 - until 8am 16 - until 9am 18 - until 9pm 18 - until 12am	-
Canteen	25 - All hours	-	12 - until 8am 16 - until 9am 18 - until 12 am	-
Mechanical	-	24 - All hours	-	21 - All hours
Storage/ Stairs	-	40 - All hours	-	15.6 - All hours
Employee Lounge/ Meeting Room/ Front Lounge/ Restroom/ Front Office	-	24 - All hours	-	21 - All hours

Table 31: Hotel Outdoor Air Flow Rates – Guangzhou and Harbin Climate Regions

	Outdoor Air Flow [m^3/sec/person]	
	China	US
Guest Rooms	0.00833	0.00943
Corridor [$m^3/s/m^2$]	-	0.00273
Front Office	-	0.00943
Shop	0.00278	-
Canteen	0.00556	-
Mechanical [$m^3/s/m^2$]	Nat. ventilation	0.00273
Storage	Nat. ventilation	None
Stairs	Nat. ventilation	None
Employee Lounge	-	0.00708
Meeting Room	-	0.00943
Front Lounge	-	0.00708
Rest Room	-	0.02358

Table 32: Hotel Domestic Hot Water Systems - Guangzhou and Harbin Climate Regions

	US	China	
System Type	Instantaneous Water Heater	Instantaneous Water Heater	Solar Hot Water
Fuel Type	Natural Gas	Electric	Solar
Max Temperature limit [deg C]	82.2	82.2	-
Heating Capacity [W]	845,000	80,000	-
Efficiency [W/W]	0.8	0.85	-
Energy Factor	0.67	0.59	-
FR(tau-alpha)	-	-	0.691
FRUL [$W/m^2/^oC$]	-	-	3.396

2.3.2 Hotel Energy Performance Comparison – Hot Summer Warm Winter Climate Region

This section will identify the effects of building envelope, HVAC system, and operation schemes on energy consumption differences between the Chinese and US hotel building models for the Hot Summer Warm Winter climate region of Guangzhou. This model is compared to that of Houston, Texas.

Figure 32 shows that the US building has a greater energy intensity under Chinese operating conditions compared to the Guangzhou benchmark model; the Houston hotel consumes about 25 percent more site energy than the Guangzhou hotel when operated according to the Chinese. However, taking a closer look one will notice that these differences are due primarily to the different facilities and HVAC systems. The total combined heating and cooling energy per unit floor area is nearly equivalent at 40 kWh/m^2, although cooling energy is approximately 32 percent greater in the Houston model while heating energy is eliminated as a result of higher internal loads associated with Chinese practice. The HVAC cooling systems utilized in the Guangzhou model have higher COP values compared to the Houston model. The Houston model utilizes packaged terminal air conditioning (PTAC) units in the guestrooms with COP values of 3.25 while the common areas use packaged single zone air conditioning (PSZ-AC) units with COP values of 3.60. The Guangzhou hotel uses a four-pipe fan coil system with cooling provided by an electric chiller (COP of 4.7). The auxiliary HVAC equipment in the Houston hotel, including fans and pumps, are less efficient on average than those in the Guangzhou model contributing to a noticeable difference in annual energy consumption. Another major difference between the models is the fact that the Houston model provides conditioned air as well as mechanical ventilation to all of the zones including the stairs, storage areas, and corridor – the Guangzhou model does not condition these areas. This additional air conditioning in the Houston model also accounts for the difference in auxiliary HVAC and cooling energy. Finally, the use of Chinese solar hot water in combination with an instantaneous hot water heater is show to be more efficient that the hot water heating/storage system used in the US model. Refer to Table 26 for all HVAC specification differences.

The excess interior equipment energy shown in Figure 32 is due to the fact that the US building has a greater number of zones with higher equipment power densities. The weighted average equipment power density of the Guangzhou and Houston models in their original state are nearly equivalent, 11.6 W/m^2 and 11.4 W/m^2 respectively. However, when the Chinese loads are used in the US model, the weighted average equipment power density of the US model increases to 14.2 W/m^2, a 25% increase. The high elevator electricity consumption associated with the US model makes up another significant category for the Houston hotel, totaling about nine percent of the total building energy consumption, whereas the elevator in the China model accounts for only 0.3 percent of the total. (The US elevator consumes 11 times more energy than the elevator in the China model.)

In general, this comparison in figure (directly above) shows that the envelope of the Houston model may provide a better thermal barrier against cooler ambient conditions than the Chinese model. However, since energy consumption is dominated by cooling, less thermal insulation may be a better option. This comparison also shows that the cooling system in the Chinese model is more efficient at meeting the load.

There are a number of different envelope differences between the Houston and Guangzhou hotels. First, the R-values of the roof and exterior walls are higher in the Houston model while the window U-values are lower in the Guangzhou model. (See Table 24 for envelope properties.) Exchanging the Guangzhou window properties and sizes with those in the Houston model shows a heating energy reduction of 33 percent and a cooling energy reduction of 24 percent. This can be seen in the comparison between the second and third models displayed in Figure 33. This is primarily a result of reducing the window to wall ratios (south façade WWRs are 42 percent for the Guangzhou model and 12.5 percent for the Houston model). The solar heat gain coefficients vary on all sides for both models; the windows on the south façade of the Houston model have lower SHGCs than the south façade windows of the Guangzhou model which is critical for keeping solar heat gains at a minimum.

The internal building loads of US and Chinese hotel models are quite different in terms of schedules and power densities. In general, the Chinese model assumes higher lighting, equipment, and occupancy densities than the US model but the schedules are generally less energy intensive. Consider the following example. The general guestrooms of the Guangzhou model have an EPD of 20 W/m^2 while the Houston model assumes an EPD of 14.3 W/m^2, however, the Guangzhou model assumes that the guestroom equipment load is zero for 17 hours a day while the US model assumes some fraction of EPD at all hours of the day. The US model includes a few unique zones with higher equipment power densities; one zone in particular is the employee lounge which has an equipment power density of about 77 W/m^2. This leads to a higher overall building electricity use intensity compared to the Guangzhou hotel seen in Figure 33. Another fact that should be pointed out is that the elevator in the US model has a much higher power draw than that in the Chinese model; the US elevator accounts for about 30 percent of the overall electricity consumption while the Chinese elevator accounts for only two percent. (See Table 28 for all building load densities and Figure 104 through Figure 106 A-2 for schedules.)

In summary, the results show that energy consumption differences between the Guangzhou and Houston hotel models are a result of envelope properties, HVAC system types and efficiencies, and building operation schemes including building load densities and schedules. The following general conclusions can be drawn from this comparison:

1. The Chinese HVAC systems are more efficient at condition the building given their higher efficiency ratings and COP values contributing to lower heating and cooling energy intensities.
2. The most significant envelope difference is the window to wall ratio; these ratios are significantly larger in the Guangzhou model compared to the US model. Heating and cooling energy could be reduced if Guangzhou accepted smaller window to wall ratios.
3. The internal gains of the Chinese model are more energy intensive than those in the US model; however, the Chinese schedules are less energy intensive and balance out the overall end use energy intensity. The results lead to similar annual building consumption values for lighting and

electrical equipment for the Guangzhou hotel compared to the hotel model of Houston. It should be noted though that the US elevator accounts for a much larger percentage of the electricity consumption than does that of the Chinese model. If the Chinese begin to increase the use of lighting and electrical plug loads, there will be a greater need to improve the efficiency of these systems.

4. Comparing the occupant energy intensity shows two things. First, the US occupants could reduce their energy intensity by incorporating the Chinese set points and schedules. However, adopting the Chinese schedules is not a practical way of reducing energy because it could be nearly impossible to change the habits of hotel occupants. Second, the Chinese occupants could benefit from the incorporation of US building design practice and the use of US HVAC equipment.

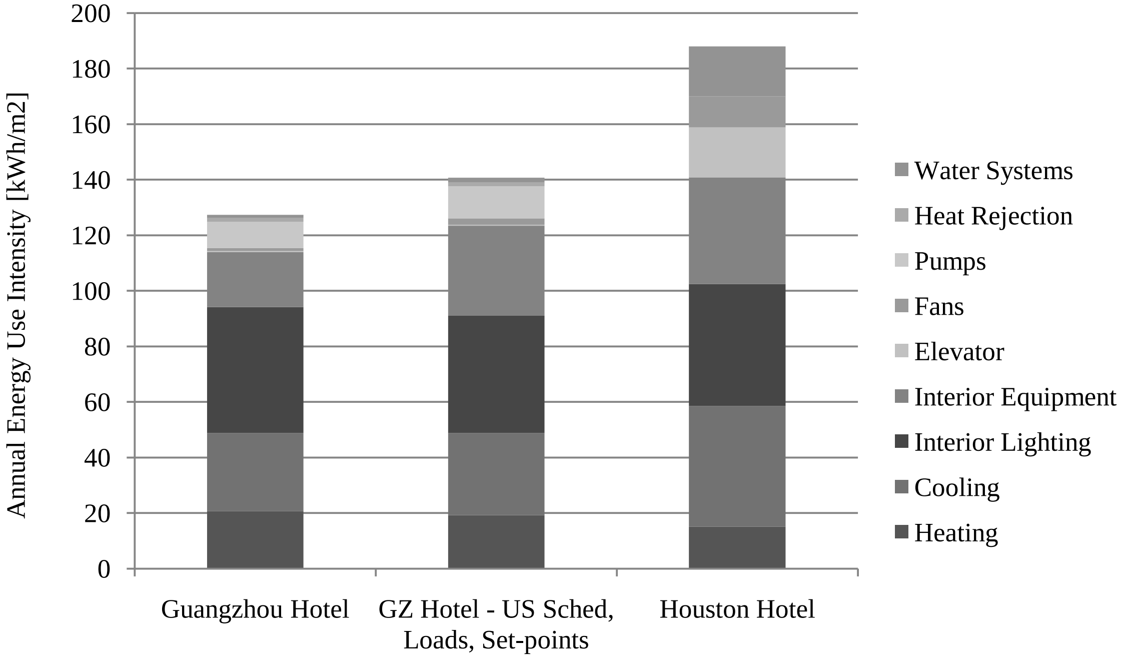

Figure 31: Guangzhou hotel in Houston, TX with US operating scheme.

Table 33: Annual EUI [kWh/m^2] of Hotel Building Models in Guangzhou, China

	GZ Hotel	GZ Hotel - US Sched, Loads, Set-points	Houston Hotel
Heating	20.8	19.3	15.1
Cooling	28.1	29.6	43.4
Interior Lighting	45.3	42.2	44.0
Interior Equipment	19.8	32.4	38.3
Elevator	0.3	0.3	18.0
Fans	1.1	2.2	11.2
Pumps	9.5	11.5	0.0
Heat Rejection	1.4	1.4	0.0
Water Systems	1.1	1.7	17.9
Total End Uses	128.1	140.7	205.9

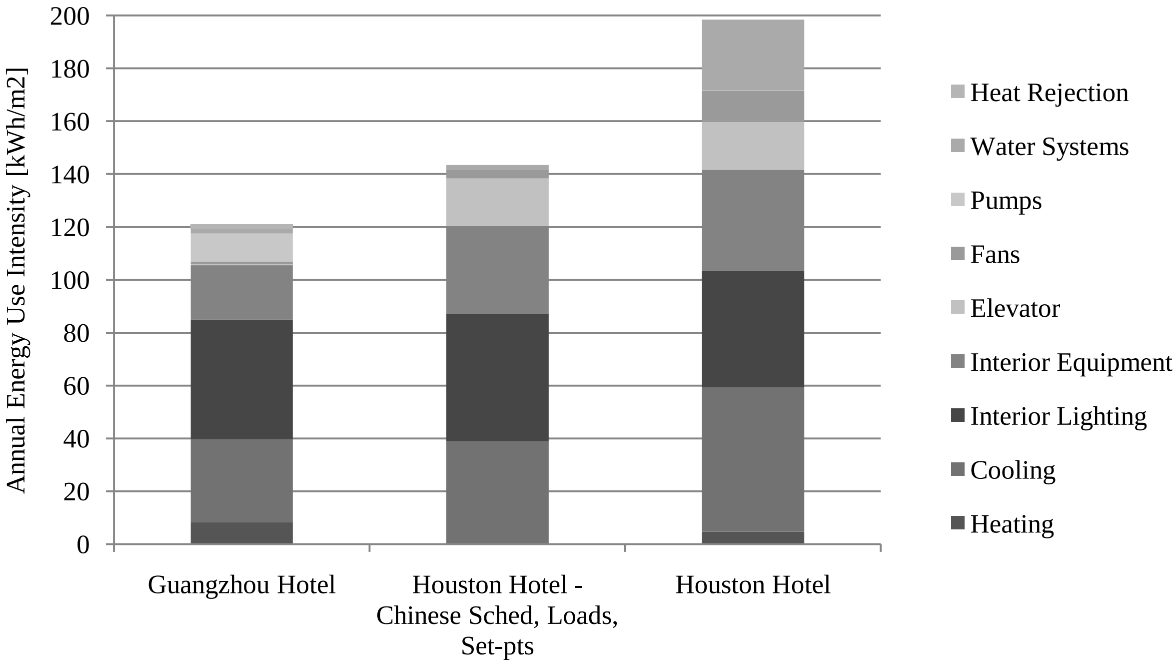

Figure 32: Houston hotel in Guangzhou with Chinese operation schemes.

Table 34: Annual EUI [kWh/m^2] of Hotel Building Models in Houston, TX

	Guangzhou Hotel	Houston Hotel - Chinese Sched, Loads, Set-pts	Houston Hotel
Heating	8.3	0.0	4.6
Cooling	31.4	38.8	54.7
Interior Lighting	45.3	48.3	44.0
Interior Equipment	20.5	33.2	38.3
Elevator	0.3	18.0	18.0
Fans	1.1	3.2	12.0
Pumps	10.6	0.0	0.0
Water Systems	1.7	2.0	26.8
Heat Rejection	1.7	0.0	0.0
Total End Uses	121.0	147.2	198.5

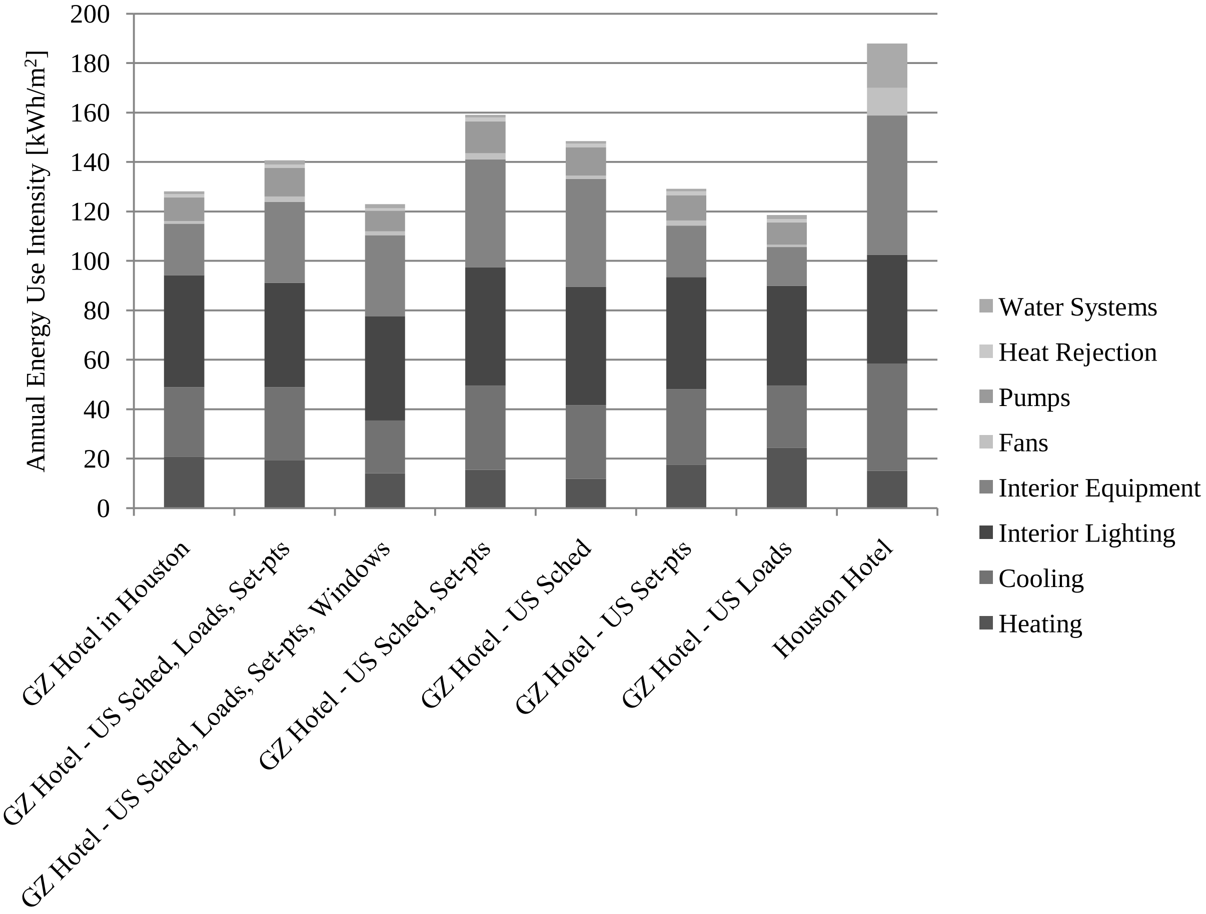

Figure 33: Effect of US operating schemes on the Guangzhou hotel energy consumption.

Table 35: Effects of US Operating Schemes on Guangzhou Hotel EUI [kWh/m^2]

	GZ Hotel in Houston	GZ Hotel - US Sched, Loads, Set-pts	GZ Hotel - US Sched, Loads, Set-pts, Windows	GZ Hotel - US Sched, Set-pts	GZ Hotel - US Sched	GZ Hotel - US Set-pts	GZ Hotel - US Loads	Houston Hotel
Heating	20.8	19.3	14.0	15.4	11.8	17.5	24.4	15.1
Cooling	28.1	29.6	21.4	34.1	29.8	30.6	25.1	43.4
Interior Lighting	45.3	42.2	42.2	47.9	47.9	45.3	40.4	44.0
Interior Equipment	20.9	32.7	32.7	43.6	43.6	20.9	15.6	56.3
Fans	1.1	2.2	1.5	2.5	1.4	2.0	0.9	11.2
Pumps	9.5	11.5	8.3	12.9	11.5	10.3	9.0	0.0
Heat Rejection	1.4	1.4	1.0	1.6	1.4	1.5	1.3	0.0
Water Systems	1.1	1.7	1.7	1.1	1.1	1.1	1.7	17.9
Total End Uses	128.1	140.7	123.0	159.1	148.5	129.2	118.5	205.9

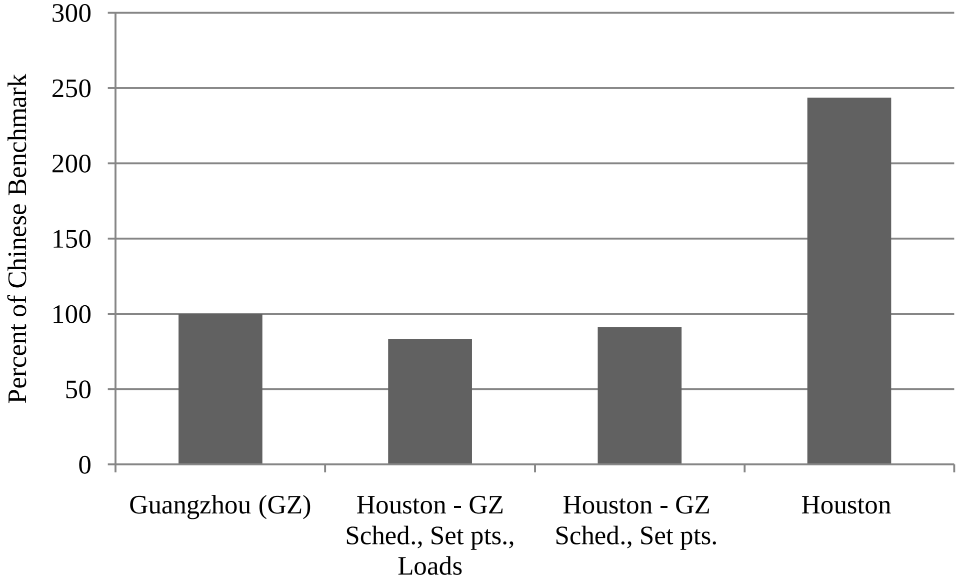

Figure 34: Energy consumption per occupant hour as a percentage of the Chinese benchmark – Guangzhou climate region.

Table 36: Occupant Energy Intensity - Guangzhou Climate Region

	GZ	Houston – GZ Sched., Set pts., Loads	Houston – GZ Sched., Set pts.	Houston
Energy consumption per occupant hour [kWh/occupant-hour]	0.54	0.45	0.5	1.3

2.3.3 Hotel Energy Performance Comparison – Severe Cold Climate Region

This section will identify the effects of building envelope, HVAC system, and operation schemes on energy consumption differences between the Chinese and US hotel building models for the Severe Cold climate region of Harbin. This model is compared to that of Duluth, Minnesota.

The result of envelope and HVAC system type and efficiency differences between the Harbin and Duluth hotel models can be observed by comparing the results in Figure 35. Given that the opaque envelope properties are fairly similar between the Duluth and Harbin models, the energy consumptions differences are primarily due to differences in the HVAC systems. Like the Guangzhou hotel model, the Harbin model uses a four pipe fan coil system with a natural gas boiler with an efficiency of 0.9 and an electric water cooled centrifugal chiller with a COP of 4.7. The Duluth model uses the same system as the Houston model including packaged terminal AC units for the guestrooms; the average COP of the DX coils is 3.1 and the electric heating coils have an efficiency of 1.0. Packaged single-zone AC units are used in the common areas of the US model with DX coil COP values about 3.1 and heating coil efficiency values of 0.9. These differences, along with opaque envelope differences, lead to a 16% difference in heating energy and about a 100% difference in cooling energy. Refer to Table 27 for a complete HVAC comparison.

Comparing model two and three in Figure 37 shows that the differences in window types and sizes have a very small impact on the energy consumption differences. In this comparison, the Harbin benchmark window types and sizes are replaced with those of the Duluth model. (Refer to Table 25 for window property comparison.) This also verifies that the envelop design differences between the US model and the Chinese model do not account for much of the energy consumption differences.

The primary differences in building loads are attributed to the elevator and the domestic hot water consumption. The elevator energy consumption in the Duluth model is significantly more than that of the Harbin model. As was seen in the case for Houston, elevator electricity consumption accounts for about 30 percent of the overall energy consumption from electric loads in the US model whereas the elevator in the Harbin model accounts for only two percent. Domestic hot water consumption per unit area in the Duluth model is about ten times more than in the Harbin model. Also, the instantaneous and solar hot water heating system of the Harbin model is shown to be more efficient compared to the heating/storage system in the Duluth mode. The difference in domestic hot water heating systems leads to an 83 percent difference in domestic water heating energy intensity.

The most striking observation in Figure 36 is the dramatic decrease in heating energy consumption in the Duluth hotel operating with Chinese schedules, set points, and building loads. There are two primary reasons for this. First, recall that the corridors, mechanical room, storage areas, and staircases are conditioned in the US building model but are not conditioned in the Chinese model. For this comparison, the HVAC systems have been removed from these zones to better represent how the Chinese would use the building. This eliminates the heating load from 20 percent of the building and as a result, dramatically reduces the heating energy consumption. The second reason for the dramatic difference is the fact that the Chinese heating set point used in the common spaces of the US model (including the employee lounge, front office, front lounge and meeting room) is three degrees lower during occupied hours than the US set points. What is more significant is the fact that the Chinese schedule incorporates a six degree Celsius temperature setback during unoccupied hours whereas the US schedules maintains a 21 degree Celsius set point 24-hours a day. Two other differences between the two US models include reduced equipment power density and increased lighting power density. Although the Chinese equipment power densities are greater than those of the US, the Chinese schedules are much less energy intensity, as discussed previously. The lighting power density in the US model with Chinese operating schemes is slightly greater than the Chinese model due to the fact that a greater percentage of the total building area incorporates the high lighting power of the Chinese shop.

In summary, the results show that energy consumption differences between the Harbin and Duluth hotel models are primarily a result of, HVAC system types and efficiencies and building schedules. The following general conclusions can be drawn from this comparison:

1. Envelope differences are not responsible for large differences in energy consumption between the Harbin and Duluth hotel models.
2. HVAC system type and efficiency differences contribute significantly to differences in heating and cooling energy consumption values.
3. The internal gains of the Chinese model are more energy intensive than those in the US model; however, as was seen in the hotel comparison for the Hot Summer Warm Winter climate region, the Chinese schedules are less energy intensive. This balances out the overall end use energy intensity and leads to similar annual building consumption values for lighting and electrical equipment. It should be noted though that the US elevator accounts for a much larger percentage of the electricity consumption than does that of the Chinese model.
4. The Harbin model incorporates heating set points which are one degree cooler than the Duluth model for the guestroom zones. The Harbin model also uses a six degree Celsius heating set back schedule for the common zones including the shop and canteen. Incorporating the more energy intensive US set points into the Harbin model results in a four percent increase in energy.
5. Comparing the occupancy energy intensity results shows that the US and Chinese occupants account for about the same amount of annual energy consumption; the US occupants consume about seven percent more energy. The US occupants could reduce their energy use intensity by adopting the Chinese schedules and set points, although as mentioned before, it may be nearly

impossible to change the habits of occupants. In addition, the Chinese occupants could reduce their energy intensity by incorporating US building design practice and HVAC equipment.

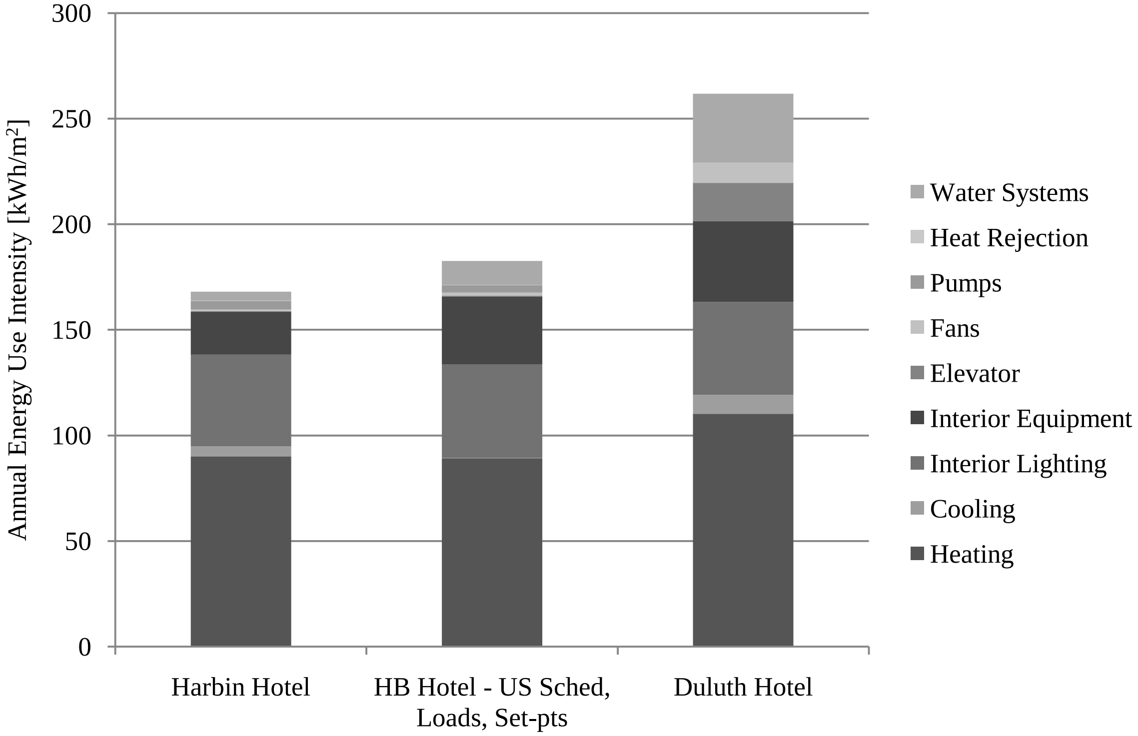

Figure 35: Hotel models in Duluth with US operation schemes compared to the Duluth benchmark.

Table 37: Annual EUI [kWh/m^2] of Hotel Building Models in Duluth, MN

	Harbin Hotel	HB Hotel - US Sched, Loads, Set-pts	Duluth Hotel
Heating	90.1	89.2	110.3
Cooling	4.7	0.2	8.9
Interior Lighting	43.5	44.3	44.0
Interior Equipment	20.2	32.1	38.2
Elevator	0.3	0.3	18.1
Fans	0.7	1.6	9.7
Pumps	4.2	3.5	0.0
Heat Rejection	0.1	0.1	0.0
Water Systems	4.3	11.4	32.6
Total	168.1	182.6	261.8

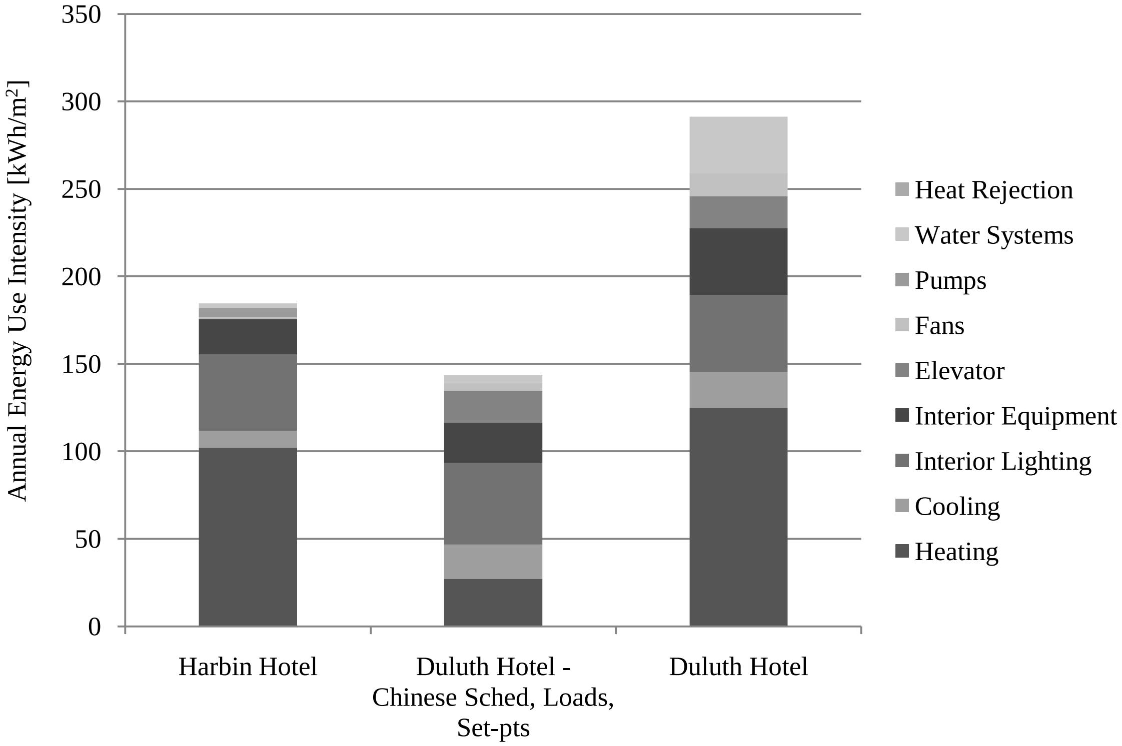

Figure 36: Duluth Hotel in Harbin with Chinese operation schemes compared to the Harbin benchmark.

Table 38: Annual EUI [kWh/m^2] of Hotel Building Models in Harbin, China

	Harbin Hotel	Duluth Hotel - Chinese Sched, Loads, Set-pts	Duluth Hotel
Heating	102.0	26.9	124.9
Cooling	9.8	19.8	20.5
Interior Lighting	43.5	46.8	44.0
Interior Equipment	20.2	22.9	38.2
Elevator	0.3	18.1	18.1
Fans	0.8	4.4	13.1
Pumps	5.3	0.0	0.0
Water Systems	2.5	4.8	32.5
Heat Rejection	0.3	0.0	
Total End Uses	184.8	143.7	291.4

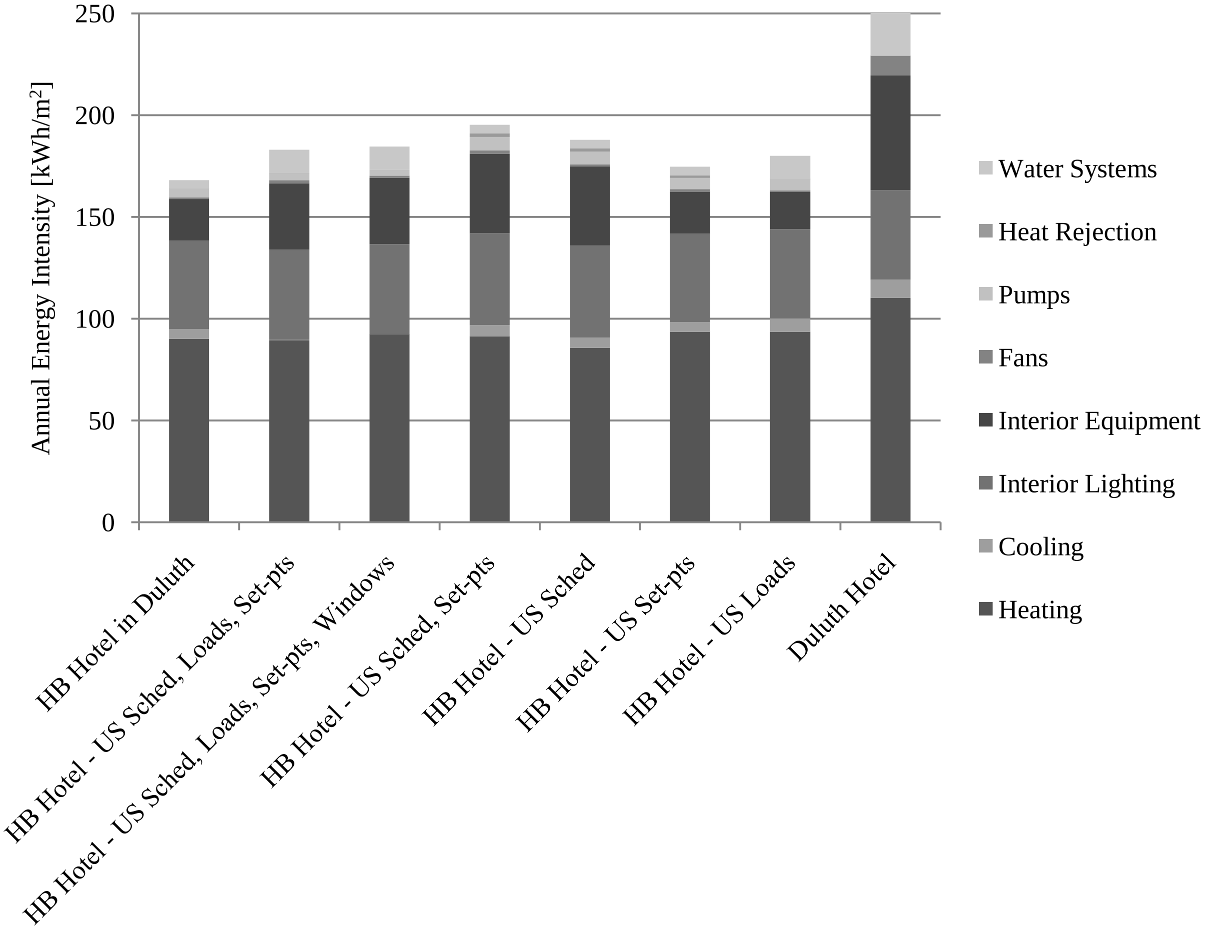

Figure 37: Effect of US operating schemes on the Harbin hotel energy consumption.

Table 39: Effects of US Operating Schemes on Harbin Hotel EUI [kWh/m^2]

	HB Hotel in Duluth	HB Hotel - US Sched, Loads, Set-pts	HB Hotel - US Sched, Loads, Set-pts, Windows	HB Hotel - US Sched, Set-pts	HB Hotel - US Sched	HB Hotel - US Set-pts	HB Hotel - US Loads	Duluth Hotel
Heating	90.1	89.5	92.4	91.3	85.7	93.5	93.5	110.3
Cooling	4.7	0.2	0.0	5.5	5.0	4.7	6.6	8.9
Interior Lighting	43.5	44.3	44.3	45.2	45.2	43.5	43.9	44.0
Interior Equipment	20.5	32.5	32.5	38.9	38.9	20.5	18.3	56.3
Fans	0.7	1.6	1.2	1.7	1.0	1.3	0.7	9.7
Pumps	4.2	3.4	2.9	6.6	6.3	5.5	5.5	0.0
Heat Rejection	0.1	0.1	0.0	1.7	1.5	1.2	0.1	0.0
Water Systems	4.3	11.4	11.4	4.3	4.3	4.3	11.4	32.6
Total End Uses	168.1	183.0	184.5	195.3	187.9	174.7	180.0	261.8

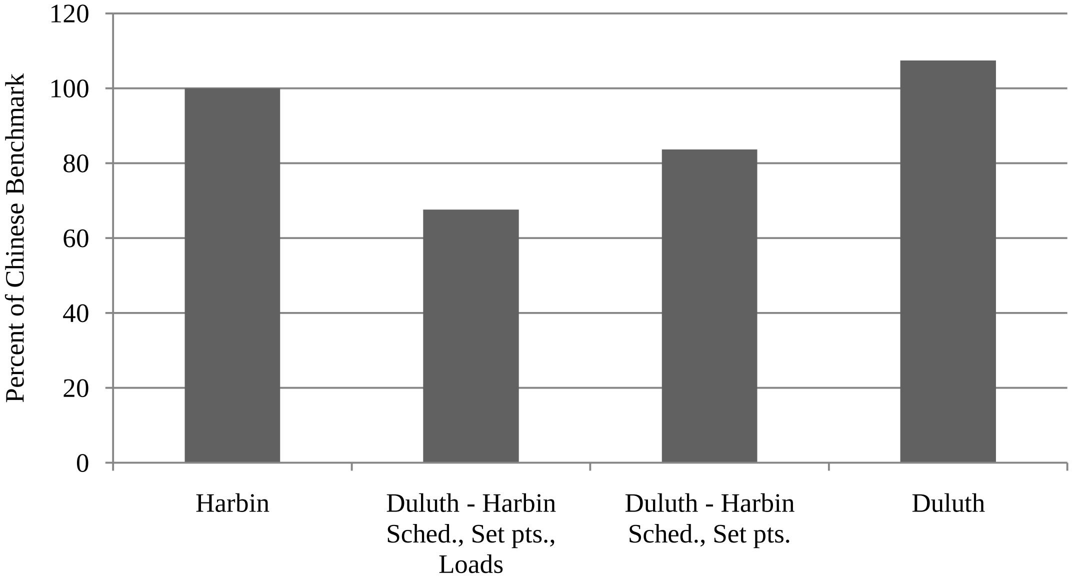

Figure 38: Energy consumption per occupant hour as a percent of the Chinese benchmark - Harbin climate region.

Table 40: Occupant Energy Intensity - Harbin Climate Region

	Harbin	Duluth – HB Sched., Set pts., Loads	Duluth – HB Sched., Set pts.	Duluth
Energy consumption per occupant hour [kWh/occupant-hour]	0.78	0.53	0.65	0.84

2.4 Summary and General Remarks

The energy performance comparison shows that in general, the Chinese building loads are more energy intensive and the set points and schedules are less energy intensity compared to those of the US. The high building loads are due to higher occupancy, lighting, and equipment power densities. However, the equipment and lighting power densities are generally less per person in the Chinese models, resulting in lower energy use per occupant. Typical HVAC systems differ quite significantly between China and the US and insulation levels are often lower in China. However, insulation level differences do not account for most of the energy performance differences; these differences are primarily due to building loads, set points, schedules, and HVAC systems types.

There are some design concerns associated with the Chinese benchmark building models that should be reevaluated so to improve the accuracy of the benchmark models. These include office occupancy density, equipment and lighting schedules, fan pressure drop, and chiller supply air reference node. In addition, the infiltration and ventilation rates in the Harbin office should be verified through direct measurement and added to the model. Modifying these input parameters could significantly change the benchmark energy consumption. The accuracy of the models will assure that future modeling results are also accurate and reliable.

Notable differences can be identified when reporting energy consumption on a per unit area basis verses a per occupant hour basis. In most cases, occupant energy intensity is significantly higher in the US models due to the fact that there are fewer people occupying the building. This brings up an interesting thought on how building energy performance ratings should be calculated. One building can outperform another on a per unit area basis, but underperform on a per occupant basis depending on the occupancy use. It is important to use building space as efficiently as possible so to reduce the energy footprint of the population. Doing so could slow the rate of building development and therefore slow the consumption of materials and energy. It should also be mentioned that source energy is the best indicator of actual consumption of a building as this figure accounts for any efficiency losses. This metric also provides the best correlation to environmental impacts and energy cost (Energy Star, 2010).

The general trends show that the Chinese office and hotel benchmark building models could save energy by adopting the lower building loads associated with the US reference building models. However, because it is difficult to change the habits of building occupants, the actual savings could be far less than what the simulation results suggest. The drawback to this modification is that the occupant energy intensity would increase significantly. Both building EUI and occupant EUI should be considered and weigh appropriately. Another general trend shows that energy savings could be achieved in the US reference building models if the Chinese building shell and HVAC systems are used. Most of these savings are associated with differences in HVAC systems rather than envelope differences. The US reference buildings would generally not save energy by adopting Chinese operation schemes on a per unit floor area basis but these incorporations would reduce occupant energy intensity.

Chapter 3: Identifying Potential Energy Savings for the Hot Summer Warm Winter Climate Region Benchmark Models

3.1 Energy Simulation and Optimization Software

The primary tools used for this research include EnergyPlus, OpenStudio, XML-Spy, and Opt-E-Plus. The building energy simulation software, EnergyPlus was developed by the US Department of Energy (DOE, 2010) and the associated national laboratories and is selected as the simulation engine for this research for two reasons. First, EnergyPlus computes building energy use based on interactions between the building components, climate, location, and renewable energy systems such as photovoltaics and solar hot water systems. Secondly, the optimization tool, Opt-E-Plus, can be used as an interface to EnergyPlus to find alternative building designs that lead to potential energy savings. Opt-E-Plus, also developed by national labs of the US DOE, allows the user to select a wide range of design options to test on a baseline building model. These design options are referred to as energy design measures (EDMs) as their applications are intended to impact the building's energy use (Hale, et al., 2009). Opt-E-Plus also allows the user to compare the performance of these optional designs to the baseline model with respect to different performance metrics including energy savings, carbon savings, and a variety of economic functions. This chapter will describe how Opt-E-Plus operates and will also outline the step by step procedure used to identify potential energy savings in the Guangzhou office and hotel benchmark models. In addition, recommendations for improved building code standards will be presented for this climate region.

3.1.1 Creating the Building Input Files and Running Opt-E-Plus

There are a number of preliminary steps that must be carried out before Opt-E-Plus can run an optimization. First, the user must create an XML file of the building model, as this is the input file type used by Opt-E-Plus. This model is used as the baseline and is the reference point for the alternative models that Opt-E-Plus generates. Google SketchUp and the associated EnergyPlus plunging tool, OpenStudio (Google, 2010), are used to create the building geometry (i.e. interior and exterior walls, floors, ceilings, roof and slab). The building geometry is then saved as an EnergyPlus IDF file with the use of OpenStudio. This simple IDF file can then be converted to an XML file using Opt-E-Plus. The remaining building components (including building loads, material types, schedules, set points, and the primary supply and demand components of the HVAC system) are then added to the XML file. Operation schedules, utility rates, and location dependent data sets are defined in the common files of the Opt-E-Plus preprocessor. The preprocessor can be thought of as the engine that imports preassembled chunks of EnergyPlus code into the IDF file. The user can also input schedules directly into the XML in text format if the predefined schedules do not match those intended by the modeler.

One benefit to using the XML for completing the building models is that the user does not need to completely define each pipe, node, and branch of the HVAC system, as is required in the IDF file of EnergyPlus. This agonizing process is done by the preprocessor of Opt-E-Plus. On the other hand, the preprocessor can create errors in the model if the user fails to specifying particular inputs in the XML. This arises from the fact that there are many defaults in the XML that are not necessarily visible or explicit to the user. Other opportunities for errors arise from the fact that the preprocessor applies a predefined set of operation schedules and set points to the HVAC components which may differ from the intended settings. As a result, the model could over or under estimate energy consumption. The user should examine the final IDF file and confirm that the model is indeed built and operates according to planned. At last resort, the predefined schedules can be changed in the preprocessor.

Opt-E-Plus provides the user with a database of energy design measures (EDMs) to test on the baseline model. There are six categories of EDMs which are summarized in Table 41. Each subcategory contains a variety of options; there are, for example, roughly 100 window types with varying U-values, solar heat gain coefficients, and visual transmittances. The EDMs should be selected critically as the number of EDMs chosen for the optimization increases the number of iterations exponentially! The user must also select the optimization parameters which include a variety of energy, cost, and green-house gas related variables. The default parameters include net site energy savings and total life cycle cost savings.

Table 41: Opt-E-Plus Energy Design Measure Categories

Program Parameters	Location	Fabric	Exterior Walls
	Economics		Roofs
	Schedules		Attic Floor
	Plug Intensity		Interior Walls
	People Intensity		Exterior Slab
	Infiltration Rater		Exposed Floors
	Lighting Intensity		Swinging Door
	Utility Rates		Non Swinging Door
	Daylighting		Window Constructions
	TDD		Skylight Constructions
	Skylights	Equipment	HVAC System Type
Form	Aspect Ratio		Indirect Evaporative System
	Floor Area		Direct Control Ventilation (DCV)
	Ceiling Height		Energy Recovery Ventilation (ERV)
	Attic Height		Reheat Coil Type
	Perimeter Depth		Ventilation Rates
	Number of Floors		Refrigeration Systems
	Rotation		Water Systems
	Window Fractions		
	Shading Overhangs Depth		
	Shading Overhangs Offset		
	Shading Fins		

Once the baseline XML file is complete, the appropriate EDMs have been selected, and the optimization parameters are chosen, Opt-E-Plus can perform the optimization. Opt-E-Plus reads in an XML file and modifies it by replacing existing building components with user-selected EDMs, thus creating a new XML file and corresponding IDF file. The IDF file is sent to EnergyPlus for the annual energy performance simulation. The XML and IDF files, along with all of the output files from EnergyPlus, are stored in a unique directory. Once the simulation is complete, the results are plotted on a graph of net site energy savings verses total lifecycle cost savings (default parameters). Opt-E-Plus selects the next EDM based on these results with the goal of minimizing cost and maximizing energy savings. This iterative solving method is repeated until the building design leading to the greatest energy savings is determined. This process is summarized in the flow diagram of Figure 39.

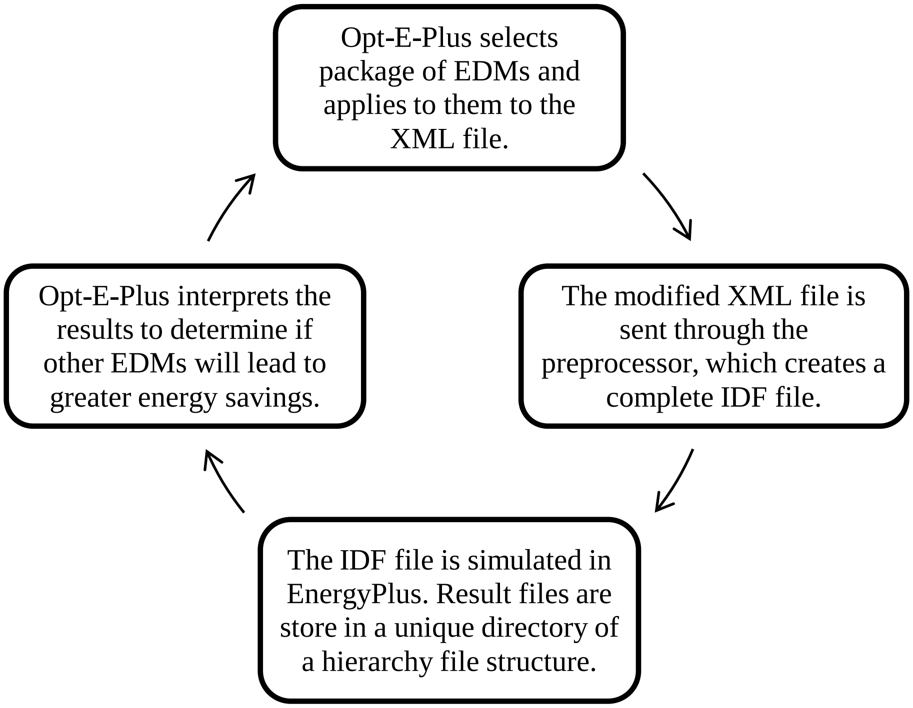

Figure 39: Summary of optimization process.

A solid black line connects the baseline model to the building designs leading to the least-cost design option and extends upward to the model with the greatest percent energy savings. This line is referred to as the *optimization results curve*. The points along the curve that begin at the least cost building and move toward the building with the greatest energy savings are termed the *Pareto points;* the segment of the optimization results curve that connects these points define the *Pareto front* (Hale, et al., 2009).

From the plot, the user can navigate to the directory of any particular case to extract specific information such as annual energy-use breakdown. The user can also output the data from the optimization plot to a CSV file which includes the total annual energy consumption and total lifecycle cost associated with each simulation, including the baseline, as well as a list of the EDMs applied to each unique simulation.

3.2 Alternative Use of Opt-E-Plus

Rather than using Opt-E-Plus to perform an optimization, this tool is used here to identify the potential energy savings in the Chinese benchmark models associated with the application of a variety of energy design measures available in the optimization database. It should be made clear that costs savings have been determined due to uncertainties in economic data. An economic optimization is included in Chapter 5 for the Harbin benchmark models. Although this analysis is not a true optimization, the term "optimization" is used here for lack of a better description but the reader should not put any emphasis on the cost savings results shown in the optimization plots in this chapter. It should also be noted that the EDMs in the Opt-E-Plus database are specific to the US and there is no guarantee that these materials are currently available in China. It is suggested that the materials included in the recommended package of EDMs be compared to products available on the market in China. Yet another issue to consider when review the optimization results: Opt-E-Plus is designed to select EMDs based on energy and cost savings; thus, the order in which Opt-E-Plus selects EDMs could be different if options were based on energy savings alone.

The methodology used to identify energy savings in the Guangzhou benchmark models involves four steps. First, an initial optimization is performed by selecting a variety of EDMs. Then, the results are analyzed to determine which EDMs have the greatest potential for energy savings. Next, a sensitivity test is performed with the most significant EDMs. For example, if alternative window types are shown to have significant impact on energy savings, a variety of window types tested on the benchmark building to identify the best alternative. A list of the most appropriate ECMs is generated after the sensitivity test. In addition, a second optimization is performed with these important ECMs to determine if there is a best package of efficiency measures. It is important to perform a second optimization because of the interactive effects of different building parameters. Each of the following sections will discuss important findings from each step in the analysis before making recommendations for improved building code standards.

3.3 Guangzhou Office Benchmark Optimization

As shown in the pie chart in Figure 40, electrical equipment, lighting, and cooling energy account for a significant percentage of the total building energy consumption (35.6, 28.4 and 21.5 percent, respectively). Obviously, selecting EDMs to reduce these components will have the most significant impact on energy savings.

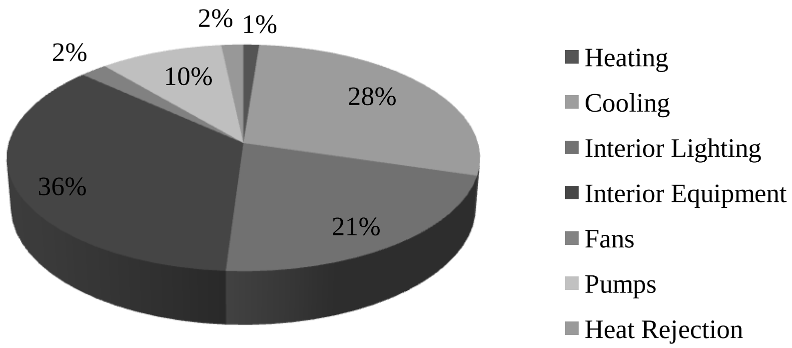

Figure 40: End Use Energy Breakdown - Guangzhou Office.

3.3.1 First Optimization

Thirty-four EDMs are selected across twelve categories for the initial optimization from the Opt-E-Plus database which are listed in Table 42. EPD reductions represent the use of using more efficient office equipments such as efficient computers, copy machines and other office equipments. Likewise, LPD reductions represent the use of higher efficient lighting systems and/or delamping. It should be noted that EnergyPlus does not calculate the lighting illuminance in the simulation so the user has no way of knowing if the required lighting levels are being met. Other simulation lighting simulation tools, such as AGI-32, Radiance, or DaySim could be used for a more in depth analysis. A 300 lux daylighting set point is selected based on the required illuminance range (300-500 lux) for office spaces as stated by Illuminating Engineering Society of North America (IES-NA, 2006). Note that this lux setting may be a bit too low for this space type since task lighting is not modeled; additional testing will address this issue later. Skylights are selected to identify if additional lighting energy can be saved when this EDM is used in combination with daylighting controls. Implementing skylights may also increase the cooling load due to additional solar heat gains on the top floor, so a range of skylight areas are selected. Window to wall ratio (WWR) reductions are selected with the intension of reducing solar heat gains in the space. Increased WWRs are also included to allow the option for more daylight into the space which could potentially help reduce lighting energy when used in combination with daylighting controls. Note that these WWR modifications are applied to each façade separately so, Opt-E-Plus has the option, for example, of reducing the WWR on the south façade and increase the WWR on the north façade. Window types were selected to identify if lower U-values and/or solar heat gain coefficients (SHGC) could decrease energy consumption. Low SHGC are important for reducing unwanted solar gains which are dominant in this climate region. Additional exterior wall and roof insulation levels are selected given that the existing levels are less than those of the US model. The option for increased chiller COP values of 10 and 20 percent are justified based on common centrifugal chiller COP values (Krarti, 2000). Increased outdoor air (OA) rates per person are selected given that the Chinese OA rates do not meet ASHRAE standards (ASHRAE, 2004). Finally, varying amounts of PV are selected to identify the amount of electricity offset potential.

Table 42: Initial Optimization EDMs - Guangzhou Office

EDM Category	EDM Selection
EPD Reduction	10% reduction
LPD Reduction	10%, 20% reduction
Daylighting Controls	400 lux set point in perimeter zones
Skylights	4%, 8%, 12% of roof area
Shading Devices	South façade shading overhangs: projection factor = 0.5
Window to Wall Ratios Reduction	50%, 80%, 120%, 150% of benchmark WWR
Window Types	U-value: 2.56, W/m^{2}K, SHGV:0.19, VT: 0.24 U-value: 3.86, W/m^{2}K, SHGV:0.36, VT: 0.46
Exterior Wall Insulation [m^{2}K/W]	R- 2.3, R-3.2
Roof Insulation [m^{2}K/W]	R-3.3, R-4.2,R-5.2, R-5.8, R-8.7
HVAC Efficiencies	10%, 20% chiller COP increase
Ventilation Rates	Double OA per person Increase OA per person by half
Photovoltaics (PV)	10%, 30%, and 50% of roof area

The results of the initial optimization are show in Figure 41. This screen shot of the Opt-E-Plus output includes all EnergyPlus simulations performed in the optimization. The EDMs selected in each model on the optimization curve (identified as the solid black line) are listed in Table 90 of Appendix A1. This table also shows the potential energy savings associated with each package of EDMs. The following results can be concluded from this analysis:

- Reducing WWRs by 50 percent on all facades is an EDM that is selected during most iteration of the optimization. About half way through the optimization the WWRs on the east and west facades are increase back to the level of the benchmark. Reducing the WWRs by 20 percent on the north and south facades may lead to less preferable working environments as this measure brings the total WWR to about 11 percent. Further discussion on this follows. Nevertheless, reducing the WWR is beneficial as this ultimately reduces solar heat gains and cooling energy.
- Skylights are shown to be beneficial when the associated area is no greater than four percent of the roof area therefore maximizes lighting energy savings and minimizes solar heat gains.

- Increasing ventilation is not shown to have energy saving potential; obviously, this measure creates a larger load on the cooling system. Therefore, if ventilation raters are increased to create a healthier building, a run-around heat exchanger or energy recovery ventilators should also be implemented to precondition the hot, humid outside air.
- Additional exterior wall insulation is snow to be an important energy efficiency measure as is additional roof insulation. However, high levels of insulation (R-values of 5.0 or higher) do not provide a significant amount of additional energy savings.
- The larges increments in energy savings occur when the following EDMs are applied: 20 percent LPD reduction, daylighting controls, 10 percent EPD reduction, and 20 percent increased chiller COP. Their applications are shown in Figure 41 between roughly 1.7 and 7.5 percent, 7.5 percent and 12.5 percent, 12.5 percent and 17 percent, and 25 and 30 percent, respectively.
- Clusters of design options are shown between six and eight and 12-14 percent and around 26 percent and 30 percent which suggests there are many design options that lead to nearly the same energy savings but have variable cost implications.

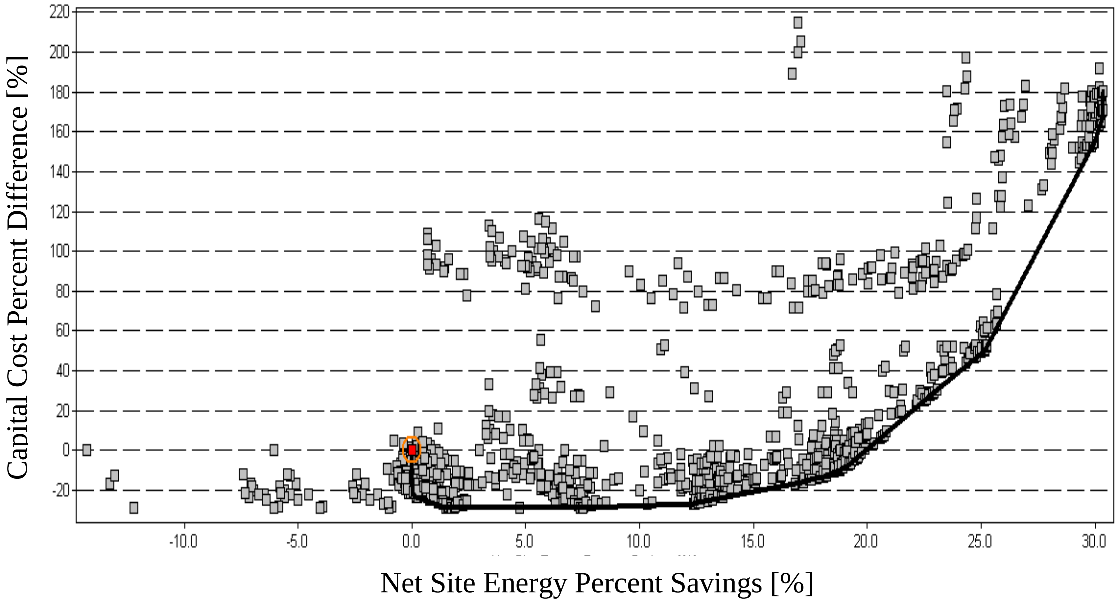

Figure 41: Initial optimization results - Guangzhou office.

3.3.2 Sensitivity Analysis – Guangzhou Office

The optimization results reveal six categories of energy design measures that have the most significant impact on energy savings. They are equipment and lighting power density (EPD and LPD) reductions, window to wall ratio reductions, increased wall and roof insulation, daylighting controls, skylights, and window shading overhangs. A sensitivity analysis is performed by applying these EDMs individuality to the benchmark model over a range of values. This process identifies which EDMs contribute the most to energy savings and shows the point of diminishing returns.

Four energy design measures are identified as having the greatest energy saving potentials. The first two are equipment and lighting power density reductions in that order. This is not surprising given that these categories make up the first and third highest percentage of end use energy as shown in Figure 40 above. The third highest energy saving measure is the use of daylighting controls, which minimize the need for electrical lighting. A regression line applied to the daylighting set point sensitivity results suggests that the energy savings associates are linearly related to the set points shown in Figure 44. Note that extreme set points have been applied to the model to identify the trends in energy savings; it is recommended that set points no less than 350 and no greater than 500 be implemented. Set points lower than 350 may lead to uniformity issues and under-lighting while set points higher than 500 may reduce the energy saving potential of these devices. Reducing the window to wall ratios has the fourth highest impact on energy savings. This helps reduce cooling energy associated with solar gains. All of these measures reduce internal heat gains and thus lower cooling energy, which makes up the second largest percentage of end use energy. Adding shading overhangs to south-facing windows has a much smaller impact on energy savings. Note that he projection factor indicates how far the overhang projects outward from the supporting wall as a fraction of the window height (DOE, EnergyPlus Building Data Input Forms). This value is clearly dependent on the shape and size of the window and thus the designer must re-evaluate this EDM if the shapes of the windows change for any reason. Increasing the wall and roof insulation levels shows insignificant energy savings, which is surprising given the low level of insulation in the benchmark. Skylights have a negative impact on energy savings when applied as a single EDM; adding skylights increase the cooling loads due to increased solar heat gains on the top level. However, skylights help reduce energy consumption as predicted when used in combination with daylighting controls and reduced lighting power densities as they allow for more natural light in the top-floor zones.

Table 43 summarizes the importance of each energy design measure based on the results of the sensitivity analysis. Note that the rankings are based on the energy saving potential of each independent EDM and do not take into account any optimal design packages. Based on these results, top priorities for improved building code standards for office buildings in the Hot Summer Warm Winter climate region are the implementation of daylighting controls, reduced lighting and equipment power densities. Other recommendations include window to wall ratio reductions and south façade shading devices. The use of skylights is shown to have no energy saving potential when used as an individual EDM; however the use of skylights could be beneficial if used in combination with daylighting controls. Although reducing equipment power density is shown to save a considerable amount of energy, this measure is currently not accounted for in the Standard.

Table 43: Important Energy Design Measure Ranking – Guangzhou Office

Energy Design Option	Energy Saving Potential	Ranking Definitions
Daylighting controls	High	7% < Energy Savings < 9%
Lighting power density reduction	Medium	1% < Energy Savings < 9%
Equipment power density reduction	Medium	
Window to wall ratio reduction	Low	0.2% < Energy Savings < 3%
South façade shading devices	Low	
Wall insulation	Very Low	Energy Savings < 1%
Roof insulation	Very Low	
Skylights	None	None

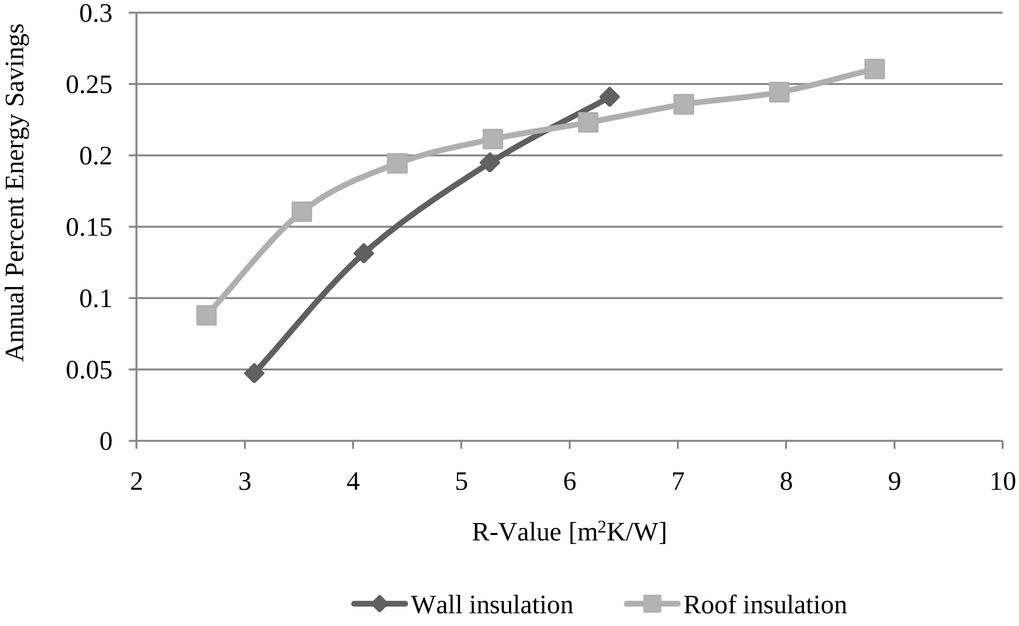

Figure 42: Insulation sensitivity analysis - Guangzhou office.

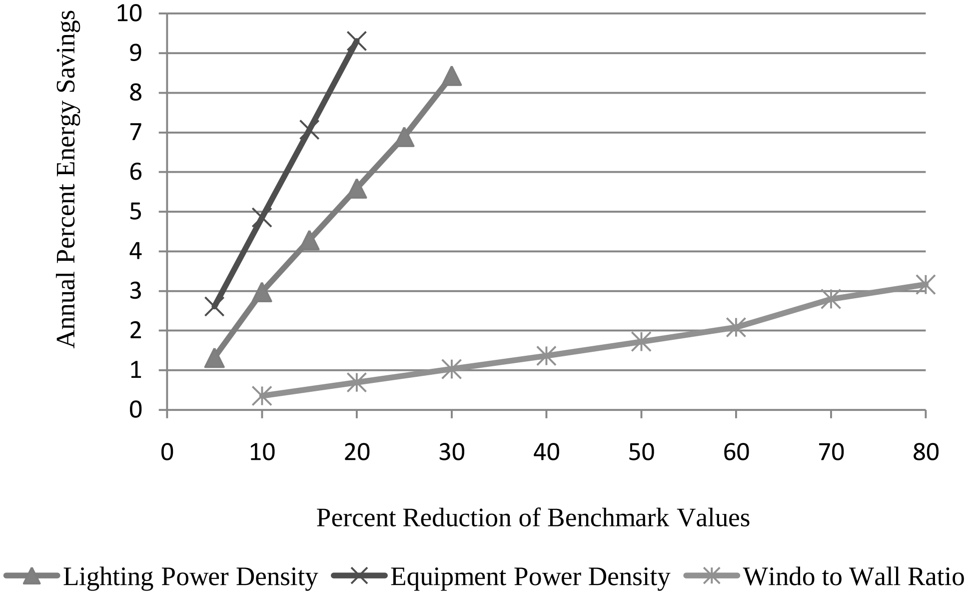

Figure 43: LPD, EDP, and WWR sensitivity analysis - Guangzhou office.

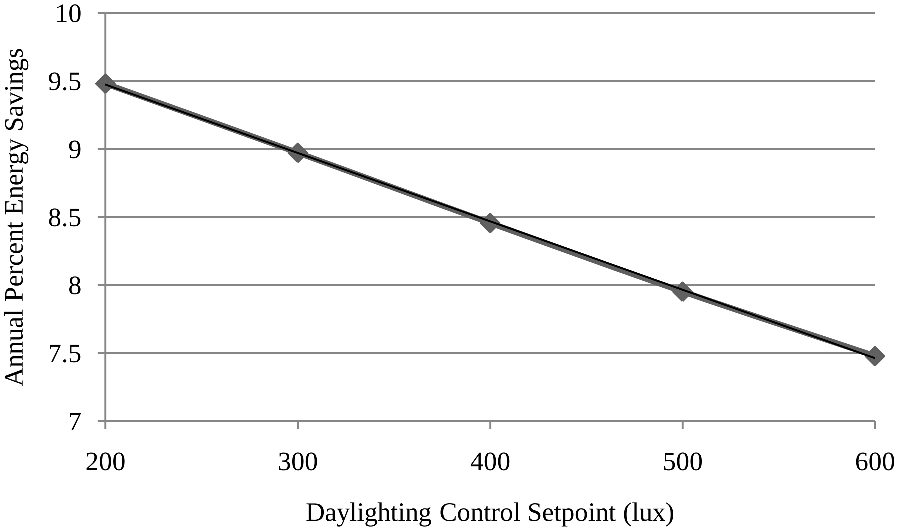

Figure 44: Daylighting control set point sensitivity analysis - Guangzhou office.

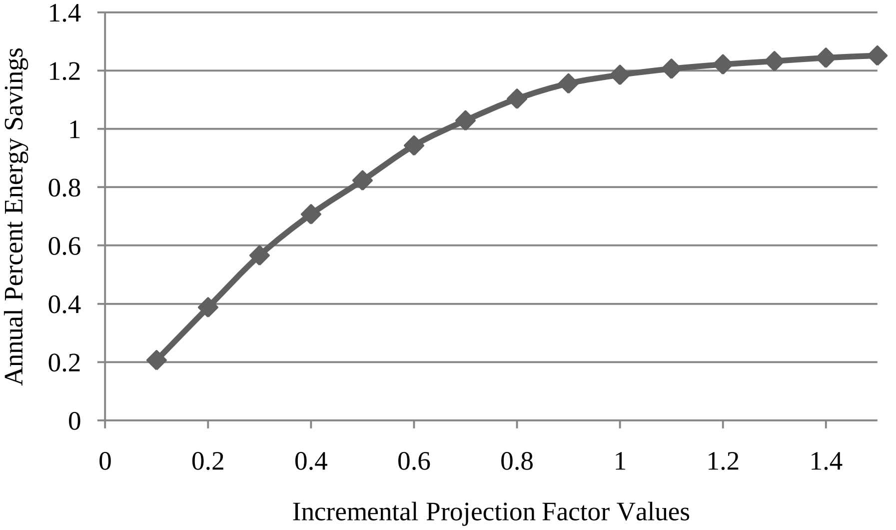

Figure 45: Shading projection factor sensitivity analysis - Guangzhou office.

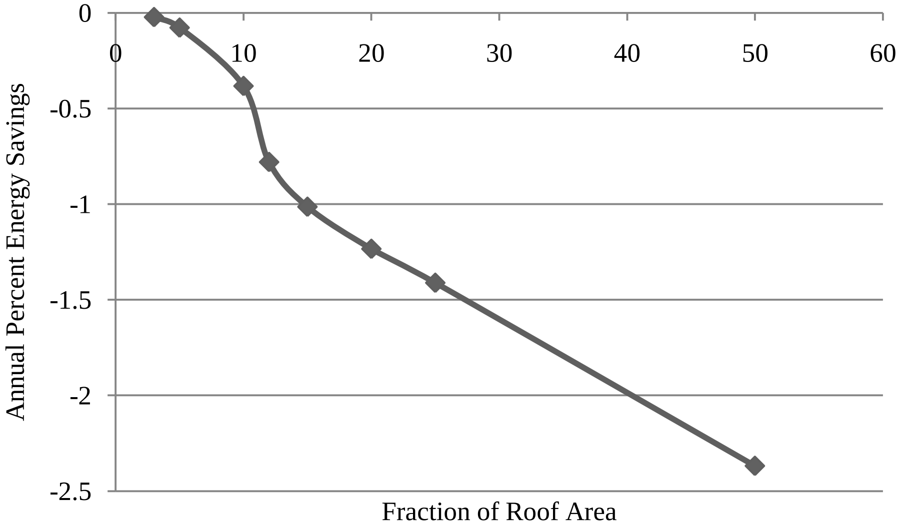

Figure 46: Skylight area sensitivity analysis - Guangzhou office.

3.3.3 Second Optimization

A second optimization is performed by selecting the most obvious EDMs as the starting point for design and varying other EDMs over a small range of values. The variable EDMs in this case are window to wall ratios and insulation levels. This is done to identify 1) if additional insulation levels lead to a significant amount of energy savings and to 2) identify the most appropriate WWR with the use of daylighting controls and overhangs. The second optimization is important because of the interplay between building components, as stated previously.

Table 44: Second Optimization EDMs - Guangzhou Office

	Starting point for second optimization	Variable EDMs
EDM	Value	Values
Exterior Wall Insulation	R-2.3	R-3.2,
Roof Insulation	R-3.2	R-4.2, R-5.2, R-5.8, R-6.7
EPD	16 (80% of benchmark)	-
LPD	7.7 (70% of benchmark)	-
WWR	50% of benchmark	80%, 75% of benchmark
Daylight controls	300 lux	-
Skylights	4% of roof area	-
Shading overhang projection factor	0.7	-
Window properties	U-value: 3.86 SHGC: 0.36 VT: 0.46	-

The results of the second optimization show that a potential energy savings of 26 percent can be achieved by applying the following EDMs:

- 20 percent EPD reduction
- 30 percent LPD reduction
- Daylighting controls (300 lux set point)
- Skylights (four percent of roof area)
- South façade shading overhang (0.7 projection factor)
- Efficient windows (U-3.86 W/m^{2}K, SHGC-0.36, VT-0.46)
- 80 percent WWR reduction (all facades)

- R-3.2 m^2K/W exterior wall insulation
- R-5.2 m^2K/W roof insulation

The Opt-E-Plus results of the second optimization are shown in Figure 47. Table 45 reports the potential energy savings in each end use category compared to the benchmark. The second optimization shows less than one half of one percent additional energy savings compared to the starting point. This shows that higher levels of insulation do not carry much impact. Note that the window-to-wall ratios have been significantly reduced and are now a very small percentage of the exterior wall area. The sensitivity analysis shows that the incremental energy savings associated with this EDM are small. Therefore, the window to wall ratios could be increased when applied with a package of EDMs without significant energy-saving penalties.

It is interesting to note that the maximum energy savings design in the initial optimization achieves a 30 percent energy savings compared to the benchmark while the maximum energy savings design in the second optimization achieves only a 26 percent energy savings. However, the second case does not include additional savings from photovoltaic application. PV will be applied to the final recommended package; results are provided in the following section.

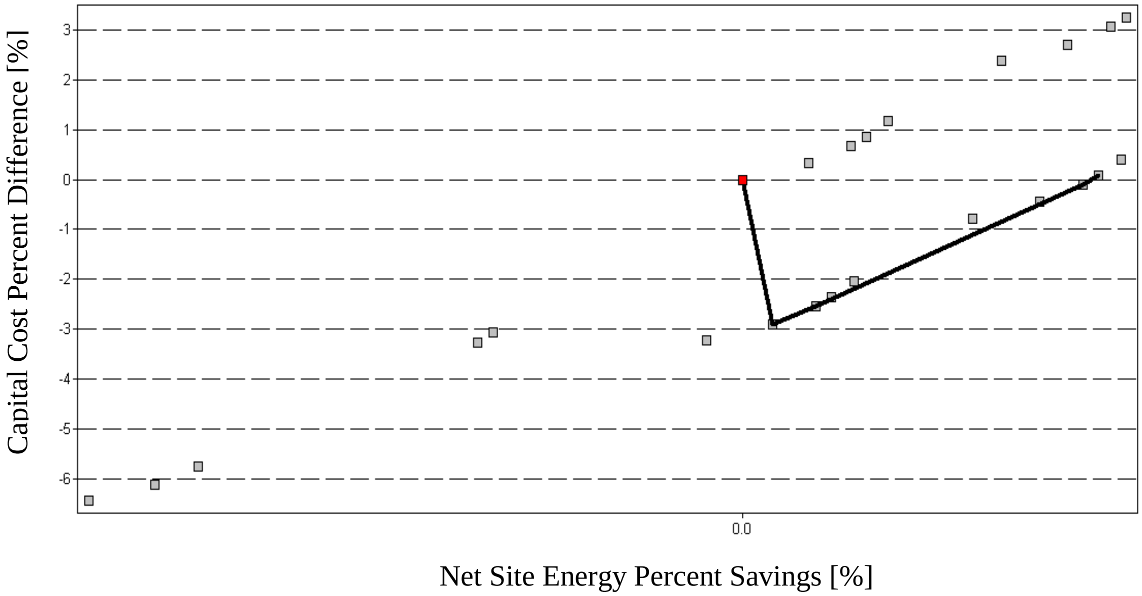

Figure 47: Second optimization results - Guangzhou office.

Table 45: End Use Energy Percent Savings from Second Optimization - Guangzhou Office

	Heating	Cooling	Interior Lighting	Interior Equipment	Fans	Pumps	Heat Rejection	Total
Percent Savings	-37.0%	20.1%	50.9%	20.05	24.3%	22.55	17.95	26.1%

3.3.4 Additional Testing and Final Recommendations

Additional testing is performed before recommending the final package of EDMs. Additional testing is performed to identify any potential energy savings associated with shading fins on the east and west facades and alternative HVAC systems; also, alternative WWRs are tested with a 400 lux daylighting set point. The resulting energy consumption differences are listed in Table 46.

Shading fins: The addition of shading fins to the east and west facades increased the lighting energy consumption and heating energy consumption but slightly decrease the cooling energy consumption. Overall, the annual energy consumption increased by about 2 percent compared to the minimum energy case and thus are not recommended. However, shading fin should be reconsidered if a more in depth daylighting analysis is performed in the future as shading fins have the potential to dramatically reduce the potential for glare issues.

Daylighting controls and window and window to wall ratios: Recall that the window-to-wall ratios are reduced to by 80 percent of the benchmark value in the minimum energy case. Although this leads to significant energy savings, the designer must take into account the aesthetics of the building and consider the indoor working environment; an office building with very small windows may be efficient, but worker productivity and may decrease dramatically without the availability of natural light and a connection to the outside environment as suggested by R.P. Leslie, 2002. Leslie also suggests that daylit work environments may be beneficial to productivity as well as health. To account for this, the window-to-wall ratios in the minimum energy case are reset to the benchmark values and the daylighting controls are increased to 400 lux. The results show additional energy savings are achieved through a reduction in electric lighting energy and cooling energy (see Table 46).

HVAC System Change: The sensitivity analysis suggested that energy savings could be achieved by reducing the outdoor air. However, ventilation levels in each zone are lower than ASHRAE standards based on a flow-rate per occupant basis; therefore, the existing four-pipe fan coil HVAC system is exchanged with a variable air volume (VAV) system equipped with an energy recovery ventilator (ERV) to precondition the outdoor air. An energy-recovery ventilator helps reduce energy consumption by pre-heating cold outdoor air and pre-cooling hot outdoor air with exhaust air from the zone. This process evolves the use of a heat exchanger. Energy-recovery ventilators also help precondition the outdoor air by adding moisture to dry outdoor air (typically associated with winter conditions) and dehumidifying wet outdoor air (as in the case of Guangzhou). Controlling indoor humidity levels also helps maintain conditions within the comfort zone. Unfortunately, the VAV-ERV system results in an increase in annual energy consumption; heating energy is reduced significantly, as is pump energy, but the increase in cooling energy outweighs the heating energy savings. The results of the VAV-ERV system are compared to the case above with the benchmark WWR, that is, the new best-case-scenario.

Table 46: End Use Energy Intensity [kWh/m^2] - Guangzhou office

	Best-case scenario from second optimization	Addition of E/W Fins	Increased WWR and 400 lux	VAV system with ERV
Heating	2.47	3.86	2.58	1.19
Cooling	28.64	28.63	26.23	57.25
Interior Lighting	13.50	13.59	12.38	12.78
Interior Equipment	36.41	36.41	36.41	36.41
Fans	2.08	2.07	2.15	3.96
Pumps	9.60	9.75	9.78	0.00
Heat Rejection	1.78	1.79	1.81	0.00
Total EUI	94.47	96.10	91.34	111.59

Finally, the recommended package of EDMs for the office benchmark in the Guangzhou climate region are listed in Table 47 below. End use energy consumption is reduced in every category except heating as shown in Table 48. This is explained from the reduced internal gains associated with efficient equipment and lighting. In addition to modifications to the building, it is recommended that PV be applied to as much of the roof area as possible. It is unknown exactly how much roof area is available, but the results list the energy offset associated with 85 percent roof area PV. Energy savings of 28.6 percent can be achieved before the application of PV; in addition, 85 percent roof area PV offsets energy consumption by 101.2 MWh/year, leading to a total energy savings of 38.0 percent compared to the benchmark.

Table 47: Recommendations for Guangzhou Office

Energy Design Measure	Benchmark	Recommendations
Wall insulation – m^2K/W	1.11	3.2
Roof insulation - m^2K/W	1.39	4.2
LPD - W/m^2	11	7.7
EPD - W/m^2	20	16
Daylighting Controls	None	400 lux
Window U-Value - W/m^2K	North: 5.06 South: 4.74 East/West: 5.77	3.86 (All facades)
Solar Heat Gain (SHGC)	North: 0.476 South: 0.425 East/West: 0.718	0.36 (All facades)
Visual Transmittance	North: 0.400 South: 0.400 East/West: 0.610	0.46 (All facades)
Window to wall ratios	North: 28% South: 33% East/West: 10%	No Change
Chiller Nominal Efficiency [COP]	4.7	5.6
Photovoltaics	None	85% Roof area
Percent Annual Energy Savings	0%	28% 38% W/PV

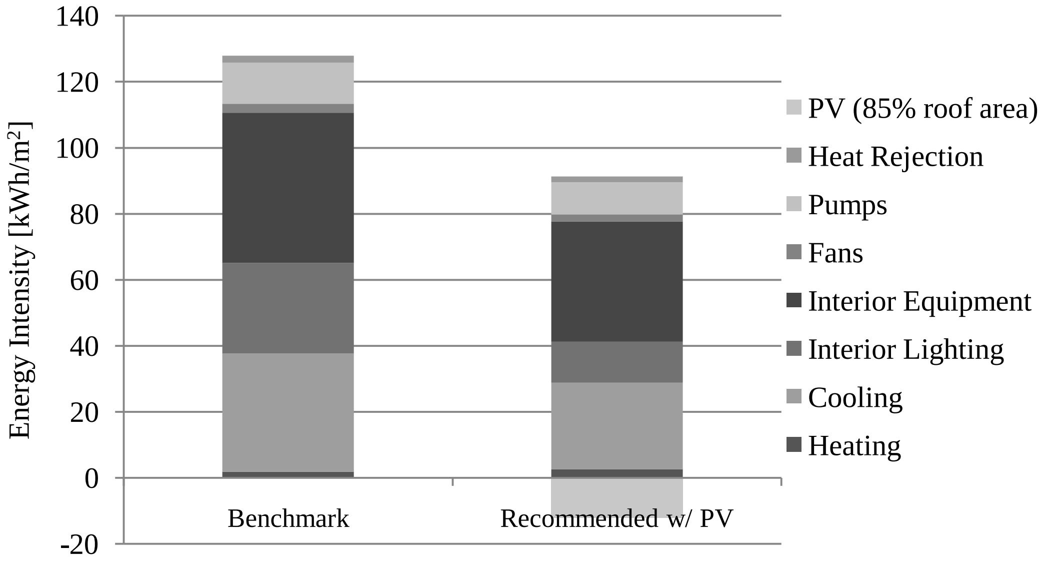

Figure 48: Potential end use energy savings - Guangzhou office.

Table 48: Percent Energy Savings - Guangzhou Office

	Heating	Cooling	Interior Lighting	Interior Equipment	Fans	Pumps	Heat Rejection	Total	Total W/PV
Percent Savings	-43.5%	26.8%	54.9%	20.0%	21.7%	21.1%	16.8%	28.6%	38.0%

3.4 Guangzhou Hotel Benchmark Optimization

As shown in the pie chart in Figure 49, lighting, cooling and electrical equipment energy account for most of the total building energy consumption (37.0 percent, 26.2 percent and 17.4 percent, respectively). As mentioned before, selecting EDMs to reduce these components will have the most significant impact on energy savings.

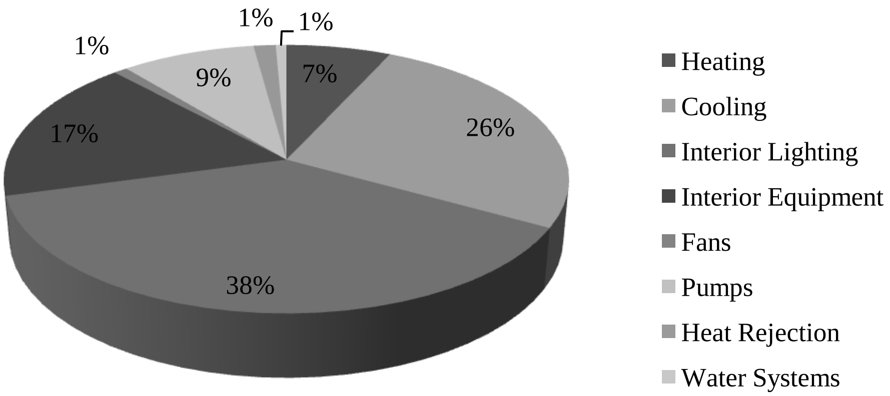

Figure 49: End use energy consumption - Guangzhou hotel.

3.4.1 First Optimization

Forty EDMs are selected across twelve categories for the initial optimization from the Opt-E-Plus database which are listed in Table 49. Many of the EDMs are the same as those selected in the office optimization. The same methodology applied to the Guangzhou office benchmark is also used here. The same justifications are also applied to most of the EDMs as well and will not be restated; instead the reader is referred to the statements made in section 3.2.1. It should be mentioned that daylighting controls in the hotel benchmark model are placed in the exterior zones including the stair cases, storage and mechanical rooms, as well as the canteen and the shop. The selected daylighting set point is constant across the zone types (400 lux) because of the limitations of Opt-E-Plus not allowing for different set points in different zones. A more detailed daylighting analysis is recommended for future research. Skylights have not been selected for the optimization because it is difficult to take advantage of the energy savings associated with natural light in guestrooms, which account for the majority of the top floor. Occupants should control over lighting levels in these spaces. This is also the same reason why daylighting controls have not been added to the guestrooms. It should also be mentioned that the original hotel building has fairly large window to wall ratios (65 percent on the north façade and 42 percent on the south façade) and thus fairly large reductions in WWRs are applicable. Recall that the US WWR ratio is 12.5 percent on all facades.

Table 49: Initial Optimization Energy Design Measures - Guangzhou Hotel

EDM Category	EDM Selection
EPD Reduction	10% reduction
LPD Reduction	10 and 20% of benchmark
South window shading overhangs	Projection factor: 0.5
Window to wall ratios	50%, 80%, 120%, and 150% of benchmark
Exterior wall insulation	R-2.3, R-5.1, R-6.2
Roof insulation	R- 3.2, R-6.5
Window Types	U-value: 3.87, SHGC: 0.36, VT: 0.46 U-value: 2.97, SHGC: 0.40, VT: 0.46
HVAC Efficiencies	10%, 20% chiller COP increase
Ventilation rates	Double the outdoor air per person Increase outdoor air per person by half
Photovoltaic application	10%, 30%, and 50% of roof area

The results of the initial optimization are show in Figure 50. This figure includes all EnergyPlus simulations performed in the optimization. The EDMs selected in each model on the optimization curve are listed in Table 91 of

Appendix B2: Selected EDMs from the Guangzhou **Hotel** Optimization also shows the potential energy savings associated with each package of EDMs. The following results can be concluded from this analysis:

- Measures applied early in the optimization include WWR reductions of 50 percent on all facades, additional wall insulation (R-2.3) and a 10 percent LPD reduction. Measures applied midway through the optimization include an EPD reduction of 10 percent, daylighting, south façade overhang projection factors of 0.5, additional roof insulation, and more efficient windows. Measures applied near the end of the optimization include higher wall insulation values (up to R-6.2) and efficiency improvements to the HVAC system (chiller and fans). Recall that the order in which Opt-E-Plus selects the EDMs is based on energy savings as well as cost savings; since cost is neglected in this analysis the order of implementation cannot be taken too seriously.
- Many alternative design options are shown with varying levels of wall and roof insulation levels and different window efficiencies but show little differences in energy savings. This shows that EDMs associated with insulation and window properties have little effect on energy savings compared to such items as LPD and EPD reductions and WWR modifications.
- Large increments in energy savings occur when the following EDMs are applied: eliminating the option for increased OA, reducing LPD by 20 percent, implementing daylighting controls, increasing chiller COP by 20 percent, and applying additional roof PV (from 30 to 50 percent). These EDM applications are shown in Figure 50 between roughly four and eight percent, eight and 16 percent, 16 and 25 percent, 30 and 33 percent, and 36 and 38 percent.

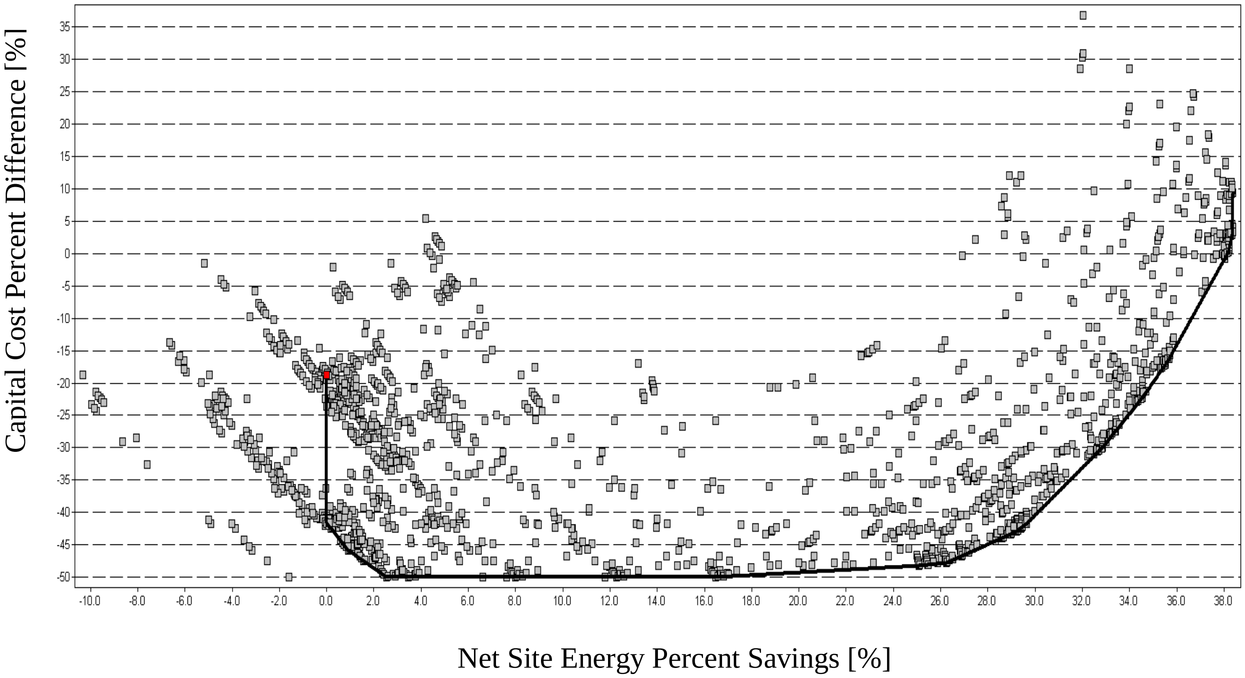

Figure 50: Initial optimization results - Guangzhou hotel.

3.4.2 Sensitivity Analysis

The optimization reveals 5 categories of energy design measures that have significant impacts on energy savings including lighting and equipment power density reductions, window to wall ratio reductions, increased wall and roof insulation, daylighting controls, and south façade overhangs. Results of the sensitivity analysis are shown in Figure 51 through Figure 55. The results are fairly self explanatory; however, there are a few particular points to be aware of. First, additional wall and roof insulation values do not contribute significantly to energy savings; additional roof insulation for example reduces energy consumption by less than one half of a percent. Reducing LPD has the greatest potential for saving energy compared to any of the other EDMs as shown in Figure 51. This can be achieved through delamping and/or using more efficient bulbs and fixtures. However, using more efficient fixtures can often come at a higher cost. South façade projection factors above 0.9 decrease the energy saving potential (see Figure 52). Energy savings reach a maximum of about 1.7 percent with projection factors of 0.9. Shading devices are therefore not that beneficial when implemented as a single design measure.

This is surprising given that overhangs can significantly reduce unwanted solar heat gains. Reducing WWRs has significant potential for reducing cooling energy as shown in Figure 53. WWRs could be reduced by 80 percent on the north façade and 70 percent on the south façade and still be comparable to the US hotel model. Doing so could save at least 10 percent of total site energy. Using smaller windows may also save in capital costs as windows tend to have a high cost per square foot compared to wall construction. Finally, the window type sensitivity analysis shows that a low SHGC is just as important if not more important than a low U-value. Total building site energy could be reduced by close to five percent by simply using more efficient windows as shown in Figure 55. Using more efficient windows could potentially save four and a half percent of total site energy.

Table 50 summarizes the importance of each energy design measure based on the results of the sensitivity analysis. Note that the rankings are based on the energy saving potential of each independent EDM and do not take into account any optimal design packages. Based on these results, the top priorities for improved building code standards for hotels buildings in the Severe Cold climate region are reduced lighting power density, window to wall ratio reductions, higher efficiency windows, and reduced equipment power density. Shading devices and increases insulation in the roof and walls are less important for incorporation into the Standard.

Table 50: Important Energy Design Measure Ranking – Guangzhou Hotel

Energy Design Option	Energy Saving Potential	Ranking Definitions
Lighting power density reduction	High	1% < Energy Savings < 13%
Window to wall ratio reduction	High	
Alternative window types	Medium	0.5% < Energy Savings < 5%
Equipment power density reduction	Medium	
South façade projection factor	Low	0.2% < Energy Savings < 1.2%
Roof insulation	Low	
Wall insulation	Very Low	Energy Savings < 1%

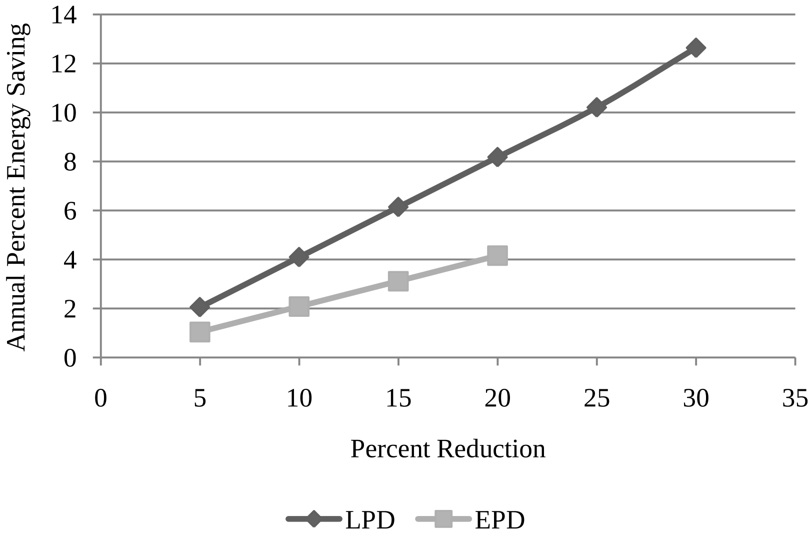

Figure 51: LPD and EPD sensitivity analysis - Guangzhou hotel.

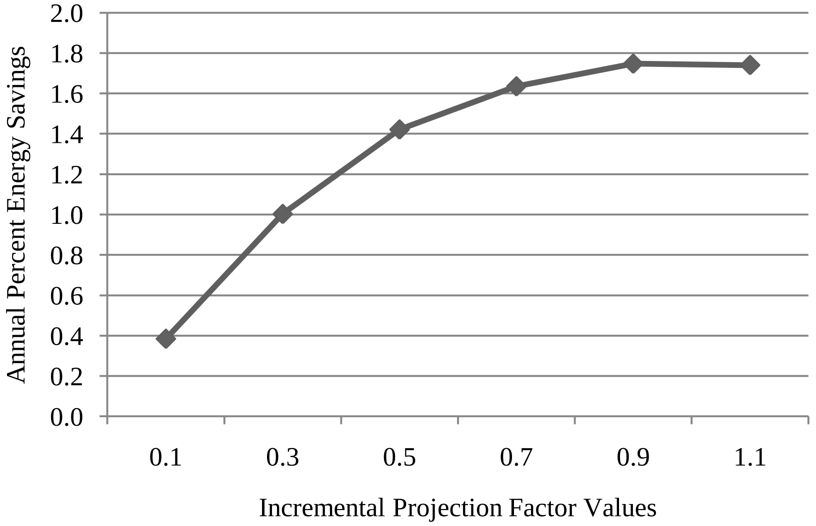

Figure 52: South shading overhang projection factor sensitivity analysis - Guangzhou hotel.

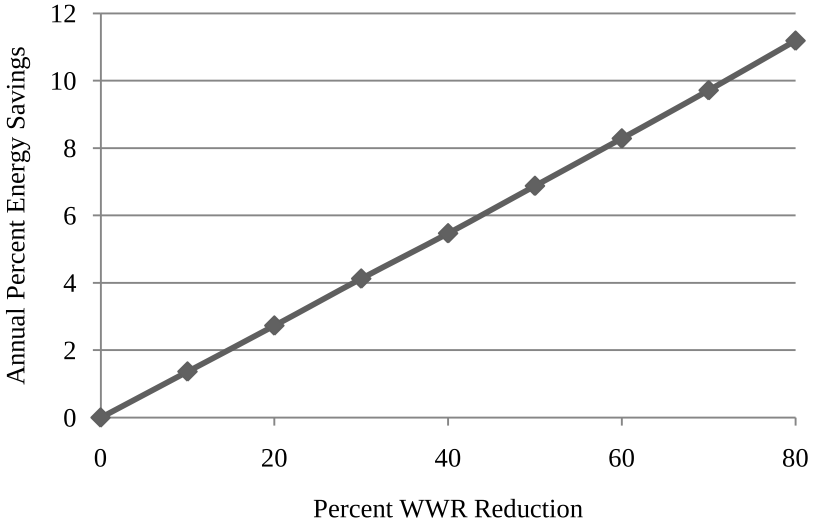

Figure 53: WWR sensitivity analysis - Guangzhou hotel.

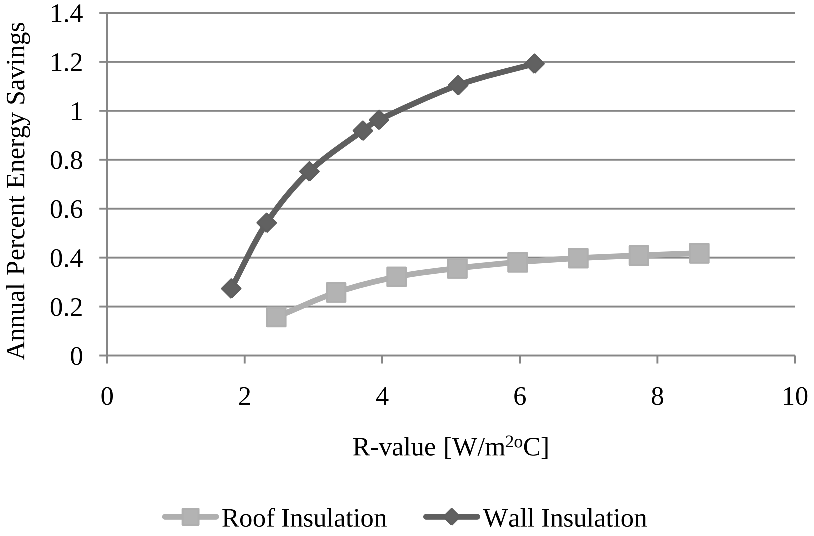

Figure 54: Insulation sensitivity analysis - Guangzhou hotel.

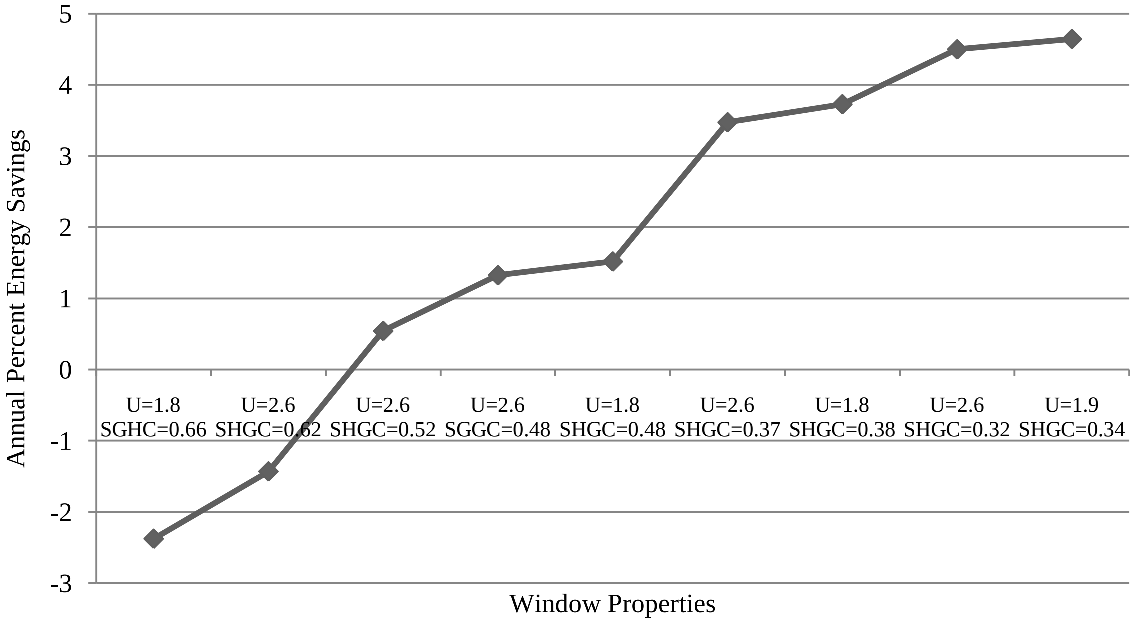

Figure 55: Window property sensitivity analysis - Guangzhou hotel.

3.4.3 Second Optimization

A second optimization is completed as before in the case of the Guangzhou office after analyzing the effects of each EDM to find the recommended optimal building configuration. As mentioned before, it is important to perform the second optimization because the overall building performance depends on the interaction between all building components. Certain energy design measures obviously have a greater impact on energy savings than others when applied individually, but the optimal design depends on how all components perform together.

The energy design measures selected for the second optimization are listed in the table below as “Variable EDMs.” The EDMs used as the starting point are also listed. The same misunderstanding occurred with the WWR reductions as before in the case of the office only this time, the mistake has not yet been corrected. Justifications for selecting the variable EDMs are the same as for the office; please refer to Section 3.4.1.

Table 51: EDMs for Second Optimization - Guangzhou Hotel

	Starting point for second optimization	Variable EDMs
EDM	Value	Values
EPD [W/m^2]	80% of benchmark	-
LPD [W/m^2]	70% of benchmark	-
WWR	9% of benchmark	6%, 12% of benchmark
Exterior wall insulation [m^{2}K/W]	R-3.9	R-5.1, R-6.2
Roof insulation [m^{2}K/W]	R-3.2	R-4.2, R-5.2, R-5.7 R-6.5
Shading overhang projection factor	0.6 (south façade)	0.7, 0.8, 0.9
Window properties	U-value: 2.67 SHGC: 0.31 VT: 0.39	U-value: 1.87 SHGC: 0.32 VT: 0.33

The results of the second optimization show that a potential energy savings of 33.5 percent can be achieved compared to the benchmark by applying the following EDMs:

- 20% EPD reduction
- 30% LPD reduction
- South façade shading overhang (0.9 projection factor)
- Efficient windows (U-1.87 W/m^{2}K, SHGC-0.32, VT-0.33)
- 90% WWR reduction (all facades)
- R-6.2 m^{2}K/W exterior wall insulation
- R-8.6 m^{2}K/W roof insulation

Opt-E-Plus results from the second optimization are shown in Figure 56. Table 54 reports the potential energy savings in each end use category compared to the benchmark. The second optimization shows an additional two and a half percent increase in energy savings compared to the starting point which indicates that high levels of roof and wall insulation are not critical EDMs. However, it is hard not to recommend the package of design measures leading to maximum energy savings when cost savings are neglected since the goal is to identify maximum energy savings potential. EDMs associated with window types, size, and shading overhangs may have only contributed very small amounts to additional energy savings given that the window areas are very small in this model. Also note that this package of EDMs does not include the application of PV. Additional testing is performed before recommending the final package of EDMs.

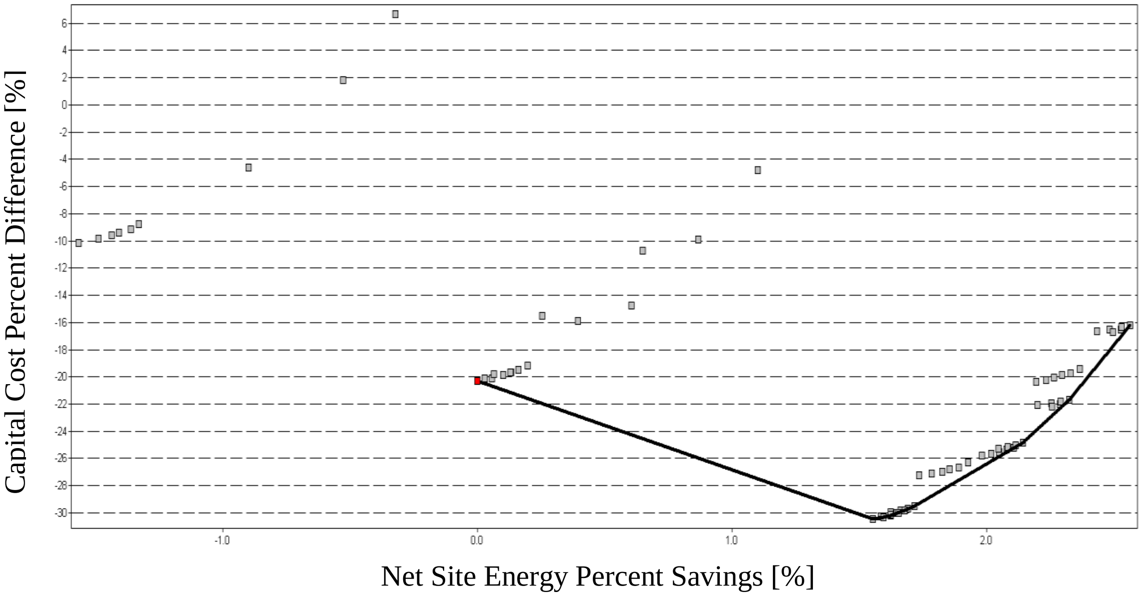

Figure 56: Second optimization results - Guangzhou hotel.

3.4.4 Additional Testing and Final Recommendations

Window shading fins on the east and west facades are added to the building design showing the greatest energy-saving potential. The results show an increase in total building energy consumption; reasons for this are twofold. First, adding fins increases the annual heating use as they reduce the amount of available heat gains during cooler months. Second, fins reduce the amount of light entering the stairwell windows and thus more lighting electrical energy is required to meet the set points of the daylighting controls. Thus, adding fins in combination with daylighting controls is not recommended with amount of window area. Increasing the window areas could significantly change the results. Proposed corrections will address this issue by rerunning the second optimization with appropriate window areas, fins and daylighting controls.

The second optimization failed to include the more efficient chiller so this design measure was added as an additional test. As shown in Table 52, the efficient chiller saves 25 percent of the cooling energy but leads to an increase in pump and heat rejection energy. The overall site energy savings total less than one half of one percent. More efficient chillers could induce higher capital and lifecycle costs so the recommendation for a higher efficiency chiller is debatable.

Table 52: Additional Testing Results - Guangzhou Hotel

	Max savings from Second Optimization [kWh/m^2]	East/West Shading Fins [kWh/m^2]	20% Chiller COP [kWh/m^2]
Heating	1.70	2.70	1.40
Cooling	20.4	20.3	15.0
Interior Lighting	31.7	31.7	31.7
Interior Equipment	16.7	16.7	16.7
Fans	0.52	0.52	0.52
Pumps	6.50	6.40	9.00
Heat Rejection	1.10	1.20	3.90
Water Systems	0.84	0.84	0.84
Total End Use Intensity	79.5	80.4	79.1

Total site and source energy can be reduced by 33.9 percent compared to the benchmark building by implementing the recommended EDMs listed in Table 53. Figure 57 shows the resulting energy savings graphically. Applying PV to 85 percent of the roof area produces 387 GJ of energy annually, offsetting site energy by an additional 12 percent. In addition, the existing solar hot water system provides 58.59 GJ of energy annually which equates to about one half of the total energy demand for domestic hot water.

Table 53: Recommendations for Guangzhou Hotel

Energy Design Measure	Benchmark	Recommendations
Wall insulation – m^2K/W	1.17	R-6.2
Roof insulation - m^2K/W	1.23	R-6.6
LPD - W/m^2 Weighted average	12.3	8.6
EPD - W/m^2 Weighted average	4.9	3.5
Window U-Value - W/m^2K	N/S/W: 5.36 East: 5.89	1.86 (All facades)
Solar Heat Gain (SHGC)	North: 0.448 South: 0.417 East: 0.610 West: 0.43	0.337 (All facades)
Visual Transmittance	North: 0.680 South: 0.410 East: 0.610 West: 0.230	0.328 (All facades)
Window to wall ratios	North: 65% South: 42% East: 10% West: 51%	North: 6.5% South: 4.0% East: 1.0% West: 5.1%
Photovoltaics	None	85% Roof area
Percent Annual Energy Savings	0%	33.8% 38.6% W/PV

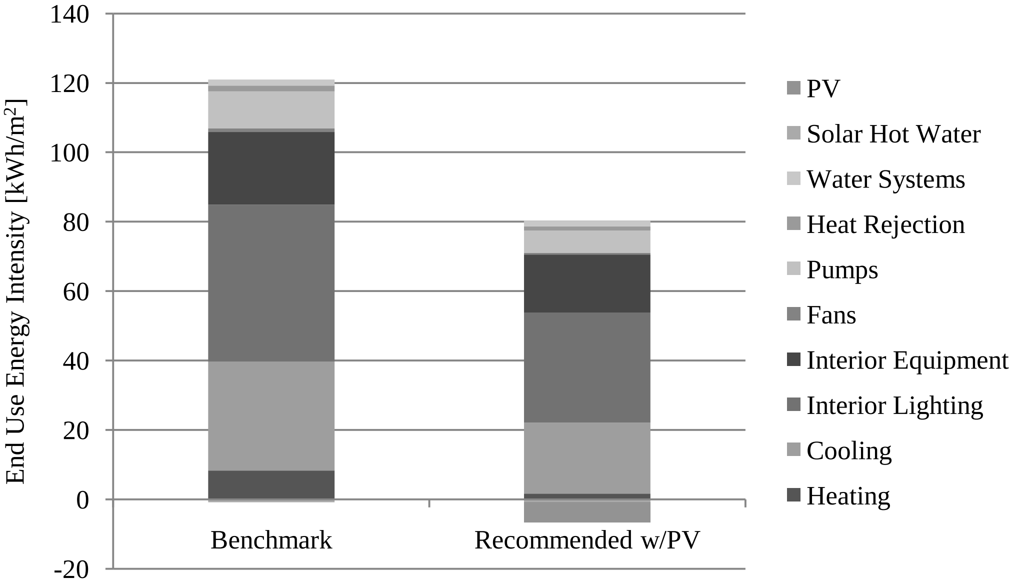

Figure 57: Potential site energy savings - Guangzhou hotel.

Table 54: End Use Energy Percent Savings [%]

Heating	Cooling	Interior Lighting	Interior Equipment	Fans	Pumps	Heat Rejection	Total	Total w/ PV
79.5	35.0	30.0	20.0	52.0	39.0	34.7	33.9	38.6

Chapter 4: Identifying Potential Energy Savings for the Harbin Benchmark Models

Opt-E-Plus is used to the identify potential energy savings of various energy design measures for the office and hotel benchmark buildings of the Severe Cold climate region. This climate region is represented by the city of Harbin, China. The methodology involves three steps. First, a parametric analysis is performed to determine the interactive effects of the existing building components. A parametric study is performed by removing each source of heat gain and each thermal component from the baseline model separately and comparing the consumption differences to the baseline. The results are used to select a range of EDMs to use in Opt-E-Plus, which applies the selected EDMs to the particular building model to determine the potential energy savings. These results also provided information on what packages of EDMs are most effective. Next, a sensitivity analysis is performed on each of the EDMs selected by Opt-E-Plus. This test is done by varying each key EDMs identified by Opt-E-Plus over a range of values at relatively small increments. For example, the roof insulation is varied from R-2 to R-8 at R-1 (SI) increments. The variation in the energy design measure is plotted as a function of energy savings to show the relationship between the two and to identify the point of diminishing returns, if one should exist. Finally, recommendations for building code standard improvement are made by ranking the individual EDMs according to their energy saving potential.

The following sections will present the results of each step in this methodology.

4.1 Identifying Potential Energy Savings for the Harbin Office

Recall that the Harbin office is a 5,979 m^2, three story building. Heating is provided by radiant baseboard heaters with hot water supplied by a district heating system. The end use site energy consumption breakdown is shown in the pie chart of Figure 58. As is shown, electrical equipment, heating, and lighting are the primary end use categories, respectively; pump energy accounts for a very small percentage of the total. This section applies the optimization process outlined above and presents the recommendations for energy efficiency improvements.

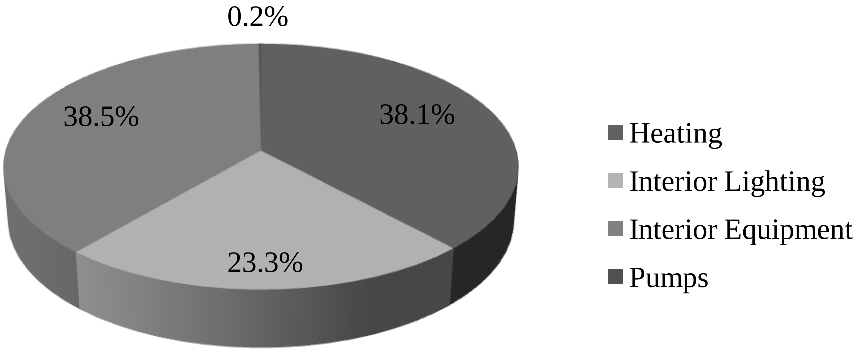

Figure 58: Harbin office benchmark end use energy breakdown.

4.1.1 Harbin Office Parametric Analysis

Figure 59 illustrates what happens when different heat transfer paths or building load components are removed from the building including exterior walls, roof, slab, outdoor air flow rates, ventilation rates, windows, and internal gains. These results also provide insight into which EDMs are most important for the Opt-E-Plus analysis. The parametric analysis leads to the following results:

- *R-35 Exterior Walls, Roof, and Slab:* Eliminating heat-transfer through the exterior walls results in a significant reducing in heating energy, about 60 percent savings. This suggests that there is significant room for improvement to the insulation level of the exterior walls. Eliminating heat transfer through the roof results less energy savings, 14 percent heating energy savings and only five percent annual site energy savings. This is due to the fact that the existing insulation level in the roof is much higher than the walls and the roof accounts for a smaller percentage of the exposed envelope. The results show the slab does not contribute significantly to heating energy consumption. This may be in part due to the ground heat transfer calculations used by EnergyPlus. Eliminating the heat transfer through the entire envelope, minus the windows, results in an 87 percent annual site energy savings. This is slightly greater than the additive energy savings of 75 percent from each separate envelope component. This suggests that EnergyPlus takes into account integrated building dependencies when calculating energy consumption.

- *Outdoor Air Flow/Infiltration:* Eliminating infiltration and natural ventilation saves nearly 55 percent of heating energy and 17 percent total site energy. Infiltration is the dominant component contributing to 53 percent of the required heating load (see the results for *No infiltration* and *No ventilation air* in Figure 59 below). Outdoor air brought in by natural ventilation contributes little to the heating load. This is primarily due to the restrictions put on this component of the model. Recall, natural ventilation is allowed when indoor temperatures are about 18 degrees Celsius and when outdoor temperatures are above about five degrees Celsius.
- *No Windows:* Removing the windows increases the heating and cooling energy by five percent and two percent, respectively. Heating energy increases due to the fact that beneficial solar heat gains are no longer available.
- *Internal Gains:* Removing the occupants, electric lighting and electric plug loads shows the affects of \ internal gains on heating energy as well as total site energy. The results suggest that the occupants generate a large amount of heat. This is not surprising given the extremely high occupant density in all of the zones (25 people per 100 square meters). The electric lighting also helps meet the heating requirement; removing this internal gain results in a 25 percent increase in heating energy although the total annual site energy is reduced by about 18 percent. The electric plug loads have the greatest affect on heating energy as well as total annual energy consumption; heating energy increases by 44 percent while the total site energy decreases by about 29 percent. This shows that the reducing in electric plug load energy is enough to outweigh the relatively large increase in heating energy.

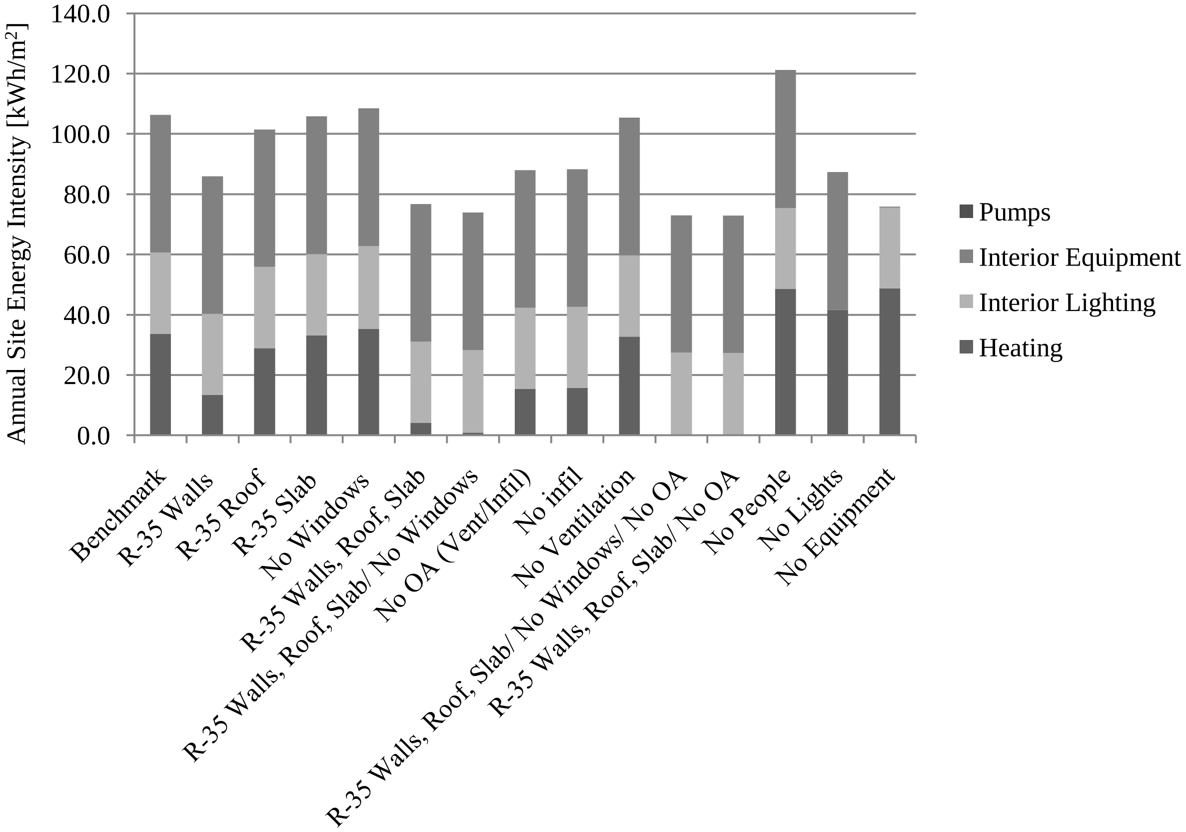

Figure 59: Parametric analysis - Harbin office.

4.1.2 Harbin Office Opt-E-Plus Analysis

The results of the parametric analysis are used to guide the selection of EDM to use in the Opt-E-Plus analysis. Table 55 lists the EDMs selected in Opt-E-Plus.

Table 55: Selected Energy Design Measures for the Harbin Office

Energy Design Measure	Value	Benchmark value
Reduced ventilation rate	0.0025 m^3/person	0.00833 m^3/person
South façade shading	0.5 projection factor	None
Photovoltaics	50% Roof area	None
Skylights	4% Roof area	None
North façade window properties	U-Value: 2.10, SHGC: 0.19, VT: 0.30; U-Value:1.14 , SHGC: 0.40, VT: 0.65; U-Value: 1.42, SHGC: 0.32, VT: 0.33	U-Value: 3.06, SHGC: 0.70, VT: 0.78
South façade window properties	U-Value: 2.10, SHGC: 0.19, VT: 0.30; U-Value:1.14 , SHGC: 0.40, VT: 0.65; U-Value: 1.42, SHGC: 0.32, VT: 0.33; U-Value: 1.70, SHGC: 0.45, VT: 0.45	U-Value: 3.06, SHGC: 0.70, VT: 0.78
East façade window properties	U-Value: 2.10, SHGC: 0.36, VT: 0.53; U-Value:1.14 , SHGC: 0.40, VT: 0.65;	U-Value: 3.06, SHGC: 0.70, VT: 0.78
West façade window properties	U-Value: 2.10, SHGC: 0.36, VT: 0.53; U-Value:1.14 , SHGC: 0.40, VT: 0.65;	U-Value: 3.06, SHGC: 0.70, VT: 0.78
WWR - Percent of benchmark value	150% to 40%	North/South: 25%, East: 10%, West: 21%
Exterior wall insulation	R- 2.74, R-4.41, R-7.70	R-0.747
Roof insulation	R-3.47, R- 7.67, R-11	R-2.76
EPD reduction	30%	20 W/m2
LPD reduction	30%	11 W/m2
Daylighting controls	Set point: 500 lux	None
Infiltration reduction	50%, 25%	0.3 ACH

The resulting Opt-E-Plus output is show in Figure 60. As in the case of the Guangzhou models, the cost values show on the plot are not applicable to the results due to the fact that Chinese economic data has not been applied. Table 92 in Appendix B3: Selected EDMs for Harbin Office Optimization lists all of the EDMs applied in each building models along the optimization curve (the solid black line) in Figure 60. These results are used to identify which measures are most important in achieving energy savings and are used to carry out the sensitivity analysis. An EDM is show to be important if 1) it is indeed selected for the optimization and 2) it is applied multiple times during the Opt-E-Plus analysis.

In the plot of Figure 60, the first large increase in energy savings occurs when the lighting and equipment power densities are reduced to 30% below the benchmark values. This occurs between about two percent and 15 percent energy savings. The next jump occurs between 15 percent energy savings and 20 percent energy savings with the implementation of a 500 lux daylighting set point. Next, the window efficiencies increase from a U-value of 2.1 to U-1.14 on the north façade which brings the energy savings to about 25 percent. Reducing infiltration from the benchmark value of 0.3 ACH to 0.05 ACH pushes the energy savings from about 32 percent to 46 percent. Between 46 percent and roughly 57 percent, R-16.4 wall insulation is applied. The last significant boost in energy savings between roughly 60 percent and 74 percent is the application of PV on 50% of the roof area. Other EDMs applied the application of PV include R-4.4 wall insulation, R-11 roof insulation, R-7.7 wall insulation, and reduced window to wall ratios on the west façade (50 percent of the benchmark value). These EDMs do not result in significant energy savings. For a detailed list of EDMs applied to each model on the optimization curve, please refer to Table 92 in Appendix B3: Selected EDMs for Harbin Office Optimization.

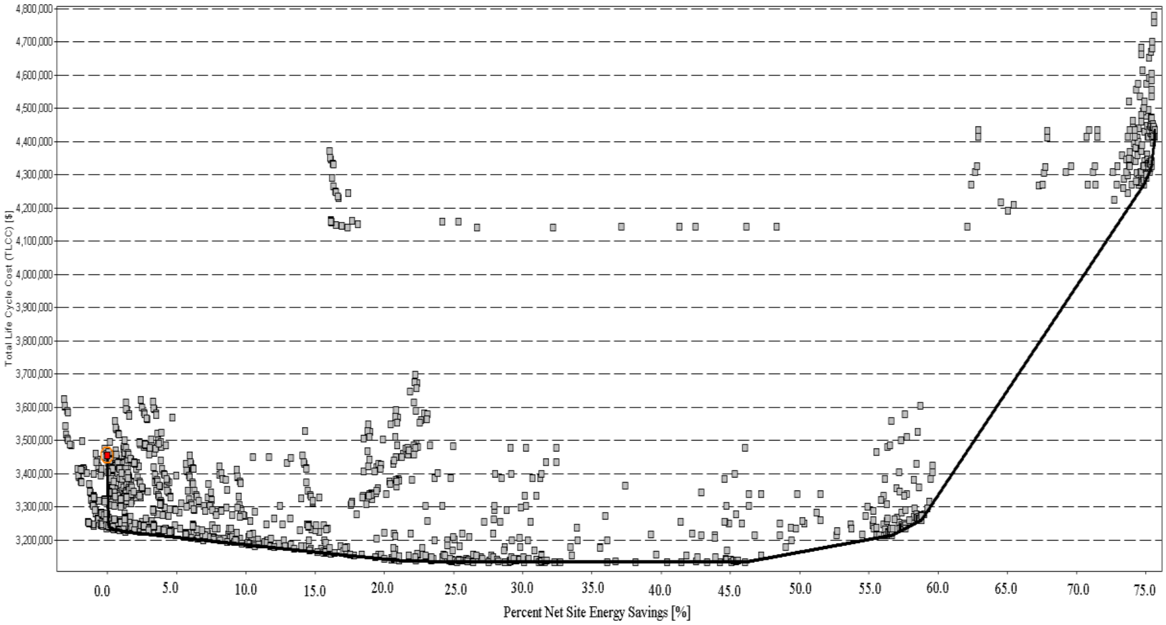

Figure 60: Harbin office Opt-E-Plus analysis results.

4.1.3 Harbin Office Sensitivity Analysis

The sensitivity analysis focuses on each of the important EDMs from the Opt-E-Plus analysis. To do this, recall that each EDM is applied to the benchmark building individually and varied over a range of values. This shows the potential energy savings of each EDM as well as the relationship the varying values and energy savings. The results of each sensitivity analysis are illustrated in Figure 61 through Figure 72.

- *Daylighting Set Point*: Appropriate lighting level for office work spaces are taken from IES-NA 2006 which states a lux range of 300-500 lux for this space type. The results show that daylighting controls have a significant potential for energy savings and should be considered for code implementation. As the lighting set point decreases, energy savings associated with electric lighting decreases. This analysis reduces the lighting levels below the appropriate amount so to identify the trends in energy savings. It is recommended that daylighting control set points stay within the range of 300 to 500 lux.
- *Lighting Power Density Reduction*: Reducing the lighting power density is linearly related to energy savings and has a relatively high potential for energy savings. The annual energy is reduced by approximately 1.8 percent for every ten percent reduction in lighting power density. A 30 percent LPD reduction equates to 7.7 W/m^2 which is realistically achievable based on the required lux for the space and current lighting technologies (NREL, 2010). These savings can be achieved by delamping (i.e. reducing the number of fixtures per unit area of floor space), implementing more efficient ballasts and lamps, or using a combination of techniques.
- *Insulation*: The exterior wall and roof insulation levels have a parabolic correspondence with energy savings; both EDMs approach a point of diminishing returns as can be seen in Figure 63 and Figure 64. Increasing the wall insulation is the single most effective design measure for saving energy. As shown in Figure 63, 22 percent of the annual energy consumption is saved by

increasing exterior wall insulation to R-8 m^2K/W. Figure 64 shows that increasing the roof insulation has less potential for energy savings. The reason for this is twofold. First, the existing insulation level is substantially higher in the roof than the walls (R-2.76 m^2K/W compared to 0.747 m^2K/W, respectively) and second, the roof area is a smaller percentage of the envelope. Increasing the roof insulation to R-8.8 m^2K/W leads to about a 3.3% energy savings.

- *Window Types:* The sensitivity analysis for window types tests a range of U-values (2.1 to 1.47 W/m^2K) with varying solar heat gain coefficients (SHGC 0.19 t0 0.55) and visual transmittances (VT 0.17 to 0.65). The results identify which window property, U-value or SHGC, is more important for energy savings. The results for the south façade show that heating energy consumption is more sensitive to SHGC than to U-values. Figure 65 shows that windows with high SHGCs and low U-values are the best option for the south facade. This allows the perimeter spaces to maximize solar heat gains during the day while minimizing heat loss through the glass. Energy consumption is more sensitive to U-values on the north façade. This is due to the fact that north facing windows do not provide any beneficial solar heat gains. Windows with low U-values are recommended for the north façade; note, however, that energy savings may approach a point of diminishing returns around U-values of 1 W/m^2K. East and west window type options are determined from an optimization so to determine which façade has a larger impact on energy consumption. Given that the existing window to wall ratios on the east façade are much smaller than then west façade it is no surprise that energy consumption is more sensitive to window types of the west façade (see Figure 67). The results also show that higher SHGC are beneficial on east and west facades while lower U-values are more critical for west facing windows.
- *Window to Wall Ratios:* As shown in Figure 68 energy savings is achieved when window to wall ratios (WWRs) are increase on the south façade which allows more solar heat gains into the space thus reducing the heating load. Reducing the WWRs reduces the amount of available solar gains and thus increases heating energy. The opposite is true for the north façade; reducing the WWR reduces the heat loss through the window glass. The window sizes of the east and west façades

are optimized to identify which façade has more of an impact on energy consumption. The results in Figure 70 show varying the east/west window areas have a very small impact on energy use although small energy savings can be achieved by increasing the WWR on both facades. Increasing the west facing window areas is more critical than increasing the window areas of east facing windows. Although these window modifications can lead to energy savings, other factors associated with daylighting should be considered when seeking optimal window areas. For example, high VT and large south window areas could potentially lead to glare issues while very small windows on the north façade could lead to dark dismal working environments. Combining these window configurations could also lead to poor lighting uniformity.

- *Infiltration and Ventilation:* Reducing infiltration is the second most effective strategy for reducing energy consumption as can be seen in Figure 71. Heating energy consumption is reduced by approximately 3% for every air change per hour reduction of 0.05 ACH. Increasing the ventilation rate is shown to increase the energy consumption (see Figure 72). This is to be expected since allowing more frigid outdoor air to enter the building creates a greater heating load. This suggests that a mechanical ventilation system with heat recovery should be considered for use during the heating season.

Table 56 summarizes the importance of each energy design measure based on the results of the sensitivity analysis. Note that the rankings are based on the energy saving potential of each independent EDM and do not take into account any optimal design packages. Based on these results, the top priorities for improved building code standards for office buildings in the Severe Cold climate region are increase wall insulation, reduced infiltration, reduced lighting power density, the implementation of daylighting controls, increased roof insulation, and higher efficiency windows on the north façade. Other, slightly less important improvements include window to wall ration reductions and higher efficiency windows on the south, east, and west facades.

Table 56: Important Energy Design Measure Ranking

Energy Design Option	Energy Saving Potential	Raking Definitions
Exterior wall insulation	High	3% < Energy Savings < 22%
Reduced infiltration rate	High	
Lighting power density reduction	Medium	2% < Energy Savings < 7.5%
Daylighting Controls	Medium	
Roof insulation	Medium	
North façade window type	Medium	
South façade WWR	Low	0.1 < Energy Savings < 3.7%
South façade window type	Low	
East/West façade window type	Low	
North façade WWR	Low	
East/West façade WWR	Very Low	Energy Savings <= 1%

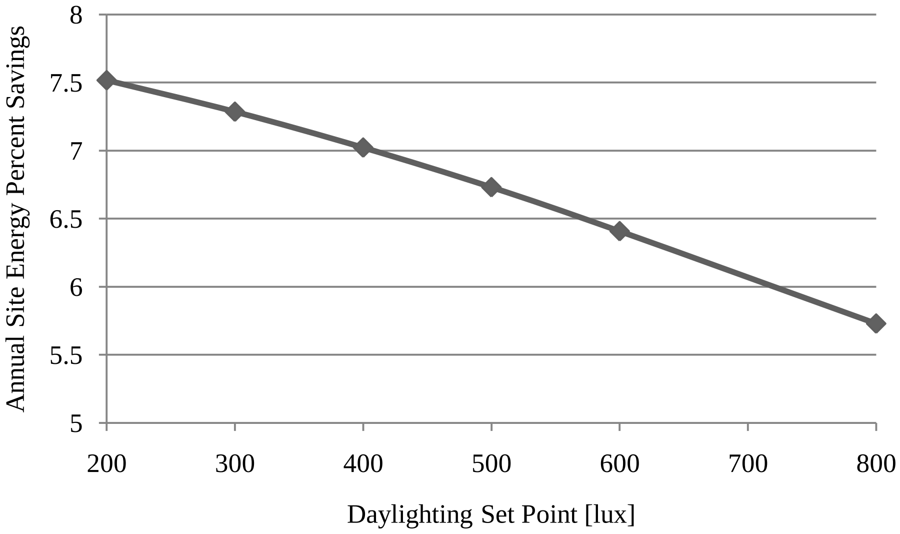

Figure 61: Daylighting controls sensitivity analysis – Harbin office.

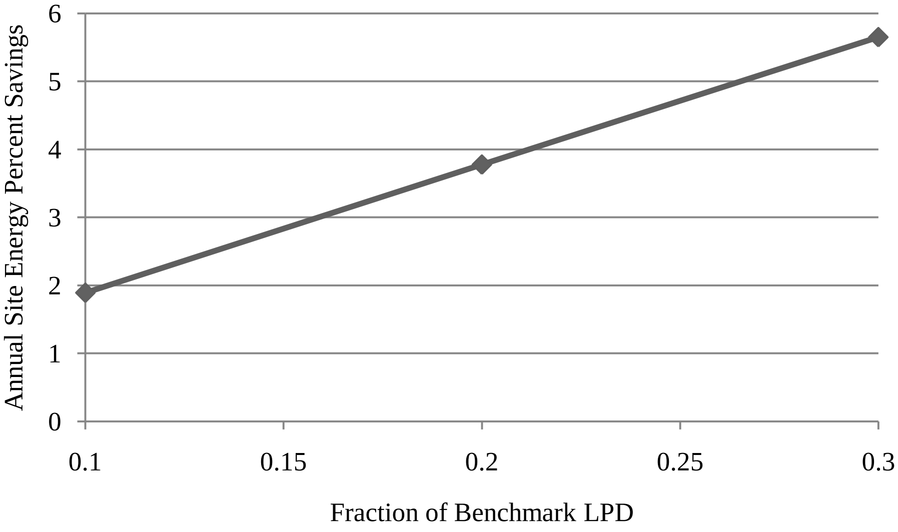

Figure 62: Reduced lighting power density sensitivity analysis – Harbin office.

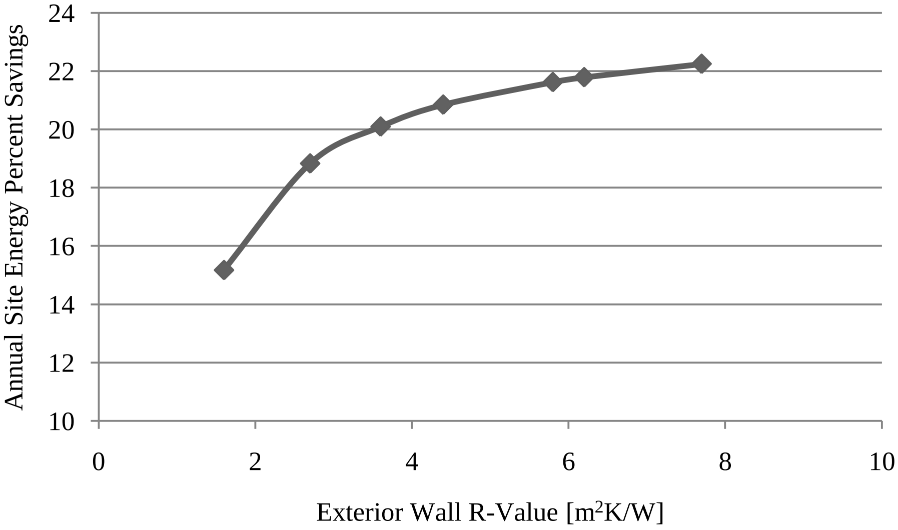

Figure 63: Exterior wall insulation sensitivity analysis – Harbin office.

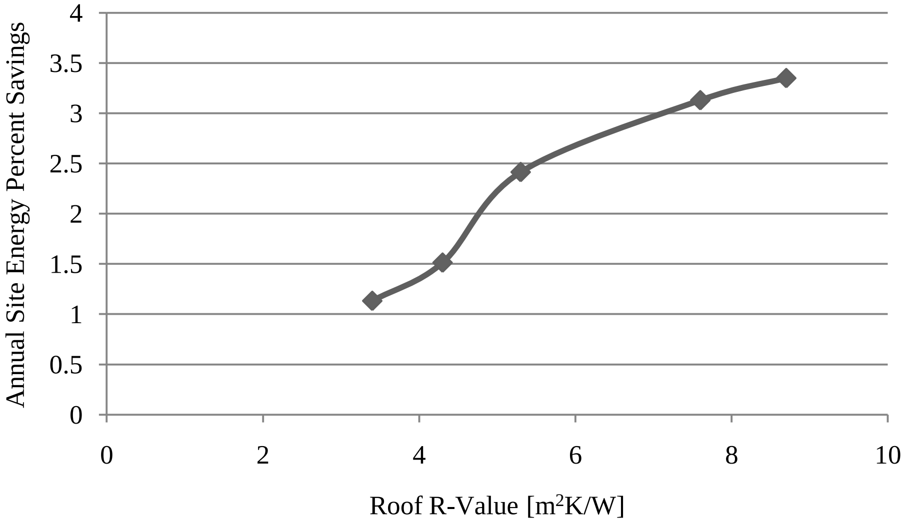

Figure 64: Roof insulation sensitivity analysis – Harbin office.

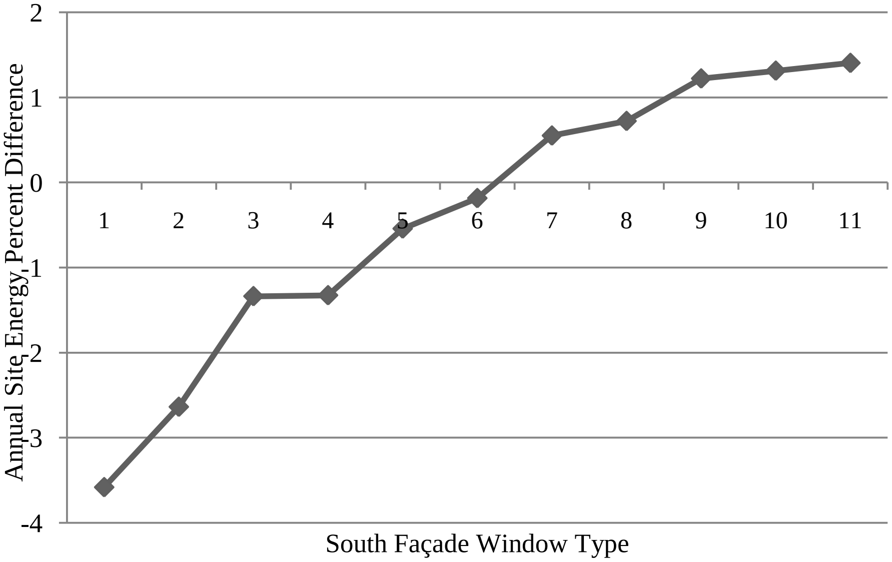

Figure 65: South façade window type sensitivity analysis – Harbin office.

Table 57: South Facade Window Types – Harbin office

	South Window Type
1	UValue_2.101_SHGC_0.19_VT_0.3
2	UValue_1.363_SHGC_0.13_VT_0.17
3	UValue_1.363_SHGC_0.22_VT_0.32
4	UValue_2.101_SHGC_0.36_VT_0.53
5	UValue_1.7_SHGC_0.35_VT_0.44
6	UValue_1.363_SHGC_0.31_VT_0.46
7	UValue_1.7_SHGC_0.45_VT_0.45
8	UValue_2.101_SHGC_0.55_VT_0.61
9	UValue_1.136_SHGC_0.4_VT_0.65
10	UValue_1.419_SHGC_0.46_VT_0.494
11	UValue_1.476_SHGC_0.48_VT_0.61

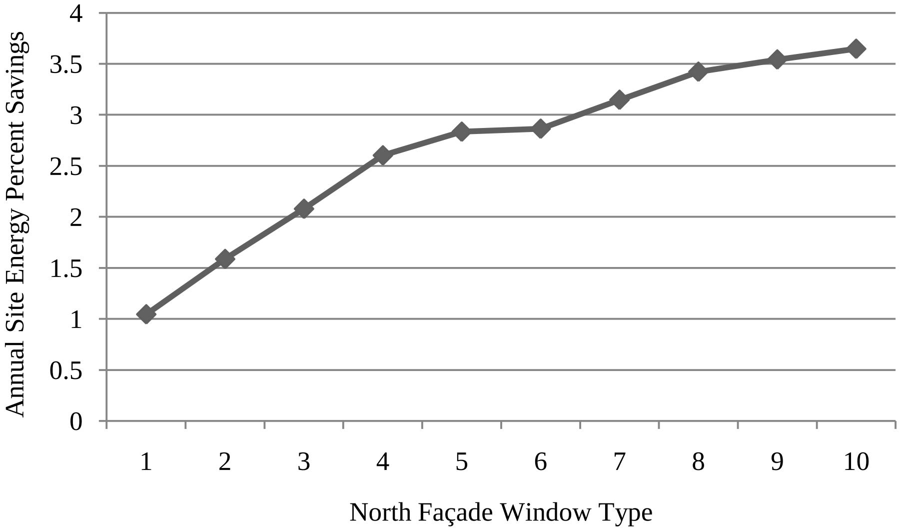

Figure 66: North façade window type sensitivity analysis – Harbin office.

Table 58: North Façade Window Types – Harbin Office

	North Window Type
1	UValue_2.101_SHGC_0.19_VT_0.3
2	UValue_2.101_SHGC_0.36_VT_0.53

3	UValue_2.101_SHGC_0.55_VT_0.61
4	UValue_1.7_SHGC_0.35_VT_0.44
5	UValue_1.7_SHGC_0.45_VT_0.45
6	UValue_1.363_SHGC_0.22_VT_0.32
7	UValue_1.363_SHGC_0.31_VT_0.46
8	UValue_1.476_SHGC_0.48_VT_0.61
9	UValue_1.419_SHGC_0.46_VT_0.494
10	UValue_1.136_SHGC_0.4_VT_0.65

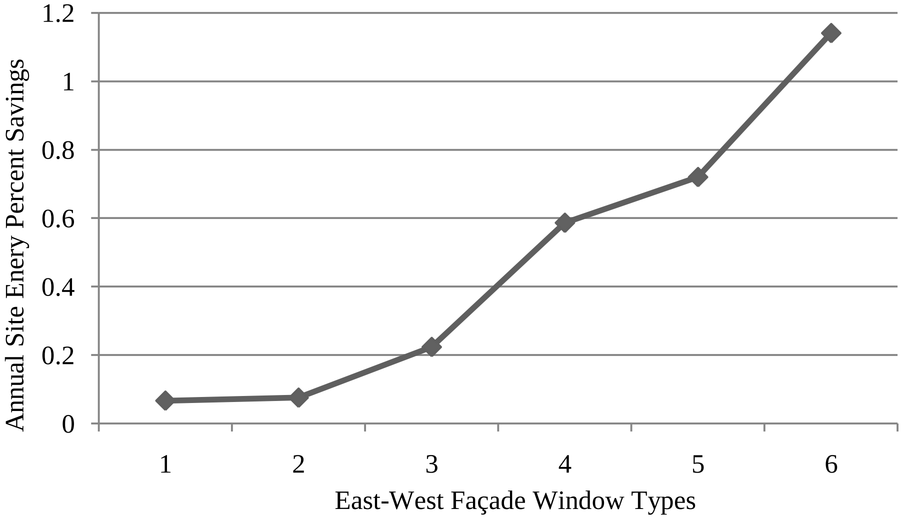

Figure 67: East/West façade window type sensitivity analysis - Harbin office.

Table 59: East/West Façade Window Types

	East/West Window Type
1	East (UValue_2.101_SHGC_0.19_VT_0.3) West (UValue_1.363_SHGC_0.13_VT_0.17)
2	East (UValue_2.101_SHGC_0.19_VT_0.3) West (UValue_2.101_SHGC_0.36_VT_0.53)
3	East (UValue_2.101_SHGC_0.36_VT_0.53) West (UValue_2.101_SHGC_0.36_VT_0.53)
4	East (UValue_2.101_SHGC_0.36_VT_0.53) West (UValue_2.101_SHGC_0.55_VT_0.61)

5	East (UValue_2.101_SHGC_0.55_VT_0.61) West (UValue_2.101_SHGC_0.55_VT_0.61)
6	East (UValue_2.101_SHGC_0.55_VT_0.61) West (UValue_1.136_SHGC_0.4_VT_0.65)

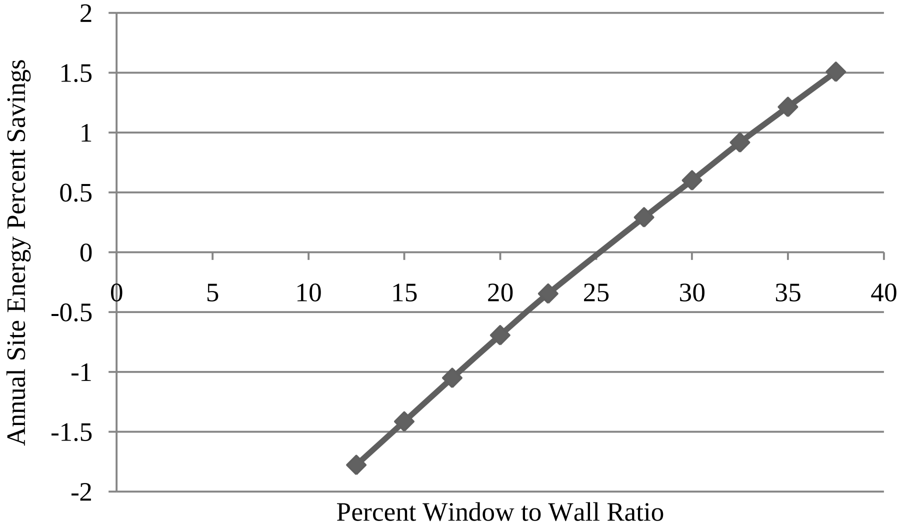

Figure 68: South façade window to wall ratio sensitivity analysis – Harbin office.

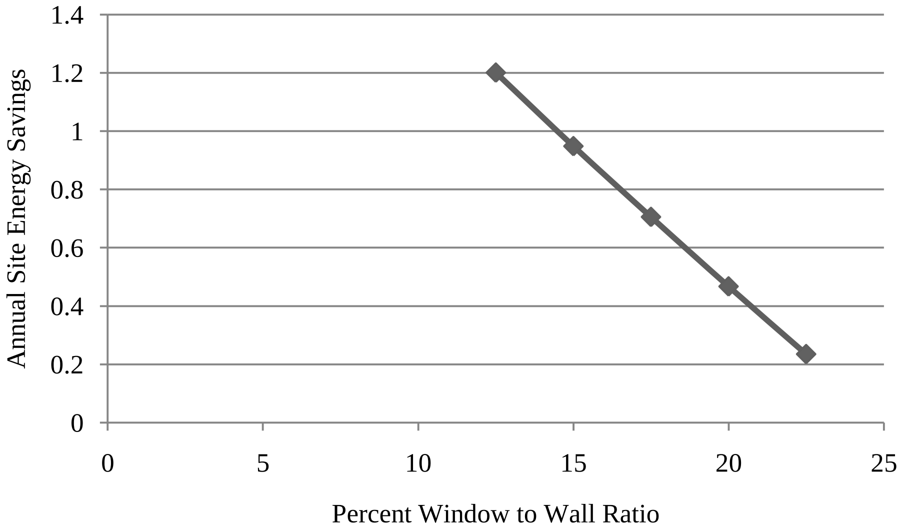

Figure 69: North façade window to wall ratio sensitivity analysis – Harbin office.

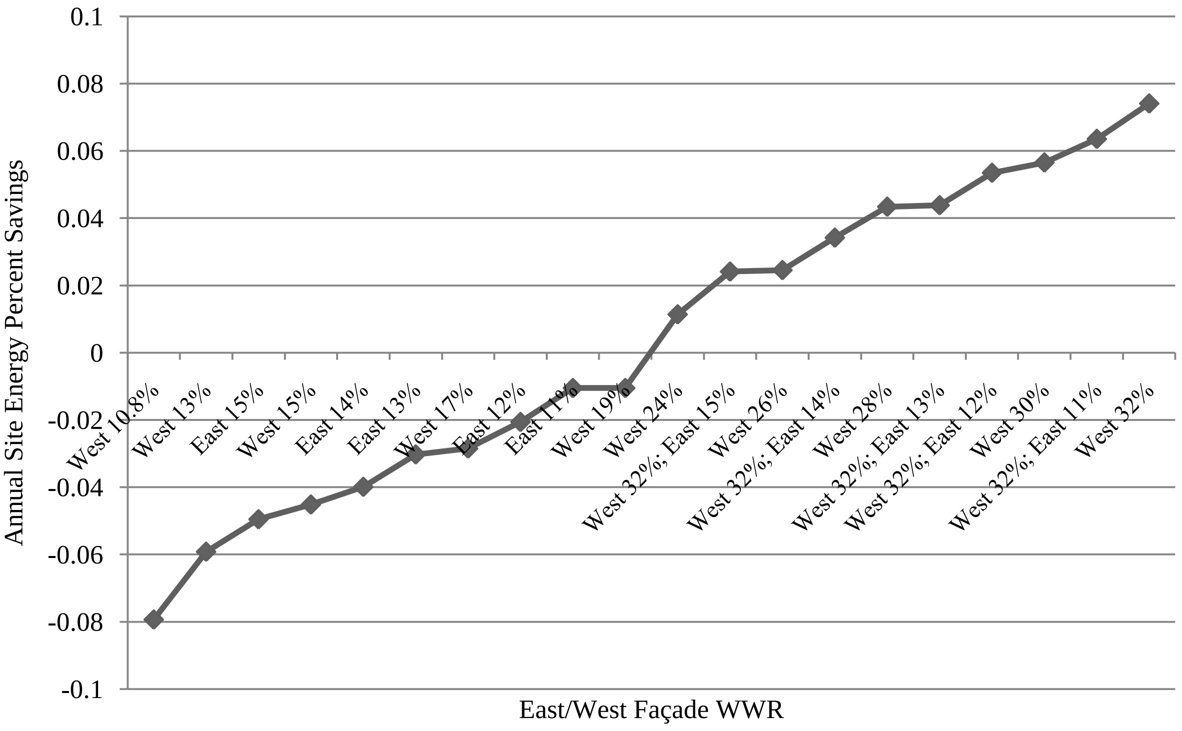

Figure 70: East/West façade window to wall ratio sensitivity analysis – Harbin office.

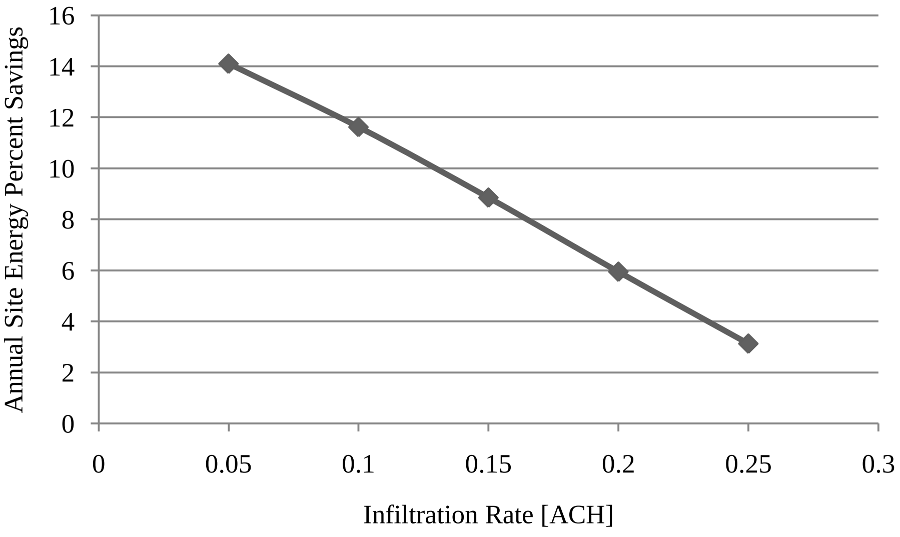

Figure 71: Infiltration sensitivity analysis – Harbin office.

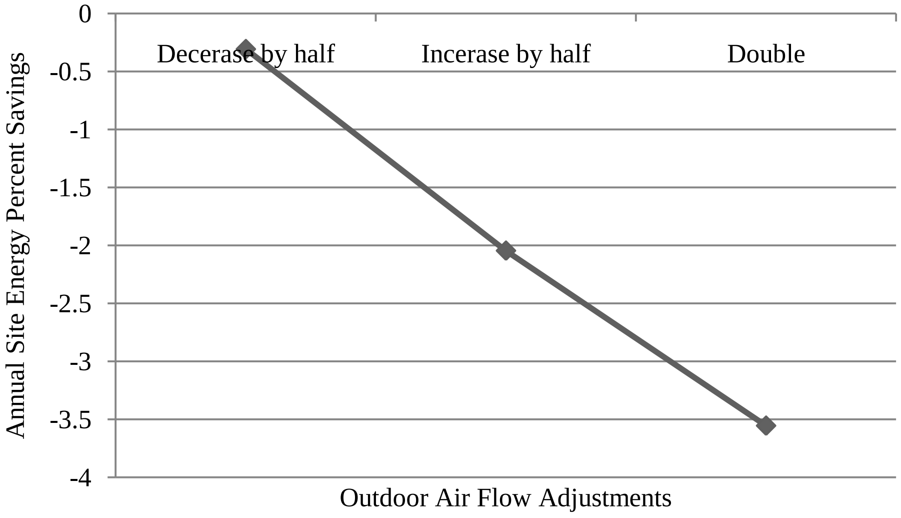

Figure 72: Outdoor air flow sensitivity analysis – Harbin office.

4.2 Identifying Potential Energy Savings for the Harbin Hotel

Recall that the Harbin hotel is a 9,288 m^2, three story building. Heating and cooling are provided by a four-pipe fan coil system with heating supplied by an natural gas boiler and cooling provided by an electric chiller. The end use site energy consumption breakdown is shown in the pie chart of Figure 73. As is shown, heating, lighting, and electrical equipments are the primary end use categories, (55 percent, 23.5 percent and 11 percent, respectively); cooling accounts for only 5.3 percent of total site energy while the other auxiliary HVAC components account for less than five percent. Obviously, energy efficiency strategies should target heating, lighting, and electrical equipments. This section applies the optimization process outlined above and presents the recommendations for building code standard improvements.

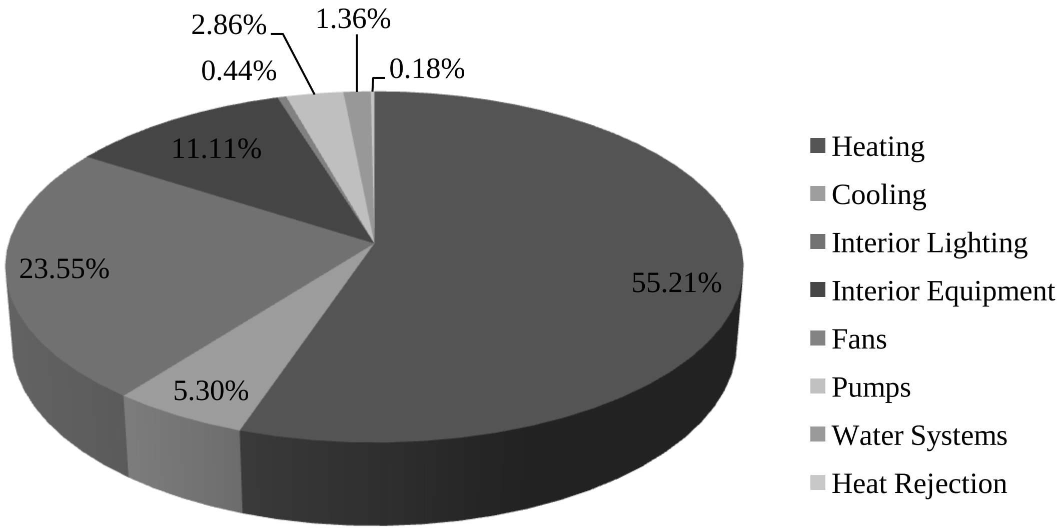

Figure 73: End use energy breakdown - Harbin hotel.

This section will discuss the results of the parametric, Opt-E-Plus, and sensitivity analyses for the Harbin hotel benchmark model. The same methodology had been applied t as was outlined in Section 4.1 for the Harbin office benchmark model.

4.2.1 Harbin Hotel Parametric Analysis

Figure 74 illustrates what happens when different heat-transfer paths or building load components are removed from the building including exterior walls, roof, slab, outdoor air flow rates, ventilation rates, windows, and internal gains. These results also provide insight into which EDMs are most important for the Opt-E-Plus analysis. The parametric analysis leads to the following results:

- *R-35 Exterior Walls, Roof, and Slab:* Setting the R-value of the exterior walls, roof, and slab to R-35 m2K/W eliminates all significant heat loss through the building envelope. Eliminating heat transfer through the exterior walls shows a 13 percent savings in heating energy and a seven percent overall annual site energy savings. This suggests that the exterior walls do not contribute significantly to energy consumption. Eliminating heat transfer through the roof shows similar results. The result of eliminating heat transfer through the slab suggests that ground heat transfer is an insignificant contributor to energy consumption; in reality, however, the slab may contribute more to heating energy consumption. These results are simply limited to the calculation method used in EnergyPlus. Eliminating the collective heat transfer through the envelope has a greater effect on energy savings; doing this results in a 28 percent savings in heating energy and a 16 percent annual site energy savings. This is nearly equivalent to adding the energy savings from each individual case. Note that the windows have not been modified or removed in this set of analyses.

- *No Outdoor Air/Infiltration:* This case eliminates all outdoor air entering the building including infiltration, natural ventilation, and designated outdoor air. The results show a large savings in heating energy, roughly 88 percent, which leads to a 44 percent savings in annual site energy. This suggests that energy savings can potentially be achieved by reducing infiltration and preconditioning outdoor air. Eliminating the only the infiltration shows that just over half of this energy savings is associated with infiltration while the remainder is associated with natural ventilation and designated outdoor air.
- *No Windows:* Eliminating the windows shows a two percent decrease in energy consumption. This savings is primarily a result of the 33 percent energy savings associated with cooling energy. However, cooling energy is only a small percentage of the total so the overall effect is small. Heating energy increases by just over one percent as a result of reduced solar heat gains in south-facing zones. This also suggests that the conductive and convective heat transfer through and around the window is slightly less effective than the added benefit of solar gains.
- *Adiabatic Envelope:* Eliminating all heat transfer through the envelope, including the walls, roof, slab, and windows results in about 22 percent energy savings. This is roughly 20 percent more than the sum of the savings from the individual components. This suggests that the calculation method used in EnergyPlus accounts for integrated effects of building components.
- *Envelope and Outdoor Air:* Removing all outdoor air and eliminating the heat transfer through the envelope (including through the windows) completely eliminates the need for heating and doubles the cooling. This is to be expected. The annual site energy is reduced by 50 percent due to the fact that the heating energy savings outweigh the additional cooling energy consumption. It should be noted that the efficiency of the cooling system (COP of 4.7) is over four times more efficient than the heating system (natural gas boiler efficiency of 0.9). Therefore, the additional cooling energy is (as expected) still a small percentage of the total annual consumption. Adding

the windows back into the model leads to an additional 12.5 percent increase in cooling energy. This is due to the additional of solar heat gains which are no longer beneficial.

- *No Internal Gains:* Eliminating the people, lights, and electrical plug loads shows the significance of these internal gains on heating energy consumption as well as the overall annual site consumption. The results suggest that electrical lighting is the most significant internal load contributing to about 42 percent to the cooling load while helping meet nearly 22 percent of the heating requirement. Electrical plug loads contribute to about 25 percent of cooling load and help meet 10 percent of the heating requirement. The occupants of the building contribute to about 23 percent of the cooling load and help meet roughly eight percent of the heating load.

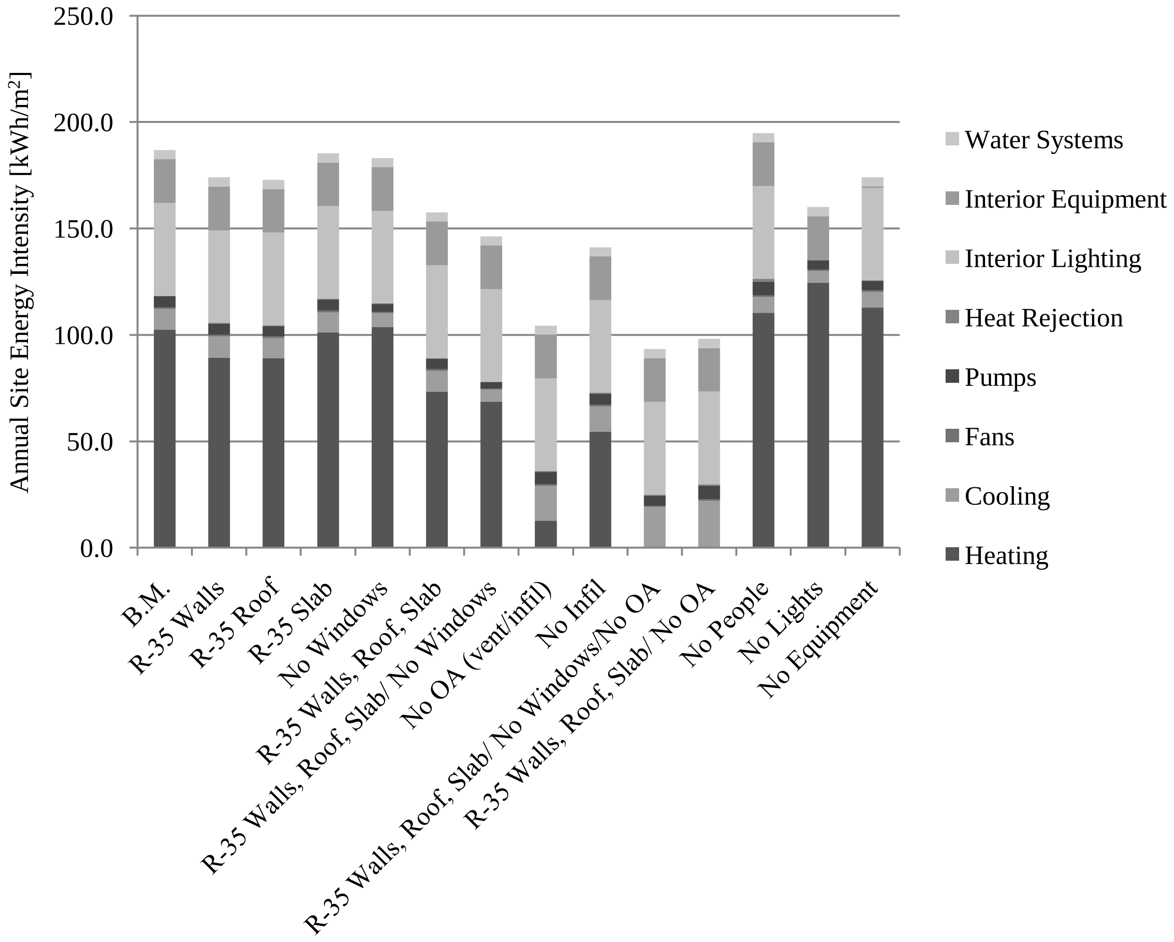

Figure 74: Parametric analysis - Harbin hotel.

4.2.2 Harbin Hotel Opt-E-Plus Analysis

The results of the parametric analysis are used to guide the selection of EDM to use in the Opt-E-Plus analysis. Table 55 lists the EDMs selected in Opt-E-Plus.

Energy Design Measure	Value	Benchmark value
Reduced ventilation rate	0.0025 m3/person	Refer to Table 31
South façade shading	0.5 projection factor	None
Photovoltaics	50% Roof area	None
North façade window properties	U-Value: 2.10, SHGC: 0.19, VT: 0.30; U-Value:1.14 , SHGC: 0.40, VT: 0.65; U-Value: 1.42, SHGC: 0.32, VT: 0.33	U-Value: 2.67, SHGC: 0.703, VT: 0.781
South façade window properties	U-Value: 2.10, SHGC: 0.36, VT: 0.53; U-Value:1.14 , SHGC: 0.40, VT: 0.65; U-Value: 1.42, SHGC: 0.46, VT: 0.49; U-Value: 1.70, SHGC: 0.45, VT: 0.45	U-Value: 2.67, SHGC: 0.703, VT: 0.781
East façade window properties	U-Value: 2.10, SHGC: 0.36, VT: 0.53; U-Value:1.14 , SHGC: 0.40, VT: 0.65;	U-Value: 2.67, SHGC: 0.703, VT: 0.781
West façade window properties	U-Value: 2.10, SHGC: 0.36, VT: 0.53; U-Value:1.14 , SHGC: 0.40, VT: 0.65;	U-Value: 2.67, SHGC: 0.703, VT: 0.781
Percent of benchmark WWR	300% to 40%	North: 25%, South: 30%, East/West: 20%
Exterior wall insulation	R- 2.74, R-4.41, R-7.70	R-2.08
Roof insulation	R-3.47, R- 7.67, R-11	R-2.77
EPD reduction	30%, 10%	Refer to Table 28
LPD reduction	30%, 10%	Refer to Table 28
Daylighting controls	Set point: 500 lux	None
Infiltration reduction	50%, 25%	0.3 ACH

The resulting Opt-E-Plus output is show in Figure 75. As mentioned in Section 4.1, the lifecycle cost results are irrelevant. Table 92 in Appendix B3: Selected EDMs for Harbin Office Optimization lists all of the EDMs applied in each building model along the optimization curve in Figure 75. As in the case of the Harbin office, the results are used to identify which measures are most important in achieving energy savings and are used to carry out the sensitivity analysis.

Alternative window constructions, reduced window to wall ratios, and an LPD reduction of 10 percent are the first series of EDMs applied in the optimization and do not lead to significant energy savings. The first major jump in energy savings occurs between six and 34 percent and is a result of reducing the ventilation rate from 0.00833 m3/sec/person to 0.0025 m3/sec/person. Although this is not an appropriate amount of ventilation air, it does show that heat recovery could lead to significant energy savings. Reducing the infiltration rate from 0.3ACH to 0.2 ACH pushes the energy savings from 34 percent to about 42 percent while reducing infiltration further (to 0.05ACH) pushes savings to 52 percent. The last major jump in energy savings occurs between about 54% and 79 percent; this is a result of PV on 50% of the roof area. The last EDMs to be applied after PV include R-7.7 exterior wall insulation, south façade window types, and south façade window shading devices. These EDMs do not result in any significant energy savings. Refer to Table 93 in Appendix B3: Selected EDMs for Harbin Office Optimization for all EDMs applied in each alternative model along the optimization curve.

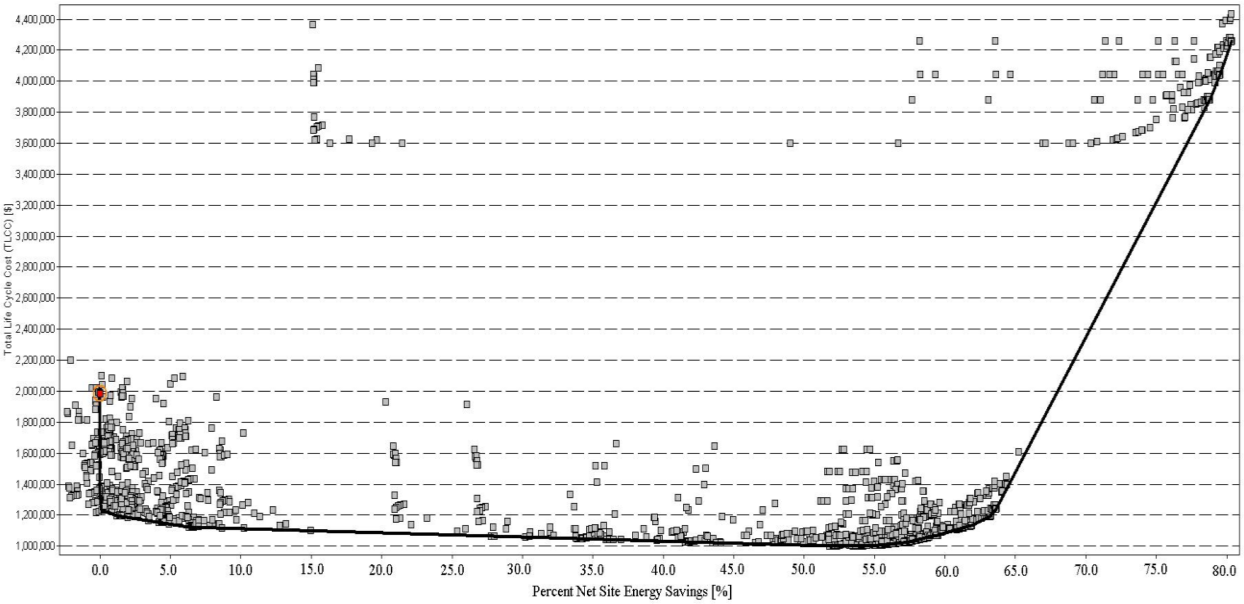

Figure 75: Harbin hotel - Opt-E-Plus analysis results.

4.2.3 Harbin Hotel Sensitivity Analysis

The sensitivity analysis focuses on each of the important EDMs from the Opt-E-Plus analysis. The same methodology applied in the sensitivity analysis for the other benchmark models is also applied here (refer to Section 4.1.3). The results of each sensitivity analysis are illustrated in Figure 76 through Figure 87.

- *Daylighting Controls:* Implementing daylighting controls in the stair cases contributes minimally to energy savings. There are two primary reasons for this. First, the existing window area in these zones is relatively small (10% WWR). Secondly, the total lighting energy associated with the staircases is a small percentage of the total building energy so significant savings are not achievable.
- *Lighting Power Density:* Reducing the lighting power density (LPD) can reducing energy consumption a fair amount. A 15 percent energy savings can be achieved for every ten percent reduction in LPD.
- *Insulation levels:* Exterior wall insulation is somewhat parabolically related energy savings, as shown in Figure 78. Energy savings approach 6% at R-values above 8 m^2K/W. Roof insulation is also parabollically related to energy savings. The results of Figure 79 show that savings approach seven percent at roof R-values of 16 m^2K/W. Implementing roof insulation levels above R-8 may not be economically feasible however, because higher insulation levels tend to come with higher costs. The energy saving potential diminishes dramatically above R-8 m^2K/W.
- *Window to Wall Ratios:* Increasing or decreasing the window area has very small effects on energy consumption. Reducing south window to wall ratios (WWRs) leads to an increase in energy consumption as shown in Figure 80. Reducing the window area lessens the amount of available solar heat gains that help meet the heating load. Increasing the WWRs allows for greater solar heat gain contributions but the energy savings associated with this modification are very low. Reducing WWRs on the north façade shows small energy savings equating to about 0.35 percent for every five percent reduction in WWR. The east and west window areas are optimized to determine if one particular side of the building is more sensitive to solar heat gains and or heat loss through the glazings. Recall that the only windows on these facades are located in the staircases and are relatively small to begin with, a WWR of 10 percent. As Figure 82 shows, increasing the window area on the west side has a larger negative impact on energy

consumption. Reducing or eliminating the windows altogether results in energy savings. As mentioned before, however, the overall energy consumption differences are very small - less than one percent.

- *Window Types:* A variety of window U-values are tested (U- 2.101 to 1.136 W/m^{2}K) with varying solar heat gain coefficients (SHGC) and visual transmittances (VT) to identify which window property has the most significant impact on energy savings (0.13 – 0.55 and 0.17 – 0.65, respectively). As Figure 83 shows, SHGC have a bigger effect on energy savings than do U-values for the south façade. However, combining low U-values with high SHGCs has the greatest potential for savings. This combination maximizes the beneficial solar heat gains and minimizes the conductive heat loss through the glass. Similar results are shown for east and west window types (see Figure 85and Table 63). Implementing low U-values on the north façade is the best option for achieving energy savings; SHGC have little impact. In summary, improving the window properties leads to small on energy savings; the greatest potential for energy savings is by implementing lower U-values on the north façade. Note that the window types represented in Figure 83 through Figure 85 are listed directly below in Table 61throughTable 63.
- *Infiltration Rates and Outdoor Air Flow:* Reducing infiltration is the single most effective measure for achieving energy savings. A four percent energy savings is achieved for every 16 percent reduction in ACH (or an ACH reduction of 0.05 ACH). As Figure 86 shows, energy savings are linearly related to the infiltration rate and a maximum energy savings of about 20 percent is achieved at an infiltration rate of 0.05. Surprisingly, increasing the outdoor air flow rate by one-half of the existing flow rate leads to an energy savings of about 20 percent. The results show that these savings are primarily associated with reduced heating energy. Not surprisingly, doubling the outdoor air flow rate leads to about a 54 percent increase in heating energy and about a 30 percent increase in total site energy. From these results, it is recommended that the outdoor air flow rate be increased by one-half. However, depending on the outdoor air

quality in Harbin, it may not be favorable to increase OA flow rates due to air pollutants that may lead to unacceptable indoor air quality.

Table 60 summarizes the importance of each energy design measure based on the results of the sensitivity analysis. Note that the rankings are based on the energy saving potential of each independent EDM and do not take into account any optimal design packages. Based on these results, the top priorities for improved building code standards for hotel buildings in the Severe Cold climate region are reducing outdoor air flow rates (by reducing infiltration and incorporating heat exchangers for OA preconditioning), increases insulation levels, and reduced lighting power densities. Although the results show high potential for reduced OA rates, it is not recommended that outdoor air volumes be reduced necessarily, but preconditioned with the use of exhaust air; further analysis is needed to determine the best option for preconditioning the outdoor air supply.

Table 60: Important Energy Design Measure Ranking – Harbin Hotel

Energy Design Option	Energy Saving Potential	Ranking Definitions
Reduced infiltration rate	High	Energy Savings > 10%
Outdoor air flow rate	High	
Exterior wall insulation	Medium	0.5% < Energy Savings < 6%
Roof insulation	Medium	
Lighting power density reduction	Medium	
North façade window type	Low	0.3% < Energy Savings < 2.5%
North façade WWR	Low	
South façade WWR	Very Low	Energy Savings < 4%
South façade window type	Very Low	
East/West façade window type	Very Low	
East/West façade WWR	Very Low	
Daylighting controls	Very Low	

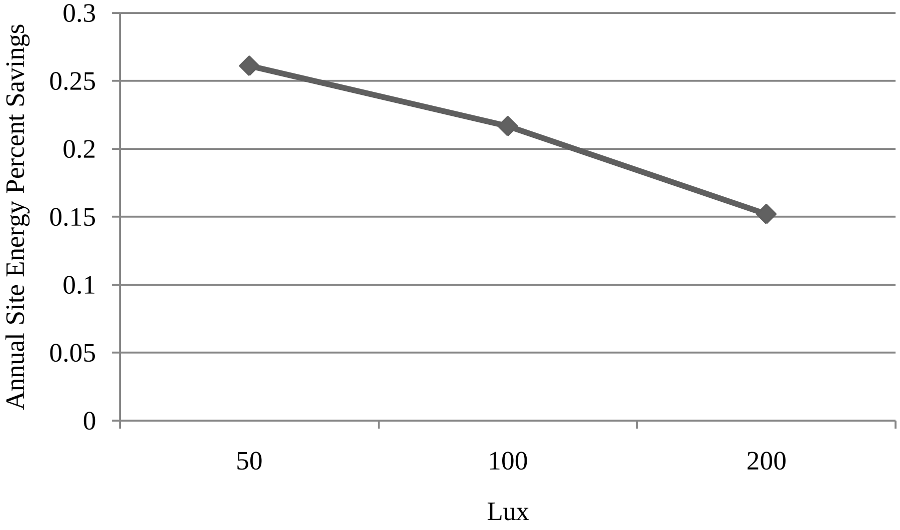

Figure 76: Daylighting controls sensitivity analysis - Harbin hotel.

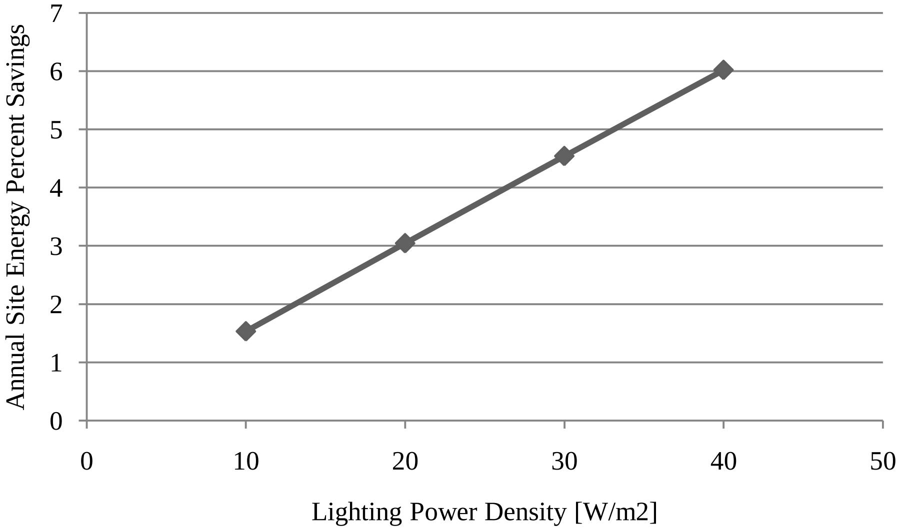

Figure 77: Lighting power density sensitivity analysis - Harbin hotel.

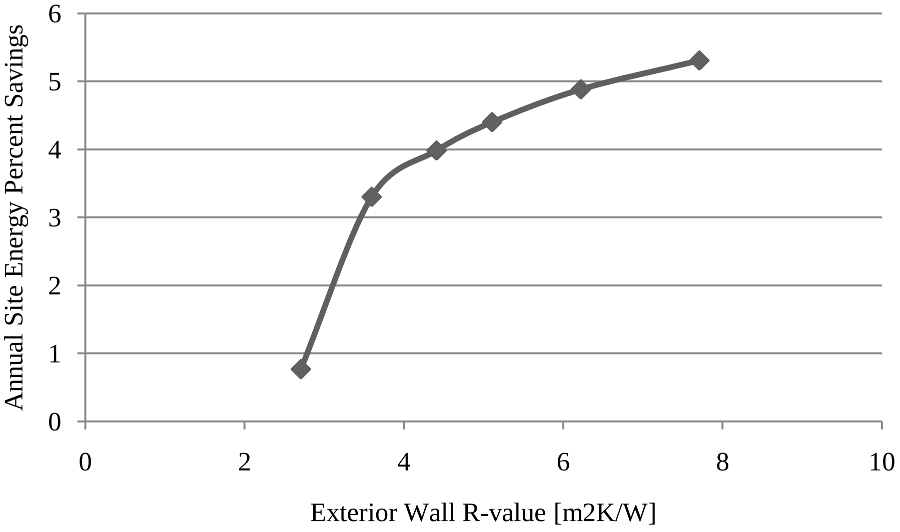

Figure 78: Wall insulation level sensitivity analysis - Harbin hotel.

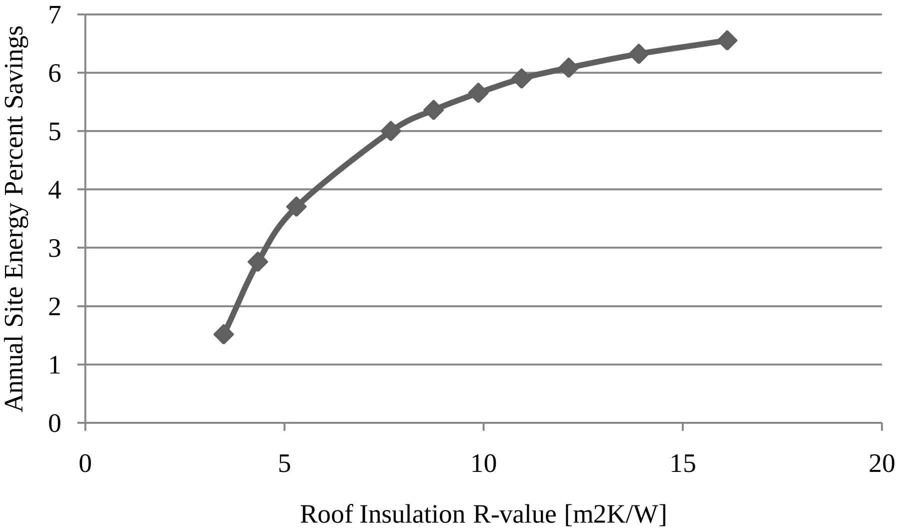

Figure 79: Roof insulation sensitivity analysis - Harbin hotel.

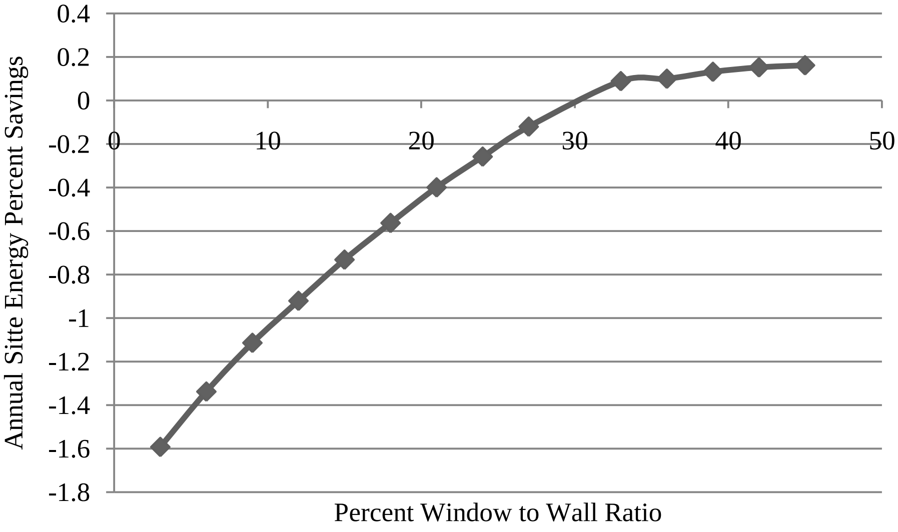

Figure 80: South window to wall ratios sensitivity analysis - Harbin hotel.

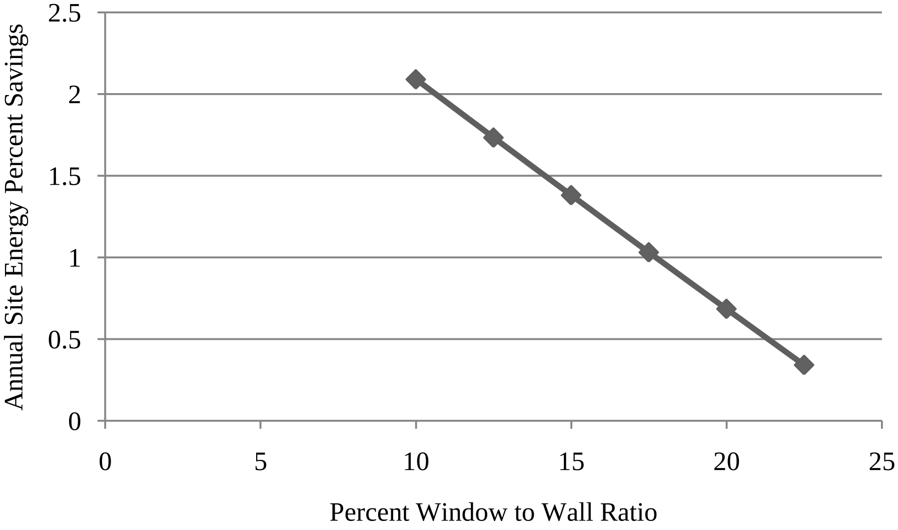

Figure 81: North window to wall ratio sensitivity analysis - Harbin hotel.

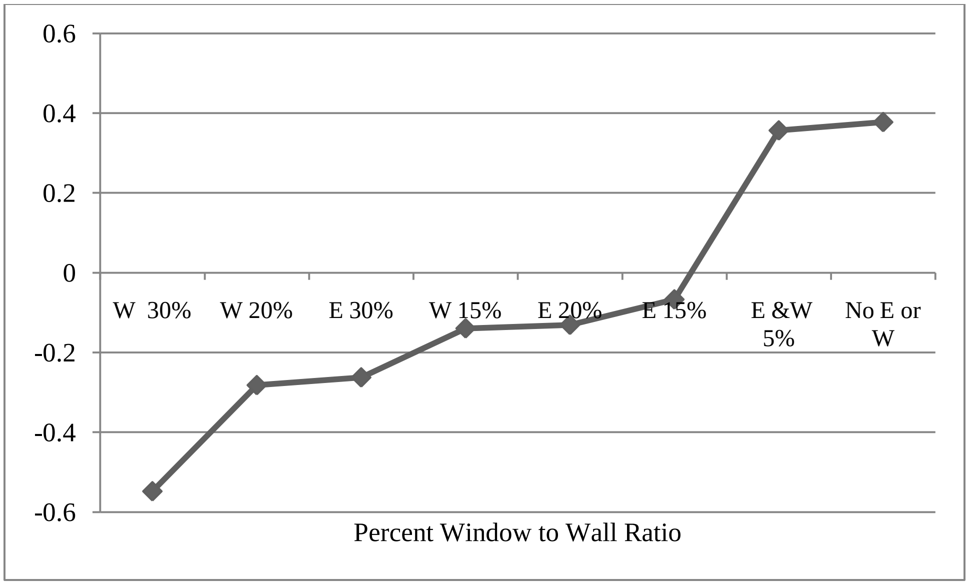

Figure 82: East/West window to wall ratio sensitivity analysis - Harbin hotel.

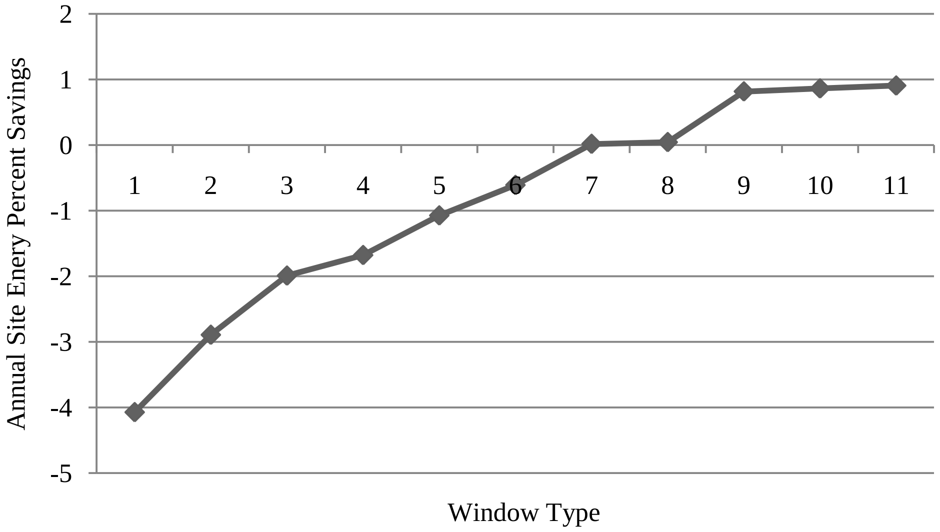

Figure 83: South window type sensitivity analysis - Harbin hotel.

Table 61: South Façade Window Types - Harbin hotel

	South Window Type
1	Uvalue: 2.101; SHGC: 0.19; VT: 0.3
2	Uvalue: 1.363; SHGC: 0.13; VT: 0.17
3	Uvalue: 2.101; SHGC: 0.36; VT: 0.53
4	Uvalue: 1.363; SHGC: 0.22; VT: 0.32
5	Uvalue: 1.7; SHGC: 0.35; VT: 0.44
6	Uvalue: 1.363; SHGC: 0.31; VT: 0.46
7	Uvalue: 1.7; SHGC: 0.45; VT: 0.45
8	Uvalue: 2.101; SHGC: 0.55; VT: 0.61
9	Uvalue: 1.136; SHGC: 0.4; VT: 0.65
10	Uvalue: 1.419; SHGC: 0.46; VT: 0.494
11	Uvalue: 1.476; SHGC: 0.48; VT: 0.61

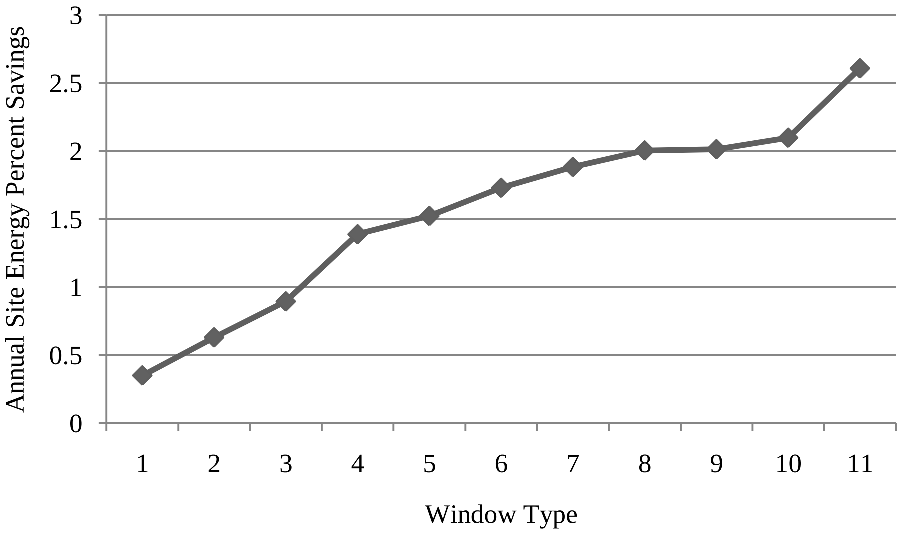

Figure 84: North window type sensitivity analysis - Harbin hotel.

Table 62: North Façade Window Types - Harbin hotel

	North Window Type
1	Uvalue: 2.101; SHGC: 0.19; VT: 03
2	Uvalue: 2.101; SHGC: 0.36; VT: 0.53
3	Uvalue: 2.101; SHGC: 0.55; VT: 0.61
4	Uvalue: 1.7; SHGC: 0.35; VT: 0.44
5	Uvalue: 1.7; SHGC: 0.45; VT: 0.45
6	Uvalue: 1.363; SHGC: 0.13; VT: 0.17
7	Uvalue: 1.363; SHGC: 0.22; VT: 0.32
8	Uvalue: 1.476; SHGC: 0.48; VT: 0.61
9	Uvalue: 1.363; SHGC: 0.31; VT: 0.46
10	Uvalue: 1.419; SHGC: 0.46; VT: 0.494
11	Uvalue: 1.136; SHGC: 0.4; VT: 0.65

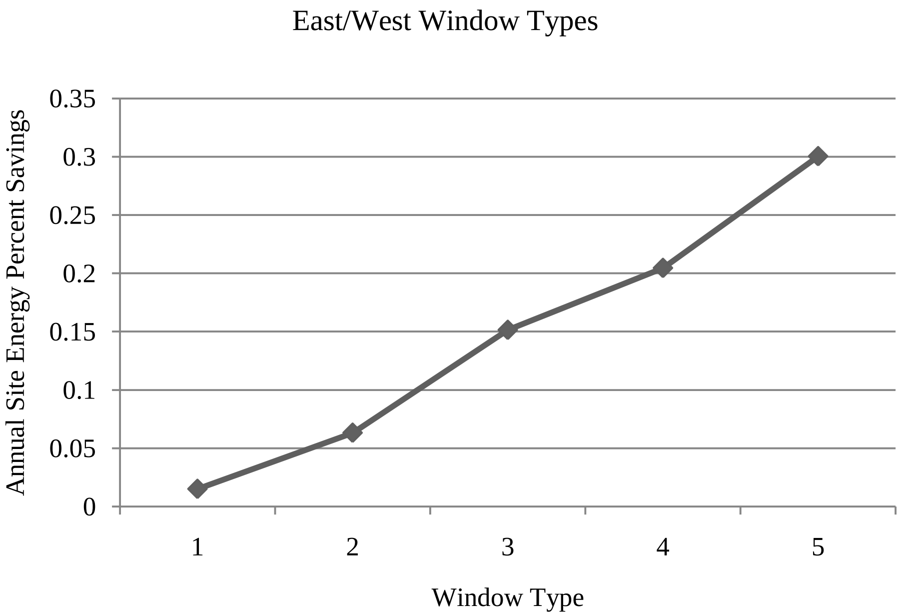

Figure 85: East/West window type sensitivity analysis - Harbin hotel.

Table 63: East/West Façade Window Types - Harbin hotel

	East/West Window Types
1	E: UValue_2.101_SHGC_0.19_VT_0.3
2	E: UValue_2.101_SHGC_0.19_VT_0.3; W: UValue_2.101_SHGC_0.19_VT_0.3
3	E: UValue_2.101_SHGC_0.19_VT_0.3; W: UValue_1.363_SHGC_0.13_VT_0.17
4	W: UValue_1.363_SHGC_0.13_VT_0.17
5	E: UValue_1.136_SHGC_0.4_VT_0.65; W: UValue_1.136_SHGC_0.4_VT_0.65

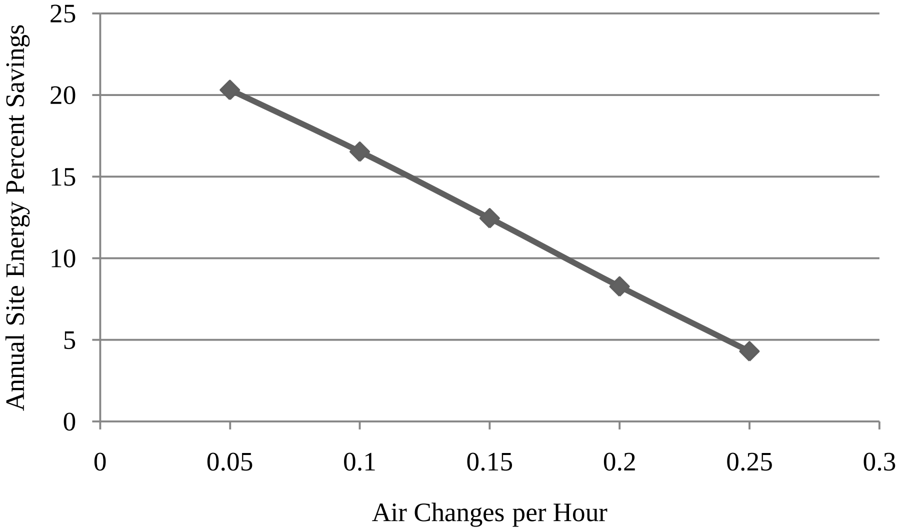

Figure 86: Infiltration sensitivity analysis - Harbin hotel.

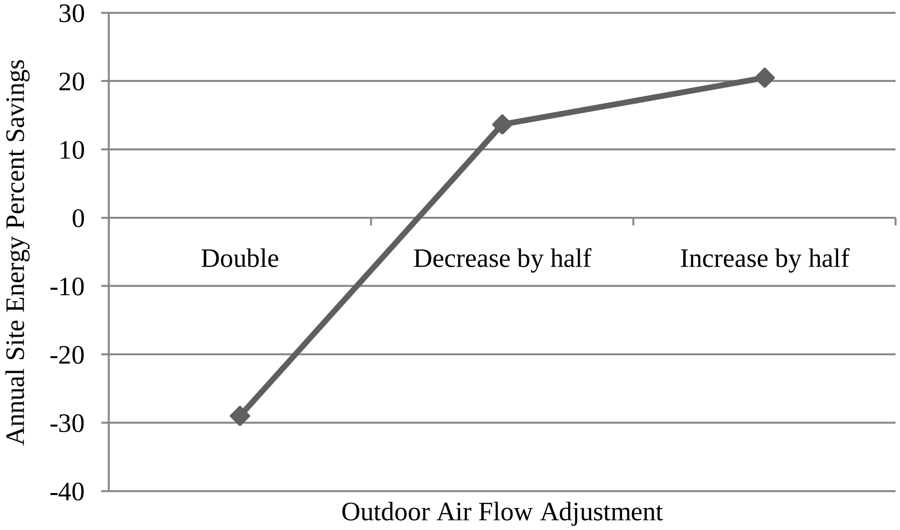

Figure 87: Outdoor air flow sensitivity analysis - Harbin hotel.

Chapter 5: Harbin Benchmark Model Economic Optimization

Optimizing a building's energy performance is an iterative process that involves finding alternative building designs that lead to energy savings as well as economic savings. Recommendations for improved building code standards have been derived in this chapter through an economic optimization for the Harbin office and hotel benchmark buildings. Unlike the previous studies presented above, this analysis is performed to demonstrate how Opt-E-Plus's economic features can be used to estimate a lifecycle cost savings associated with an optimal package of EDMs. A lifecycle cost analysis is important because it shows the economic benefit of energy efficiency measures over the lifetime of the building. This is critical in when the promoting improvements to energy efficiency standards and creating a market for more energy efficient buildings in China.

The procedure carried out for this analysis is slightly different than the previous methodologies because of the added dimension related to economics. The following passage describes the proposed methodology for performing an economic optimization with Opt-E-Plus.

It is difficult to choose appropriate EDMs for the optimization if little is known about how the building operates as a system. So, the researcher should first gain some understanding about how the building operates and how the building parameters are interdependent so that significant EDMs can be selected. This approach also provides more information about the potential for energy savings and identifies what building parameters contribute the most to energy consumption. The methodology of the optimization process, which involves some behind-the-scenes research, involves four main steps which are summarized in the flow diagram below.

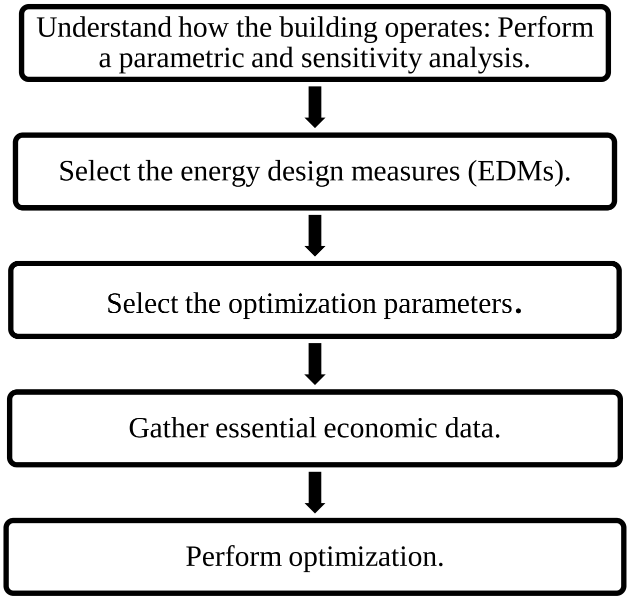

Figure 88: Schematic of pre-optimization procedures.

Each of these steps will be described in detail in the subsections of 5.1. In addition, all relevant economic assumptions and sources of data are explained in the subsections of 5.2. Finally, the results of the optimization procedure and final recommendations for the Harbin office and hotel benchmark building models are presented in sections 5.3 and 5.4, respectively.

5.1 Pre-optimization Procedures and Assumptions

The following sections will briefly describe the procedures and background research performed prior to the optimization.

5.1.1 Understand How the Building Operates

A building is an integrated system; each component has an impact on the other. It is therefore important to gain an initial understanding of how the building operates and the components that contribute most to energy consumption. It is also important to limit the number of selected EDMs used in the optimization because the required runtime and memory storage increases exponentially with the number of selected inputs. Therefore, two simple tests, including a parametric and sensitivity analysis, are performed to address these points.

A parametric analysis is carried out early in the energy-analysis routine to understand how each building component interacts within the system and to determine which variables have the greatest impact on overall building energy consumption (Deru, et al., 2005). This analysis also helps to identifies which EDMs should be included in the optimization. Refer to Chapter 4 for details on how this analysis is performed.

Once the key energy-consuming components have been identified, a sensitivity analysis is performed. This test is done by varying each key component identified in the parametric analysis over a range of values at relatively small increments. The variation in the energy design measure is plotted as a function of energy savings to show the relationship between the two and to identify the point of diminishing returns, if one should exist. These results also identify the range of values that should be selected for the optimization. For example, if the sensitivity analysis shows a parabolic relationship between roof insulation and energy savings, there is a point, say at R-6, beyond which energy savings is no longer significant. Therefore, insulation levels greater than R-6 are superfluous and may lead to results with costs that are higher than necessary.

5.1.2 Selecting Energy Design Measures

In general, there are two other considerations for selecting EDMs in addition to the parametric and sensitivity analyses. The first is to implement good engineering intelligence; the user should think critically before selecting an EDM as some EDMs are specific to particular building, climate regions, and and/or site locations. For example, it is not necessary to select window shading overhangs on the north façade of an office building in northern climates. Including this option would be wasteful! The second strategy is to take material limitations into consideration. Some EDMs may not be readily available in the area where the project takes place or the building owner may have a certain criterion for material use.

Limiting the number of selected EDMs to those which are most appropriate is important for reducing runtime and memory storage.

Note that in this research, product availability is not taken into consideration for two reasons. First, a Chinese database of materials for each climate region is not currently available. To accommodate this, a US database of materials is used. Second, using the pre established US database minimizes the restrictions in product limitations and identifies any new materials that could be introduced into the Chinese markets to achieve maximum energy savings.

5.1.3 Selecting Optimization Parameters

Opt-E-Plus allows for the optimization of many variables including, but not limited to, site energy, source energy, total lifecycle cost, capital cost and net present value. The optimization parameters selected in this study are net site energy percent savings and total lifecycle cost percent savings. Lifecycle cost is selected as the economic parameter given that an investor will typically decide to invest in energy efficiency alternatives based on the long-term economic benefits. Therefore, it is important for investors to take the time-value of money into account. Net present value also takes into account the time-value of money but does not reveal the important differences between real and nominal discount rates. The lifecycle cost is defined as follows:

(1)

where

(2)

Here, d is the discount rate and N is the lifecycle period; the lifecycle period is assumed to be 30 years for all optimizations.

The selection of the optimization parameters and the analysis period are project dependent; these values should be specific to project goals and the audience to which the results are presented. The analysis period should be selected critically as this parameter can significantly alter the economic feasibility of alternative building designs. Longer analysis periods typically lead to greater lifecycle cost savings whereas shorter analysis periods typically lead to smaller lifecycle cost savings.

5.1.4 Collecting Economic Data

The final step before beginning the optimization includes gathering all essential economic datasets. These datasets include 1) EDM costs, including material, installation, operation and maintenance (O&M), and salvage costs, 2) utility rate structures and prices and, 3) economic rates and fees, including discount, inflation, tax rates, as well as any fees associated with the construction project. Collecting this data can be a challenging process, especially for foreign countries, and could be a research project in itself! Nonetheless, this process is very important as the resulting estimates of energy efficient design option feasibility will only be as accurate as the inputs. The expected lifetime of the EDM must also be provided as an input; this figure is important when considering the total lifecycle cost of the building. Default values are used in this research.

5.2 Economic Input Data: Sources and Assumptions

Unfortunately, economic data for China is not easily accessible. This section describes all of the assumptions behind the economic inputs included in the Harbin office and hotel optimizations. Note that all monetary values have been converted from Chinese RMN to US dollars using the conversion factor of 6.8 RMB per US dollar (Shea, 2010).

5.2.1 Benchmark Construction Cost

The benchmark building capital cost is set as a fixed value in Opt-E-Plus based on average capital costs per square meter of finished floor area. This method of pricing the benchmark building is adopted from the technical document, *Strategies for 50% Energy Savings in Large Office Buildings*, (NREL, 2010). Construction costs for Chinese buildings are taken from the *Quarterly Hong Kong Construction Cost Report* (Rider Levett Bucknall, 2010). The quarterly cost report compares approximate construction costs for different types of buildings in a number of cities in China including Guangzhou, Shanghai, and Beijing. The range of construction costs for these three cities are listed in Table 64 below. Note that costs for Harbin are not explicitly listed; for this case, the overall average construction cost is used. This is a safe assumption because the costs do not vary significantly from city to city.

Table 64: Office and Hotel Construction Costs for Major Cities in China

	Guangzhou	Shanghai	Beijing	Average (Harbin)
Typical Office [$/m^2]	$480-$628	$503-$650	$506-$680	$575
Three-Star Hotel [$/m^2]	1,086-1,315	$1,123-$1,382	$1,123-$1,411	$1,240

5.2.2 Utility Pricing and Rate Structure

The cost and rate structures of utilities in China are based on building type and size. The qualifying pricing scheme is an annual flat rate for offices and hotels in Guangzhou and Harbin (Wei, 2010). Prices are provided in RBM per kWh of electricity and per cubic meter of natural gas and have been converted to USD/kWh and USD/Therm, respectively. The energy intensity of natural gas is taken to be 8,500 kcal/m^3 (Wei, 2010). The Table 65 below lists the utility prices used for the optimization.

Table 65: Energy Prices for General Commercial Buildings in China

	Guangzhou	Harbin
Electricity	$0.1387/kWh	$0.1268/kWh
Natural Gas	-	$1.183/Therm

It should be noted that water costs are absorbed into the capital cost of the building due to the very low price of this utility in China. Water costs in Harbin are reported to be 0.64 cents per cubic meter for water consumption and 0.16 cents per cubic meter for sewage disposal (GDPI). As a comparison, water prices in the US range from $13 per cubic meter to $47 per cubic meter (Walton, 2010).

5.2.3 Lifecycle Costs of Energy Design Measures

Each EDM in the Opt-E-Plus database of materials is assigned a material, installation, operation and maintenance (O&M) cost, and salvage cost (if applicable), which are priced on a per unit basis. These costs are specific to the US and are taken from a number of US sources. It is assumed that material and labor costs in China are lower than those in the US and so a number of assumptions have been made to account for these differences.

Commodity prices in China are assumed to be lower in China than in the US. Therefore, a scaling factor is used to adjust each selected EDM material cost. This scaling factor is derived based on the capital cost ratio of Chinese to US office building benchmark capital costs, as this value is known for both countries. Note that the capital cost values include material and labor costs but unfortunately, the disaggregated values are unknown. Although this is not the ideal method for adjusting material costs, this ratio provides the best possible assumption for the time being. It is recommended that a more accurate method be applied as data becomes available. Table 66 summarizes the average capital costs for office buildings and lists the ratio used to adjust the material costs. It is assumed that the capital cost ratio for different building types is equivalent (i.e. the same material costs are used in the hotel optimization).

Table 66: Office Building Capital Cost

	China	US	Material Cost Ratio
Average Office Building Capital Cost [\$/m^2]	$575	$1,294	44.1%

The costs of services in China are also assumed to be less than those in the US. Therefore, installation and O&M costs are adjusted based on the ratio of average gross net income per capita (GNIPC) between China and the US. The annual GNIPV values are taken from the World Bank database, 2009 and are based on the Atlas Method and purchasing power parity (PPP). PPP indicates that an international dollar has the same purchasing power over gross national income as a US dollar has in the US (World Development Indicators Database, World Bank, 2010). Table 67 summarizes these economic figures and lists the ranking of each country's income compared to the 213 countries monitored by the World Bank.

Table 67: Gross National Income per Capita (GNIPC) - 2009

	China	US	Income Ratio
GNIPC	$3,620	$47,240	7.66%
Ranking	124/213	17/213	-

Costs of EDMs are input into Opt-E-Plus in two ways: on a cost-per-unit basis or as a cost difference. The method depends on whether the EDM replaces an existing building component or if it is simply a scalar multiple of an existing component. For instance, roof insulation is applied based on a $/m^2 amount while the cost of a lighting power density reduction is input as a price difference between an estimated benchmark lighting cost and an energy efficient lighting design cost. Note that the income ratio is applied to installation and O&M costs only when items are priced on a per-unit basis and is applied to the price differences when the second costing approach is used. Specific costing methods are listed here:

- *Equipment Power Density:* No cost adjustment is implemented for reducing the electrical equipment power density. It is assumed that efficient office equipment is cost competitive with standard equipment. Furthermore, it is assumed that the initial cost of the building does not include the cost of office equipment so this price increase can be neglected. These assumptions are taken from the NREL report titled *50 percent Energy Savings in Office Buildings – Technical*

Support Document. This report is referenced a number of times and will be referred to as the *Office TSD report.*

- *Lighting Power Density:* The lighting power density reduction cost increase is a complicated one to say the least. The benchmark lighting power density was estimated based on dollars per kilowatt. The Office TSD report lists an estimated cost per area for a typical lighting design and for an efficient lighting design. Since the Chinese baseline lighting power density and the efficient lighting EDM (30 percent LPD reduction) fall between these two values their costs are linearly interpolated from the values stated in the Office TSD report. Then, the cost difference is found and multiplied by the China/US income ratio. This value is input into Opt-E-Plus for the LPD EDM. Table 68 summarizes these assumed costs. Lighting power density reductions could include reduced number of fixtures, reduced number of bulbs, and/or different fixture designs. These components could lead to cost savings. However, dimmable ballasts used in conjunction with daylighting controls could increase the cost significantly. This feature is assumed here and therefore leads to a cost increase.

Table 68: Linear Interpolation of LPD Costs

	Linear Interpolation		
Case Scenario	LPD [W/m^2]	Cost [$/kW]	Cost Difference (Opt-E-Plus input)
Typical US design	12.2	$9,418	
Chinese baseline	11.0	$11,385	$5,410
30% LPD reduction	7.7	$16,795	
Efficient US design	6.8	$18,270	

- *Daylighting Controls:* Daylighting controls are priced based on material cost and installation cost per square meter. The existing installation cost in the database has been adjusted by the income ratio.
- *Window to Wall Ratios:* There is no cost associated with modifying the window to wall ratios; these costs are absorbed into the exterior wall construction and fenestration costs.

- *Building Envelope Construction and Shading Devices:* Exterior wall, roof, fenestration, and window shading devices (including overhangs and fins) are priced based on material and installation costs per square meter. The existing installation costs in the database have been adjusted by the income ratio. There is no O&M costs associated with these building materials.
- *Efficient Chiller Costs:* The pricing method is again adopted from the office TSD report which assumes a cost increase of 10 percent for a 13 percent increase in chiller COP. The cost is applied on a dollar per unit cooling capacity basis in Opt-E-Plus. The Office TSD report estimates that the cooling system accounts for 18 percent of the building's total capital cost which can be determined by dividing the total cooling system cost by the total capital cost. The same percentages are applied to the Chinese case. Knowing the total capital cost of the benchmark, the cooling cost can be determined. Linear interpolation is used to determine the appropriate increase in cost associated with a 10 percent and 20 percent increase in chiller COP. The cost calculations are summarized in Table 69. A 7.7 percent increase in cooling cost is applied to a chiller COP increase of 10 percent and a 15.3 percent cooling costs increase is applied to a chiller COP increase of 20 percent. Note that these costs are not adjusted by the income ratio because they are derived from the capital cost of the benchmark which has already been appropriately adjusted. In addition, the O&M cost associated with the chiller is a fixed amount and is therefore adjusted by the income ratio.

Table 69: Pricing Method for Increased Chiller COP - Guangzhou Office

Benchmark Chiller Capacity	1864.15 kW
Benchmark capital cost	$4,627,183.14
Cost of cooling system (18% of capital cost)	$851,566.29
Cooling cost per unit capacity	$456.18/kW
10% COP increase (7.7% cost increase)	$491.98/kW
Change in cost for 10% COP increase	$35.17/kW
20% COP increase (15.3% cost increase)	$526.70/kW
Change in cost for 20% COP increase	$69.89/kW

Table 70: Pricing Method for Increased Chiller COP – Harbin Hotel

Chinese benchmark chiller capacity	330 kW
Approximate benchmark capital cost	$12,277,526
Cost of cooling system (18% of capital cost)	$2,210,00
Cooling cost per unit capacity	$5,583/kW
10% COP increase (7.7% cost increase)	$5,974/kW
Cost increase for 10% COP increase	$391/kW
20% COP increase (15.3% cost increase)	$6,437/kW
Cost increase for 20% COP increase	$854/kW

5.2.4 Economic Discount Rate

Another important input parameter in Opt-E-Plus is the discount rate. A discount rate is a mathematical combination of tax rate, interest rate, and inflation rate and is used to determine the present value of future cash flows. The expression for discount rate is as follows:

(3)

where t is the tax rate, *i* is the interest rate, and *λ* is the inflation rate. There are two types of discount rates, real and nominal. A nominal discount rate takes into account inflation whereas a real discount rate does not. The relationship is as follows:

(4)

Rate values are provided by M. Levine at the Laurence Berkeley National Laboratory (September, 2010). His team of researchers suggests that during the general economic evaluation of projects, the inflation rate for long-term analyses is usually assumed to be three percent. The discount rate is usually assumed to be around 10 percent but can often be 20 percent or higher for some energy conservation projects. It is not certain whether this discount rate is nominal (does not account for inflation rates) or real (accounts for inflation rates) although there is a greater probability that the discount rate is nominal. To account for this uncertainty, an economic sensitivity test analysis has been performed by evaluating the optimization results under all four of these scenarios (real and nominal discount rates of 10 percent and 20 percent). The results will be presented later on in this chapter. The four economic terms will be referred to from here on as follows:

Table 71: Discount rate abbreviations

Abbreviation	Definition
d_R-10	Real discount rate of 10%
d_N-10	Nominal discount rate of 10%
d-10	Generic case of a 10% discount rate
d_R-20	Real discount rate of 20%
d_N-20	Nominal discount rate of 10%
d-20	Generic case of a 20% discount rate

Note that the generic term will be used when referencing both instances (real and nominal) of one particular discount rate value. In comparison, it is typical to use values between two and five percent and sometimes as high as 10 percent in the United States (Krarti, 2006)

5.2.5 Comments on Assumptions

The accuracy of these pricing schemes is very uncertain. Another source of GNI derived from the ILO LaborStar website for China segregates different occupations. This source suggests that the average income for construction workers in 2000 and 2006 was $1,199 and $1,591 per year. Projecting this cost out linearly suggests the average income is $1,982 per year for 2009 (Aulisio, 2010). Comparing this to the US GNI results in an income ratio of 4.20 percent which is 45.2 percent lower than what is used in the optimization. However, this compares Chinese construction wages to US national averages which could different than US construction wages. Therefore, the initial assumptions probably lead to a better approximation of the income ratio.

Obviously, the economic assumptions have a significant impact on the economic results of the optimization. However, costs of materials and new technologies are ever changing and their costs could be obsolete in just a few years. Changing the capital cost of the building and or the cost of ECMs will result in shifting the optimization curve up or down while changing the discount rate, inflation rate, and or utility costs could change the overall shape of the curve, that is, creating a deeper or more shallow trough. The optimal building design may also change depending on the economic inputs. It is therefore important to perform an economic sensitivity test to identify the impact of uncertain economic parameters on the optimization results.

5.3 Harbin Office Optimization

Much of the pre-optimization work has already been completed in Chapter 4, including the parametric and sensitivity analysis, so the process and results will not be presented again. Please refer to Chapter 4 for complete details on these processes. The following subsections will describe the methodologies for selecting the EDMs, the optimization results, and the resulting package of EDMs recommended for implementation.

5.3.1 Selecting Energy Design Measures

The energy design measures selected for the optimization of the Harbin office are chosen based on the results of the parametric and sensitivity analyses presented in Section 4.1.1 and 4.1.2 are listed in Table 72 below. Recall that Opt-E-Plus has the option to choose any of the selected EDMs in addition to the benchmark values. This results in a total of 186,624 different combinations of possible building designs.

Table 72: Selected Energy Design Measures - Harbin Office

EDM Category	EDM Selection
EPD Reduction	20% reduction
LPD Reduction	30% reduction
Daylighting Controls	400 lux set point in perimeter zones
Shading Devices	East façade shading fins: projection factor = 0.5
	West façade shading fins: projection factor = 0.5
Window to Wall Ratios Reduction	20% of benchmark value on south façade
	20% of benchmark value on north façade
Window Types	U-value: 2.56 W/m^{2}K, SHGV:0.46, VT: 0.46
	U-value: 1.82 W/m^{2}K, SHGV:0.46, VT: 0.49
Exterior Wall Insulation	R-3.9 m^{2}K/W
	R-6.2 m^{2}K/W
Roof Insulation	R-4.3 m^{2}K/W
	R-8.6 m^{2}K/W

The TSD for the US reference office building model (Leach et. al., 2010) is referenced for acceptable limits for EPD and LPD reductions; EPD and LPD reductions of 20 and 30 percent respectively, are considered achievable given the current electrical power densities of the benchmark (EPD = 20W/m^2, LPD = 11W/m^2). A daylighting control set point of 400 lux falls in the middle of the acceptable range of required illuminance for office spaces (300-500 lux) according to IES-NA, 2006; this assures sufficient lighting levels and allows for significant energy savings according to the sensitivity analysis. Shading devices are not predicted to save energy but are included in the optimization to identify if their application results in any significant energy increase of decrease. The application of shading devices on the east and west facades helps eliminate direct sun during early morning and late afternoon hours which could potentially cause glare on the work-plan and become a visual discomfort for occupants.

Window to wall ratio reduction of 20 percent on the north and south facades are selected based on the energy saving potential resulting from reduced heat loss through the windows. A 20 percent reduction results in a decrease in WWR from 25 percent to 20 percent, which is considered acceptable for office spaces (IES-NA, 2006). The WWR are not reduced on the east and west facades because the existing values are quite small to begin with (10 percent). Window types are selected based on the results of the sensitivity analysis which showed that more efficient windows have energy-saving potential and that higher SHGC should be considered. SHGC and visual transmittance (VT) values are closely related according to the Opt-E-Plus database of window options. More efficient window options are selected with a middle-of-the-road SHGC value (and therefore VT value) in an effort to balance heat loss, allow for beneficial solar gains, and reduce the potential for glare from direct sun. Exterior wall and roof insulation values are also selected based on the results of the sensitivity analysis; the highest R-values selected are shown to be near the point of diminishing returns.

5.3.2 Harbin Office Optimization Results

The results of the optimization show many important points worth discussing. First, it is obvious that the discount rate has a definite impact on the optimization results. Lifecycle cost savings are greater when the discount rate is a smaller value. The second point is that the type of discount rate has a more significant impact on the results at lower discount rate values. This is simply because the three percent inflation rate is a greater percentage of 10 percent than it is of 20 percent (see equations 3 and 4). The difference in total lifecycle cost between d_R-10 and d_N-10 is 7.9 percent and the difference between d_R-20 and d_N-20 is 3.8 percent. Another significant observation is that the optimal building design is dependent on the value of the discount rate but not on the type of discount rate; that is, the optimal building designs in both cases of d-10 includes the same package of EDMs and the same is true for the cases of d-20. The optimal building design results in an annual energy savings of 42 percent for the case of d-10 and 39 percent for the case of d-20. The corresponding lifecycle cost savings amounts are summarized in Table 73 below. The optimal points are identified in Figure 89 and the optimal packages of EDMs for both cases are listed in Table 74 along with the package corresponding to maximum potential energy savings.

The package of EDMs that result in maximum potential energy savings is the same for d-10 and d-20 although the path to this point is slightly different. All EDMs are selected in the same order for the d-10 cases but the type of discount rate used in the d-20 case leads to a slightly different path to the optimal package; wall insulation is selected before EPD reduction in the case of d_R-20 whereas the selection of these EDMs is reversed in the case of d_N-20 (recall that there is no cost associated with reducing EPD). These two EDMs create the large jump in energy savings between about 16 percent and 39 percent (the optimal point) as seen in Figure 89.

In general, the first set EDMs to be selected in all cases include modifications to the windows (including using window types with a U-value of 2.56 W/m^2K and reducing the WWR on the south façade), and applying R-4.3 roof insulation and shading devices on the east and west facades. Reduced electrical load densities and implementing daylighting controls are selected next followed by R-3.9 wall insulation in the case of d-10. R-3.9 wall insulation is applied before electrical load reductions in the case of d-20. Shading devices are removed for the building design package once daylighting controls are implemented in both cases. Solar PV is applied after R-8.6 roof insulation and R-3.9 exterior wall insulation but before the application of R-6.2 exterior wall insulation in the d-10 case. R-6.2 exterior wall insulation and R-8.6 roof insulation are applied before PV in the case of d-20. The final iteration in all four cases removes the WWR reduction option on the south façade and uses the benchmark WWR. Table 94 through Table 97 in

Appendix B5: Selected EDMs from the Economic Optimization of the Harbin Office summarize the order of EDM selection for all cases.

The application of PV on 95 percent of the roof area pushes the lifecycle cost beyond justifiable economic limits for the case of d-20 as the total lifecycle cost becomes greater than that of the benchmark building. It should be noted though that the increase in lifecycle cost compared to the benchmark is fairly small (1.66 percent greater for d_N-20 and 3.20 percent greater for d_R-20.) Applying PV to approximately 71 percent and 83 percent of the roof area in the d_R-20 and d_N-20 cases, respectively, would bring these cases to a neutral lifecycle cost. This amount of PV would result in an annual energy savings of 59 percent for the case of d_R-20 and 61 percent for the case of d_N-20.

In conclusion, the package leading to the maximum potential energy savings described in Table 74 results in a 64 percent savings in district heating energy, 58 percent savings in lighting energy, 20 percent savings from equipment electrical load reductions, and a 94 percent savings in pump energy. These savings lead to an overall annual energy savings of 46 percent. Applying solar to 95 percent of the roof area offsets total energy consumption by an addition 18 percent for a total energy savings of 64 percent compared to the benchmark. These results are shown graphically in Figure 90 and are listed in Table 75.

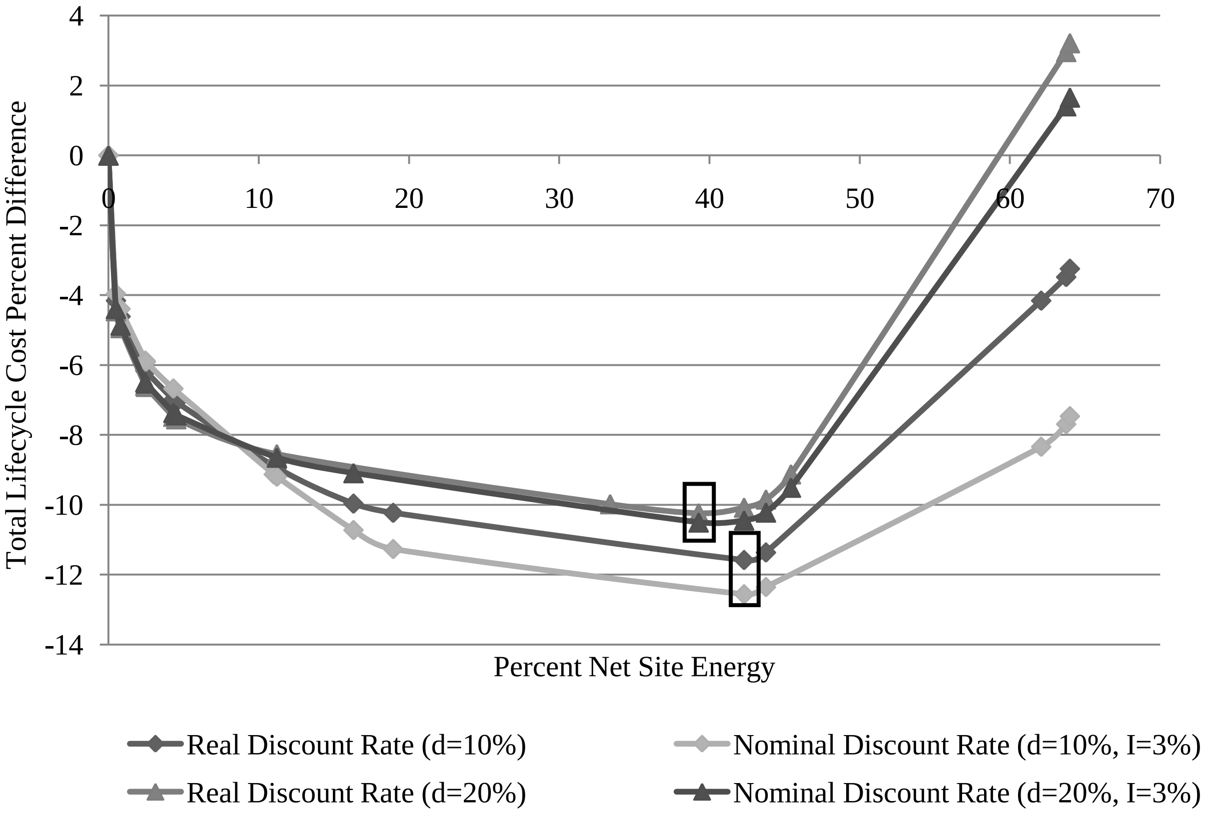

Figure 89: Optimization results - Harbin office.

Table 73: Energy and Lifecycle Cost Savings Results – Harbin Office

	Optimal		Max. Energy Savings	
	Percent Energy Savings	Percent TLCC Savings	Percent Energy Savings	Percent TLCC Savings
Nominal discount rate = 10% (Best case scenario)	42.0	12.6	64.4	7.50
Real discount rate = 10%	42.0	11.6	64.4	3.25
Nominal discount rate = 20%	39.0	10.6	64.4	-1.66
Real discount rate = 20% (Worst case scenario)	39.0	10.2	64.4	-3.20

Table 74: Optimal and Recommended Packages of EDMs – Harbin Office

Energy Design Measure	Benchmark	Optimal (d_R=20%)	Optimal (d_N=10%)	Maximum Energy Savings (Recommended Package)
Wall insulation - m^2K/W	R-0.75	R-4.0	R-4.0	R-6.2
Roof insulation - m^2K/W	R-2.67	R-4.3	R-4.3	R-8.6
LPD - W/m^2	11	11	7.7	7.7
EPD - W/m^2	20	16	16	16
Daylighting Controls	None	400 lux	400 lux	400 lux
Window U-Value - W/m^2K	3.05 (All facades)	1.82 (All facades)	1.82 (All facades)	1.82 (All facades)
Solar Heat Gain (SHGC)	0.70 (All facades)	0.46 (All facades)	0.46 (All facades)	0.46 (All facades)
Visual Transmittance	0.70 (All facades)	0.49 (All facades)	0.49 (All facades)	0.49 (All facades)
Window to wall ratios	North: 25% South: 25% East: 10% West: 20%	North: 20% South: 20% East: 10% West: 20%	North: 20% South: 20% East: 10% West: 20%	North: 20% South: 25% East: 10% West: 20%
Photovoltaics	None	None	None	95% Roof Area
Percent Annual Energy Savings	0%	39%	42%	46% 64% w/PV

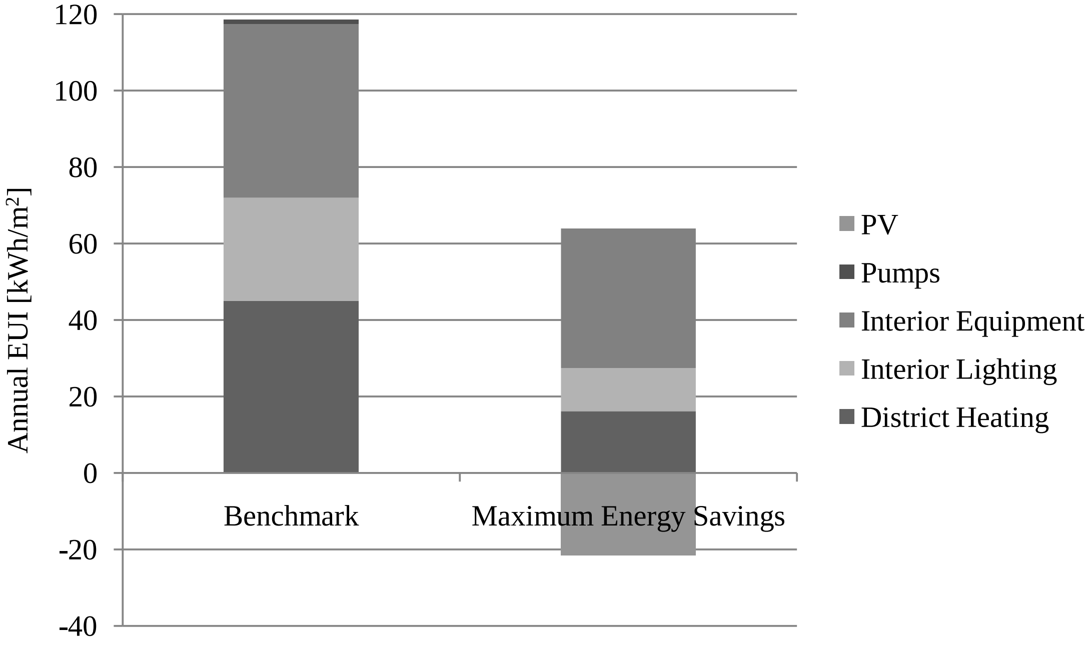

Figure 90: Energy savings potential - Harbin office.

Table 75: End Use Energy Savings - Harbin Office

District Heating	Interior Lighting	Interior Equipment	Pumps	Total
64.2%	58.0%	20.0%	93.8%	46% 64% with PV

5.4 Harbin Hotel Optimization

Much of the pre-optimization work has already been completed in Chapter 4, including the parametric and sensitivity analysis, so the process and results will not be presented again. Please refer to Chapter 4 for complete details on these processes. The following subsections will describe the methodologies for selecting the EDMs, the optimization results, and the resulting package of EDMs recommended for implementation.

5.4.1 Selected Energy Design Measures

After analyzing the results of the parametric and sensitivity analyses presented in Sections 4.2.1 and 4.2.3, EDMs are selected for the Harbin hotel model economic optimization. These EDMs are listed in Table 76. With these EDM options, there are 186,624 different combinations of possible building designs.

Table 76: Selected Energy Design Measures - Harbin Hotel

EDM Category	EDM Selection
EPD Reduction	20% reduction
LPD Reduction	30% reduction
Daylighting Controls	50 lux set point in stairwells
Window to Wall Ratios Reduction	35% of benchmark value on south façade
	35% of benchmark value on north façade
Window Types	U-value: 2.56 W/m^{2}K, SHGC:0.46, VT: 0.46
	U-value: 1.82 W/m^{2}K, SHGC: 0.64, VT:0.71
Exterior Wall Insulation	R-3.9 m^{2}K/W
	R-6.2 m^{2}K/W
Roof Insulation	R-4.3 m^{2}K/W
	R-8.8 m^{2}K/W
Photovoltaics	50% roof area PV
Chiller Efficiency Improvement	20% increase in COP

LPD and EPD reductions amounts are justified based on the same assumptions used for the Harbin office. The use of daylighting controls in the majority of the hotel are not applicable given the fact that guestrooms are typically unoccupied during daytime hours and that lighting controls should be controlled by the occupants. Therefore, daylighting controls have only been applied to the stairwells.

Controls may also be applicable for use in the shop and canteen but have not been applied to these space types. The benchmark window to wall ratios are relatively high (25 percent on the north and south facades) compared to the US reference building (average of 10.9 percent on all facades) (DOE, 2004). Therefore, a WWR reduction of 65 percent has been applied to both the north and south facades (i.e. the optimizer can select WWR reductions for the south facade, the north facade, or both). WWR reductions have not been applied to the east and west facades because of the window areas are significantly lower compared to the north and south facades. Exterior wall and roof insulation levels hare selected based on the result of the sensitivity analysis; energy savings is insignificant above insulation levels of R-6 and R-8 m^2K/W for the exterior walls and roof, respectively. Alternative window properties are also selected based on the results of the sensitivity analysis. Note that Opt-E-Plus has the option of applying different window types to different facades. This increases the number of iterations but provides the best opportunity for finding the most cost effective option. Finally, the option of PV is selected for 50 percent of the roof area. If selected, this system will share the roof space with the solar hot water system and other mechanical HVAC equipment including the cooling tower; therefore, only 50 percent of the roof area is allowed for PV application. This may be a conservative amount, but prevents over estimating the benefits of PV. Note that no EDM relating to outdoor air or infiltration reduction has been selected. The reason for this is twofold. First, Opt-E-Plus cannot facilitate the application of ERVs and or DCVs with the current HAVC equipment. Second, the benchmark infiltration rate is low to begin with and the OA rate is lower than the standard specified in the US benchmark model (DOE, 2004). It should be noted that the chiller efficiency improvement is applied after the optimization; comments are made following the optimization analysis.

5.4.2 Harbin Hotel Optimization Results

Figure 91 shows the optimization results of the hotel benchmark model in Harbin. Note that the solar hot water system has been removed from the model for the optimization due to the fact that Opt-E-Plus cannot facilitate this system. The energy savings associated with the existing solar hot water system are added on as additional savings after the optimization analysis. All energy efficient design options are economically feasible under all economic scenarios using the assumptions stated above (i.e. all cases result in lower lifecycle costs than the benchmark). This is due impart to the fact that the assumed material and labor costs are very inexpensive compared to energy costs. Recall that electricity and natural gas costs for China are comparable to those in the US while material costs are about 60 percent and installation costs are about seven percent those of the US. It is recommended that these assumptions be revisited in the future.

The optimization path is similar for all economic cases until divergence begins around eight percent energy savings. This can be seen in the sequence of building design options summarized in Table 98 through Table 101 in

Appendix B6: Selected EDMs for the Economic Optimization of the Harbin . After this point, the order in which EDMs are selected remains the same for the d-20 cases but differs for the d-10 cases. The d_R-10 case is similar to the d-20 cases while the d_N-10 case shows significant differences. Surprisingly, the first EDMs selected in all cases are associated with window options, including alternative properties and WWRs, followed by R-3.9 exterior wall and R-4.3 roof insulation. In the cases of d_R-20, d_N-20, and d_R-10, options for reducing electrical load densities and implementing daylighting controls are selected after improvements to the envelope have been made. Then, addition exterior wall and roof insulation (R-6.2 and R-8.6, respectively) is added followed by the application of PV. The last EDM applied in the d-20 cases increases the south WWR to the benchmark value after previously reducing it by 35 percent. Additional wall insulation is selected after the application of PV for the case of d_R-10. For the case of d_N-10, PV is applied early in the optimization, creating a unique path towards maximum energy savings. Here, PV is selected before the options to reduce EPD and LPD and implement daylighting controls. It is speculated that the existing EPD and LPD levels help meet the heating load which keeps heating energy lower than it would otherwise be if these EDMs were implemented. Less insulation is also selected as a result of higher internal heat gains. The resulting energy offset from PV is smaller in this case than the other economic scenarios due to the fact that the overall building energy consumption is greater at the time PV is applied; therefore the fractional offset is smaller. The final important takeaway is the fact that the package of EDMs resulting in maximum energy savings of 39 percent is the same regardless of the value or type of discount rate used in the optimization although the path is different depending on the value and type of discount rate applied.

The optimal package of EDMs for each case are listed in Table 78 in addition to the package resulting in maximum energy saving. Table 77 lists the energy savings and total lifecycle cost savings corresponding to the optimal and maximum energy savings points for each economic scenario. The optimal points for all cases show little difference in energy savings and lifecycle cost savings. The potential energy savings varies by only 0.4 percent between the optimal points of case d_R-20 and d_R-10 while the lifecycle cost percent savings varies by one percent. The optimal points for d_R-10 and d_N-10 vary by 2.4 percent for energy savings and 1.2 percent for lifecycle cost savings.

As mentioned before, the maximum energy savings achieved for all cases is the same but the resulting lifecycle costs are significantly different. The percent difference in lifecycle cost savings associated with the maximum energy savings point is 9.33 percent in the case of d-10 compared to 1.83 percent in the case of d-20. The larger percent difference in the d-10 case is due to the fact that a three percent inflation rate is a greater percentage of 10 percent than it is of 20 percent and therefore has a greater effect on the discount rate (see equations 3 and 4). This was also seen previously with the case of the Harbin office.

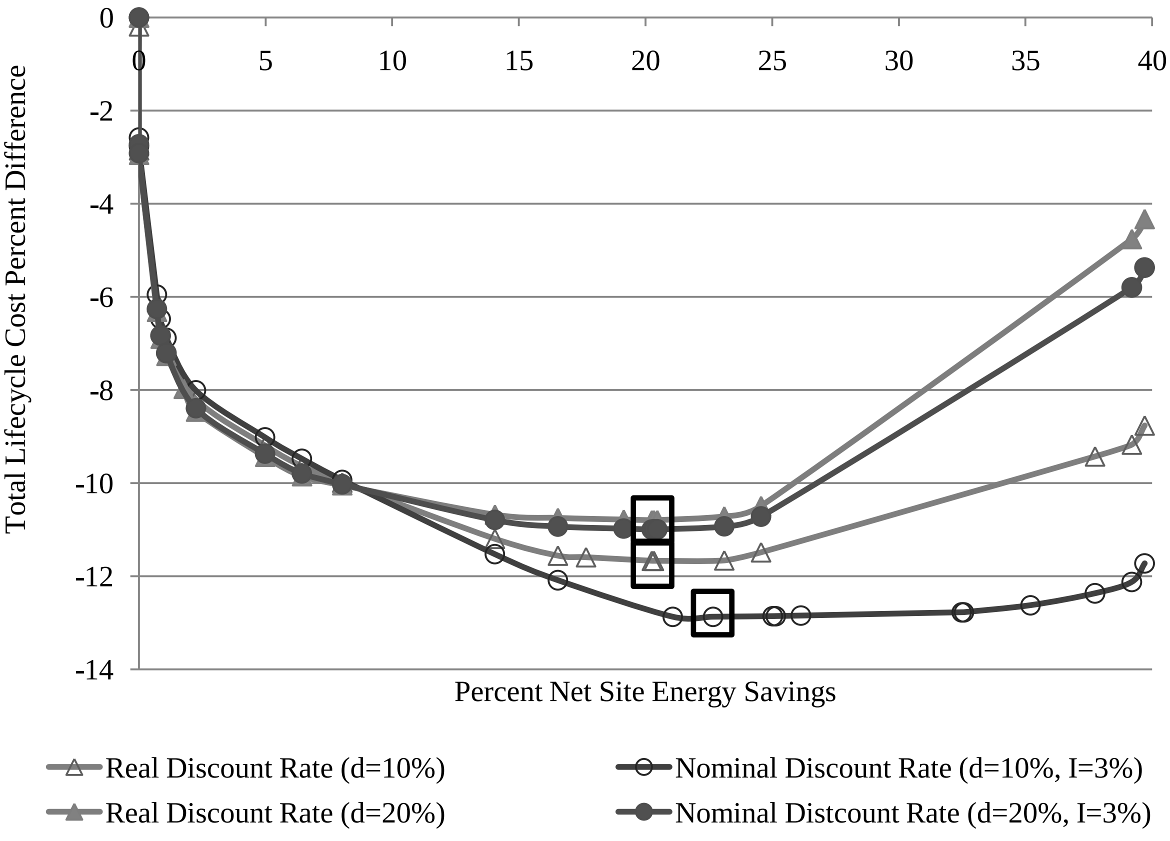

Figure 91: Optimization results - Harbin hotel.

Table 77: Energy and Lifecycle Cost Savings Results - Harbin Hotel

	Optimal		Max. Energy Savings	
	Energy Savings	TLCC Savings	Energy Savings	TLCC Savings
Nominal discount rate = 10% Best case scenario	22.7%	12.8%	39.7%	11.7%
Real discount rate = 10%	20.3%	11.6%	39.7%	8.76%
Nominal discount rate = 20%	20.4%	11.0%	39.7%	5.37%
Real discount rate = 20% Worst case scenario	20.3%	10.7%	39.7%	4.32%

Table 78: Optimal and Recommended Packages of EDMs - Harbin Hotel

Energy Design Measure	Benchmark	Optimal (d_R=10%)	Optimal (d_N=10%)	Optimal (d_R=20%)	Optimal (d_N=20%)	Max Energy Savings Recommended Package
Wall insulation – m^2K/W	R-2.1	R-3.9	R-3.9	R-3.9	R-3.9	R-6.2
Roof insulation - m^2K/W	R-2.8	R-4.3	R-4.3	R-4.3	R-4.3	R-8.6
LPD - W/m^2 (Weighted Average)	12.25	8.6	8.6	8.6	8.6	8.6
EPD - W/m^2 (Weighted Average)	11.60	9.3	9.3	9.3	9.3	9.3
Daylighting Controls	None	50 lux	None	50 lux	50 lux	50 lux
Window U-Value - W/m^2K	2.67 (All facades)	N/S/E: 1.82 West: 2.56	2.56 (All facades)	N/S:1.82 E/W: 2.56	N/S: 1.82 E/W: 2.56	1.82 (All facades)
Solar Heat Gain Coeff.	0.70	N/S/E: 0.64 W: 0.46	N/S/E/W: 0.46	N/S/E:0.64 W: 0.46	N/S: 0.64 E/W: 0.46	0.64 (All facades)
Visual Transmittance	0.78	N/S/E: 0.71 W: 0.46	N/S/E/W: 0.46	N/S:0.71 E/W: 0.46	N/S/E: 0.71 West: 0.46	0.71 (All facades)
Window to wall ratios	N: 20% S: 25% E/W: 10%	N/S: 13% E/W: 10%	N/S: 13% E/W: 10%	N/S: 13% E/W: 10%	N/S: 13% E/W: 10%	N: 13% S: 25% E/W: 10%
Chiller Nominal Efficiency [COP]	4.7	-	-	-	-	5.64
Photovoltaics	None	None	None	None	None	50% Roof area
Percent Annual Site Energy Savings	0%	20.3%	22.7%	20.3%	20.3%	26.0% (40.8% w/PV)

In addition to the energy savings identified in the optimization, the chiller efficiency is increase by 20 percent in the building design package leading to maximum energy savings to identify the potential for further energy reduction. The results show that increasing the chiller nominal capacity from 4.7 W/W to 5.6 W/W leads to an additional energy savings of approximately one percent. The total lifecycle cost savings under this new package for the d_N-10 case is 7.9 percent, which is the best case scenario. It is actually more economically feasible to apply additional PV to the roof than to increase the chiller COP under the pricing options assumed for this analysis. Adding this EDM to the maximum energy savings point in case d_R-20 result in the same energy savings but pushes the lifecycle cost savings slightly above the cost neutral point The results show that under this economic scenario, the lifecycle cost is 0.38 percent greater than the benchmark. This is close enough to the cost neutral point that an increase in chiller COP could be recommended under all economic scenarios.

A simple analysis is performed to determine the amount of roof area necessary to bring the lifecycle to the cost neutral point for the cases of the d_R-20, d_N-20, and d_R-10 before applying the chiller COP ECM. This is done by projecting the linear solar savings out to the cost neutral point. The d_R-20 case shows that 91 percent roof area PV is required to reach the cost neutral point. This corresponds to a total energy savings of 51 percent compared to the benchmark. As it turns out, there is not enough roof area to reach the cost neutral point for the cases of d_R-10 and d_N-20. For the case of d_R-10, PV area equivalent to 270 percent of the roof area could be applied to reach the cost neutral point. Similarly, PV area equivalent to 108 percent of the roof area could be applied to reach the cost neutral point. The maximum amount of PV (assuming the maximum available roof area is 90 percent of the total) results in a total building energy savings of about 48 percent for the case of d_R-10 and 51 percent for the case of d_N-20. This amount of PV is economically feasible under the associated cost assumptions.

In conclusion, it is recommended that the building design leading to the maximum potential energy savings described in Table 78 be implemented as improvements to the existing building codes for hotel buildings in the severe cold climate region. This recommendation is made based on the fact that this building design is economically feasible (or very close to cost neutral) under all economic scenarios. Total building energy savings equates to 40.8 percent compared to the benchmark model. Under the best case scenario (d_N-10), the corresponding lifecycle cost savings equate to 7.3 percent. Under the worst case scenario (d_R-20), this building design leads to approximately a neutral lifecycle cost. The total energy savings and lifecycle cost savings are shown in Table 80 as a percentage of the benchmark. The end use energy breakdown and the corresponding energy savings are shown in Figure 92 and Table 79 respectively.

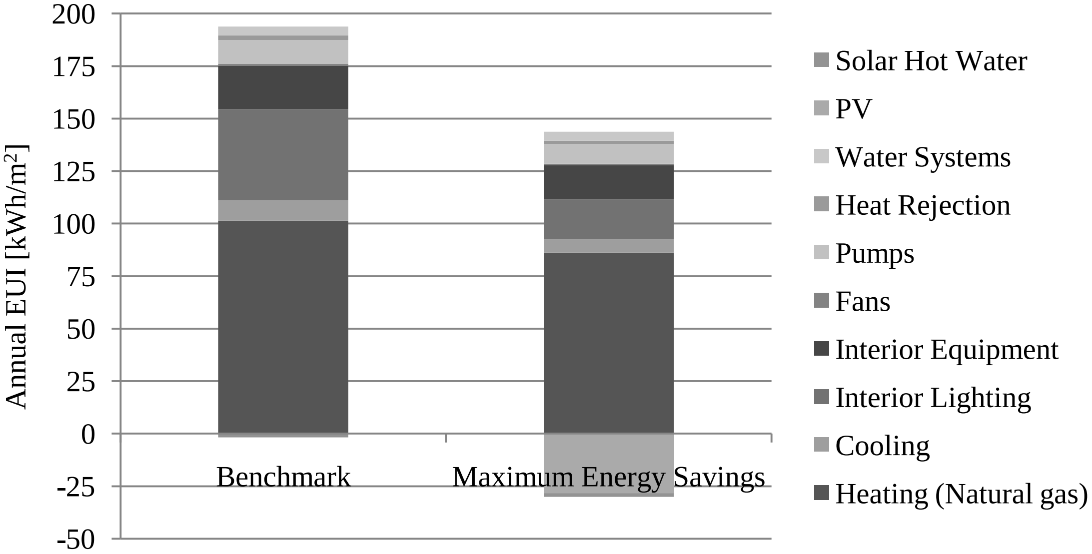

Figure 92: Energy savings potential - Harbin hotel.

Table 79: End Use Energy Savings - Harbin Hotel

Heating (Nat. gas)	Cooling	Interior Lighting	Interior Equipment	Fans	Pumps	Heat Rejection	Total Energy Savings
15.1%	34.5%	56.3%	20.0%	20.0%	18.7%	21.9%	40.8%

Table 80: Final Energy and Lifecycle Cost Percent Savings - Harbin Hotel

Economic Scenario	Total Energy Savings	Lifecycle Cost Savings

d_N-10 (Best case scenario)	40.8%	7.3%
d_R-20 (worst case scenario)	40.8%	~ 0%

5.5 Discussion

The economic analysis performed in this chapter demonstrates how a building energy optimization tool can be used to estimate the lifecycle cost savings associated with a package of energy design measures. It differs from the previous method of analysis carried out in Chapters 3 and 4 in three ways. First, the optimization takes into account economic parameter associated with the construction and operation and maintenance over the lifecycle of the building. Second, the sensitivity analysis is performed before the optimization to select the applicable EDMs rather than as a final analysis process. Lastly, the results provide a number of whole building design options with corresponding estimates of annual energy savings. The pros and cons of each method are summarized in the table below.

Table 81: Pros and Cons of Methodologies

	Method 1: EDM Sensitivity Analysis	**Method 2**: Economic Optimization
Pros	- Provides clear breakdown of savings potential of each individual EDM - Shows diminishing returns on energy savings for each EDM. - Shows which parameters of the existing building are weakest and could benefit from higher efficiency standards	- Provides an estimate of lifecycle cost savings - Provides an estimate of whole building energy savings with incorporation of a package of EDMs in addition to - Provides numerous design options
Cons	- Does not compare the performance of the existing building to estimates of whole-building energy savings associated with packaged EDMs options - Does not provide insight into the economic impact of energy efficiency improvements.	- Lifecycle cost savings are estimated based on many economic assumptions - Results focus on a single package of EDMs

Method 1 is a better option for identifying which building parameters of the existing building could benefit most from improvements. However, method 2 provides insight on the potential economic impacts of energy efficiency design alternatives. Policy makers may prefer method 1 because the results identify which parameters of the existing building could benefit most from energy efficiency improvements. The results derived from the sensitivity analysis and presented in the recommendation tables of Chapters 3 and

4 list these parameters according to their energy saving potential. On the other hand, building owners may be most interested in the results derived in method 2 because the results provide an estimate of the lifecycle cost of different energy efficient designs. However, as mentioned in Chapter 1, policy and market drivers are often seen as being equally important for increasing the implementation of energy efficient buildings.

As described throughout Chapter 5, assumptions on material, operation and maintenance, and benchmark building capita cost as well as economic discount types and values have been made in the economic optimizations demonstrated here. It is recommended that these values be verified before legitimately interpreting the resulting lifecycle cost savings. The economic sensitivity analysis has been carried out to identify a range of possible lifecycle cost savings; other sensitivity analyses should also be performed to determine the effects of variable utility costs, material and operation costs, and capital costs. Increasing material and capital costs and/or decreasing utility costs would shift the optimization curve upward resulting in less lifecycle cost savings.

Chapter 6: Conclusion and Discussion

6.1 Conclusion

At this point in history, China is experiencing a rapid rate of economic growth and as a result must deal with the effects of increasing amounts of energy consumption and the resulting impacts on the environment. Energy consumption in public buildings is just one of the many sectors guilty of unprecedented amounts of energy consumption. It was estimated by Jiang and Yang in 2006 that China's total national building energy consumption totaled 16 billion standard tons of coal, equating to 20.5 percent of the total end use energy consumption. What's more, public building energy consumption is expected to rise to 35 percent of the nation's total by 2020 (Zhou, et al., 2007). China accounts for nearly one-half of the world's new building construction and in 2004, it was estimated that large-scale public buildings in China (those with over 20,000m^2 of floor area) totaled over a half billion square meters (Cai, et al., 2009). There is obviously a dire need to address this urgent issue by enforcing and implementing energy efficient building design. It is also important to consider the economic impacts of such design as most design decisions are influenced by markets for new construction. The demand for efficient buildings in China is nearly nonexistent as these options are thought to be expensive and not worth the investment. However, it has been shown in this research that, under the given assumptions, efficient design options are economically feasible and without a doubt a good investment.

A lack of market drivers is only one of many obstacles stalling the enforcement and implementation of the current national building energy code. Other factors include the lack of supporting resources such as building materials and design tools, poor training and education, and a lack of political will. The Chinese government has recently become more concerned over the rapid growth in energy demand in the building sector and is devoting more efforts to addressing this urgent issue. One way in which the research community is contributing to these efforts is with the recent development of public building benchmark models for offices and hotels. These benchmark models can be used as common reference points for alternative design strategies by architects, engineers, and researchers alike.

This research focuses on the benchmark models for two of the five climate regions in China, the Hot Summer Warm Winter region in the south (represented by Guangzhou) and the Severe Cold region in the north (represented by Harbin). A detailed design and energy performance comparison has been carried out to determine the design and performance differences between the Chinese benchmarks and US reference building models in similar climate regions.

A number of versions of the Chinese models have been created to determine if the differences in energy consumption between the Chinese and US buildings is due to building design, operation, or occupant use. To do this, a number of Chinese and US building models have been simulated with loads, set points, schedules, and in some cases window properties of the opposite building. Three important points can be concluded about building design differences. First, the Chinese benchmark building has lower levels of insulation in the roof and exterior walls, higher solar heat gain coefficients, and lower U-values compared to the US reference building models. Second, the HVAC systems differ between all models and temperature set points are less extreme in China compared to the US. The US HVAC systems consume more energy to meet the thermal set points than the Chinese HVAC systems. Finally, there are also differences in electrical load and operation schedules. It is most often the case that the US reference building models consume significantly more energy on a per-occupant basis due to the fact that these building models assume a much smaller occupancy density compared to the Chinese models. The energy performance differences are summarized in Figure 93 through Figure 96. These figures show what would happen to total building site energy intensity and occupant energy intensity if the Chinese were to adopt the US buildings geometry, construction, and HVAC systems and operate them according to existing Chinese practice. The effects of incorporating the US building loads are also shown.

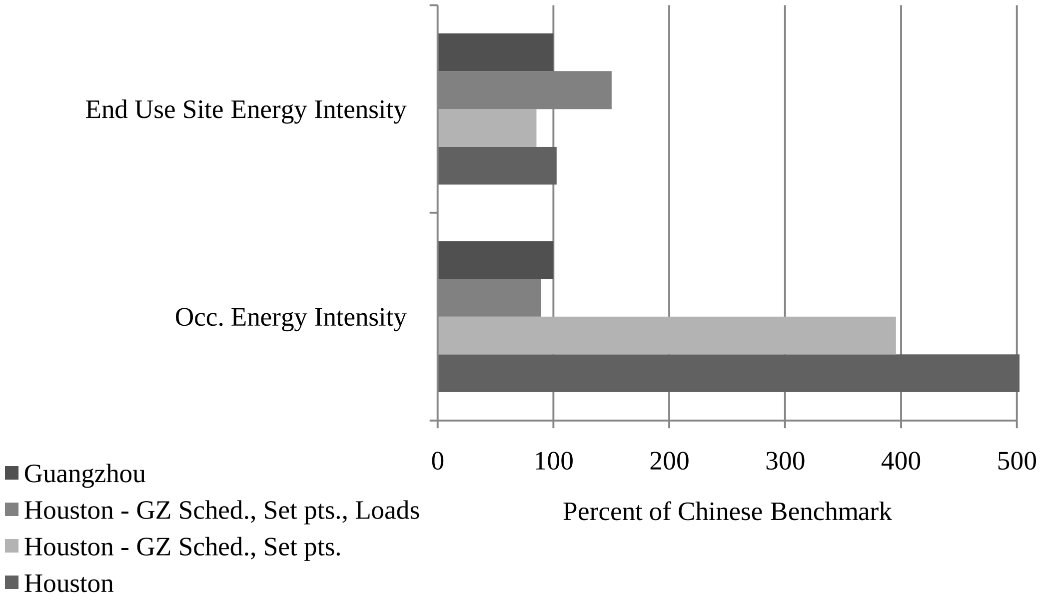

Figure 93: Office energy performance comparison - Guangzhou climate region.

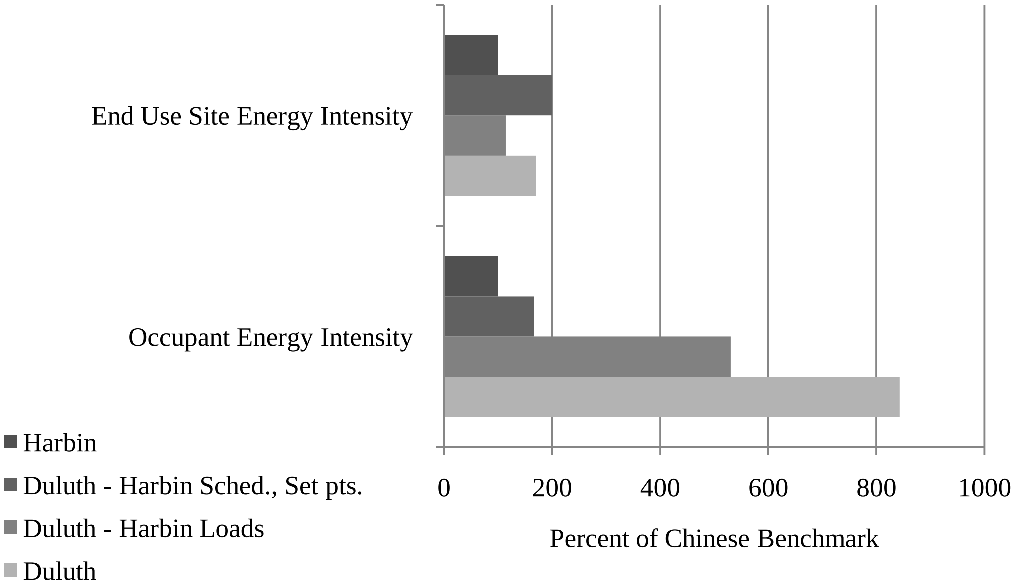

Figure 94: Office energy performance comparison - Harbin climate region.

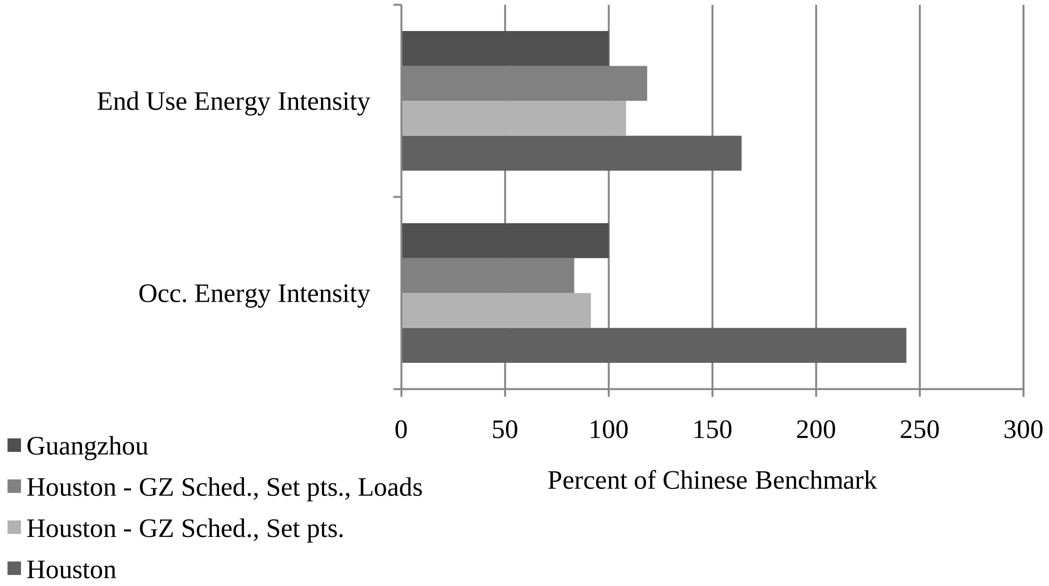

Figure 95: Hotel energy performance comparison - Guangzhou climate region.

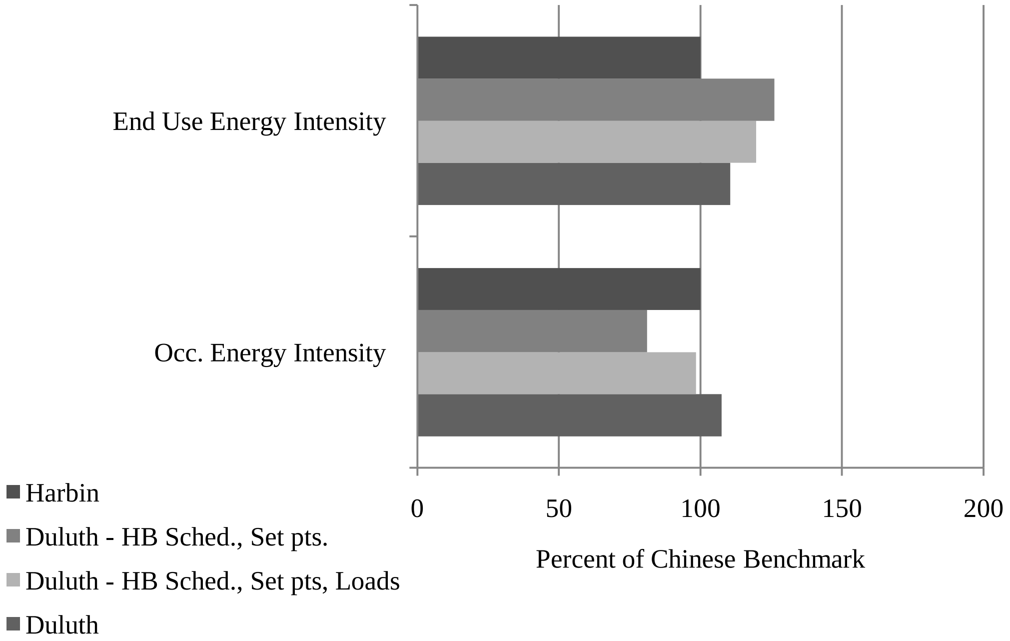

Figure 96: Hotel energy performance comparison - Harbin climate region.

The main focus of this research is to identify the potential energy savings associated with energy design measures (EDMs) with the use of the building energy optimization tool, Opt-E-Plus and to provide recommendations for improvements to the existing building code standards of China. The recommendations are based primarily on the results of the sensitivity analysis for each building model. These results provide information on the range of potential energy savings associated with each EDM as well as the relationship between energy savings and various values of each EDM. For example, energy savings are shown to be linear with varying degrees of lighting power density reductions and parabolic with vary degrees of wall and roof insulation. In addition to this, an economic optimization has been carried out for the Severe Cold climate region of Harbin to demonstrate an economic optimization with the use of Opt-E-Plus and to estimate the potential lifecycle cost savings associated with a package of EDMs. The results of this economic analysis are significant because they suggests that energy efficient building designs can be economically feasible and that Chain should work to create a larger market for efficient buildings. An economic sensitivity analysis has also been performed to account for the uncertainty in the type and value of the discount rate used in China. A package of EDMs has also been established for the Guangzhou benchmark models; however, these results are not weighted by lifecycle cost savings.

Table 82 through Table 84 provide a range of savings associated with each applicable EDM for all building models. The tables list the EDMs in order of priority and thus provide recommendations for improved building code standards. Table **86** through Table **89** list the recommended packages of EDMs for each building model along with an estimation of the potential energy savings compared to the existing benchmark building.

Table 82: Important Energy Design Measure Ranking – Guangzhou Office

Energy Design Option	Energy Saving Potential	Ranking Definitions
Daylighting controls	High	7% < Energy Savings < 9%
Lighting power density reduction	Medium	1% < Energy Savings < 9%
Equipment power density reduction	Medium	
Window to wall ratio reduction	Low	0.2% < Energy Savings < 3%
South façade shading devices	Low	
Wall insulation	Very Low	Energy Savings < 1%
Roof insulation	Very Low	
Skylights	None	None

Table 83: Important Energy Design Measure Ranking – Guangzhou Hotel

Energy Design Option	Energy Saving Potential	Ranking Definitions
Lighting power density reduction	High	1% < Energy Savings < 13%
Window to wall ratio reduction	High	
Alternative window types	Medium	0.5% < Energy Savings < 5%
Equipment power density reduction	Medium	
South façade projection factor	Low	0.2% < Energy Savings < 1.2%
Roof insulation	Low	
Wall insulation	Very Low	Energy Savings < 1%

Table 84: Important Energy Design Measure Ranking – Harbin Office

Energy Design Option	Energy Saving Potential	Raking Definitions
Exterior wall insulation	High	3% < Energy Savings < 22%
Reduced infiltration rate	High	
Lighting power density reduction	Medium	2% < Energy Savings < 7.5%
Daylighting Controls	Medium	
Roof insulation	Medium	
North façade window type	Medium	
South façade WWR	Low	0.1 < Energy Savings < 3.7%
South façade window type	Low	
East/West façade window type	Low	
North façade WWR	Low	
East/West façade WWR	Very Low	Energy Savings <= 1%

Table 85: Important Energy Design Measure Ranking – Harbin Hotel

Energy Design Option	Energy Saving Potential	Ranking Definitions
Reduced infiltration rate	High	Energy Savings > 10%
Outdoor air flow rate	High	
Exterior wall insulation	Medium	0.5% < Energy Savings < 6%
Roof insulation	Medium	
Lighting power density reduction	Medium	
North façade window type	Low	0.3% < Energy Savings < 2.5%
North façade WWR	Low	
South façade WWR	Very Low	Energy Savings > 4%
South façade window type	Very Low	
East/West façade window type	Very Low	
East/West façade WWR	Very Low	
Daylighting controls	Very Low	

Table 86: Guangzhou Office Packaged EDM Recommendations

Energy Design Measure	Guangzhou Office Benchmark	Recommendations
Wall insulation – m^2K/W	1.11	3.2
Roof insulation - m^2K/W	1.39	4.2
LPD - W/m^2	11	7.7
EPD - W/m^2	20	16
Daylighting Controls	None	400 lux
Window U-Value - W/m^2K	North: 5.06 South: 4.74 East/West: 5.77	3.86 (All facades)
Solar Heat Gain (SHGC)	North: 0.476 South: 0.425 East/West: 0.718	0.36 (All facades)
Visual Transmittance	North: 0.400 South: 0.400 East/West: 0.610	0.46 (All facades)
Window to wall ratios	North: 28% South: 33% East/West: 10%	No Change
Chiller Nominal Efficiency [W/W]	4.7	5.6
Photovoltaics	None	85% Roof area
Percent Annual Energy Savings (with PV)	0%	28.6% (38.0%)

Table 87: Guangzhou Hotel Packaged EDM Recommendations

Energy Design Measure	Guangzhou Hotel Benchmark	Recommendations
Wall insulation – m^2K/W	1.17	R-6.2
Roof insulation - m^2K/W	1.23	R-6.6
LPD - W/m^2 Weighted average	12.3	8.6
EPD - W/m^2 Weighted average	4.9	3.5
Window U-Value - W/m^2K	N/S/W: 5.36 East: 5.89	1.86 (All facades)
Solar Heat Gain (SHGC)	North: 0.448 South: 0.417 East: 0.610 West: 0.43	0.337 (All facades)
Visual Transmittance	North: 0.680 South: 0.410 East: 0.610 West: 0.230	0.328 (All facades)
Window to wall ratios	North: 65% South: 42% East: 10% West: 51%	North: 6.5% South: 4.0% East: 1.0% West: 5.1%
Photovoltaics	None	85% Roof area
Percent Annual Energy Savings (with PV)	0%	33.9% (38.6%)

Table 88: Harbin Office Packaged EDM Recommendations

Energy Design Measure	Harbin Office Benchmark	Recommendations
Wall insulation - m^2K/W	R-0.75	R-6.2
Roof insulation - m^2K/W	R-2.67	R-8.6
LPD - W/m^2	11	7.7
EPD - W/m^2	20	16
Daylighting Controls	None	400 lux
Window U-Value - W/m^2K	3.05 (All facades)	1.82 (All facades)
Solar Heat Gain (SHGC)	0.70 (All facades)	0.46 (All facades)
Visual Transmittance	0.70 (All facades)	0.49 (All facades)
Window to wall ratios	North: 25% South: 25% East: 10% West: 20%	North: 20% South: 25% East: 10% West: 20%
Photovoltaics	None	95% Roof Area
Percent Annual Energy Savings (with PV)	0%	46.0% (64.0%)

Table 89: Harbin Hotel Packaged EDM Recommendations

Energy Design Measure	Harbin Hotel Benchmark	Recommendations
Wall insulation – m^2K/W	R-2.1	R-6.2
Roof insulation - m^2K/W	R-2.8	R-8.6
LPD - W/m^2 (Weighted Average)	12.25	8.6
EPD - W/m^2 (Weighted Average)	11.60	9.3
Daylighting Controls	None	50 lux
Window U-Value - W/m^2K	2.67 (All facades)	1.82 (All facades)
Solar Heat Gain (SHGC/VT)	0.70 (All facades)	0.64 (All facades)
Visual Transmittance	0.78 (All facades)	0.71 (All facades)
Window to wall ratios	N: 20% S: 25% E/W: 10% West: 10%	N: 13% S: 25% E/W: 10%
Chiller Nominal Efficiency [COP]	4.7	5.64
Photovoltaics	None	50% Roof area
Percent Annual Energy Savings (with PV)	0%	26.0% (40.8%)

6.2 Discussion

It is suggested that a few of the questionable input parameters in the Chinese model be reconsidered. These include office occupancy density, office equipment and lighting power densities during unoccupied hours, hotel equipment power densities schedules, infiltration rates, fan efficiencies and pressure drops, and chiller outlet temperature reference nodes. Verifying these inputs would improve the validity of the models while provided a better estimation of their energy consumption, energy saving potential, and lifecycle cost saving potential.

Recommendations for long-term research regarding the development of the Chinese benchmark buildings and the implementation of improved building codes include the following:

- Verify questionable input parameters for the benchmark building models. Attention should be given to the parameters listed below.
  - Office
    - Occupancy density
    - Fan pressure drop
    - Equipment and lighting schedules
    - Infiltration rates
  - Hotel
    - Lighting and equipment schedules
    - Fan pressure drop
    - Infiltration rates
- Perform a detailed HVAC analysis to identify if alternative mechanical systems (including the use of energy recovery ventilators) provide energy savings and improved indoor air quality. This should include a sensitivity analysis on OA rates and a comparison to ASHRAE Standards as well as options for natural ventilation in appropriate climate zones.

- Perform a detailed daylighting analysis to identify the best strategies for achieving maximum energy savings from daylighting applications. This study should provide recommendations for window properties and sizes, daylighting control strategies, and shading devices.
- Seek input from the Chinese Department of Science and Technology so to assure that feasible building materials and design strategies are considered.
- Develop a national database of construction materials and costs similar to what is used in the United Sates so energy efficient design practice can be streamlined. This would be a very useful tool for designers and researchers alike.
- Verify the appropriate type and value of the discount rate as well appropriate costs for building materials, construction, and operation and maintenance to estimate lifecycle cost savings amounts with a higher degree of accuracy.
- Consider the economic impact of rising energy costs and negative externalities. Fossil fuel based energy, which makes up nearly 90 percent of China's public building energy source , will not always be as affordable as it is today due to its limited supply and detrimental environmental impacts (Zhou, et al., 2007). A carbon emission tax has been considered by national Chinese authorities. Deputy Director-General of the Energy Department of the National Development and Reform Commission, Wu Yin, stated that a carbon tax, "will [help create an] incentive mechanism for resource conservation, efficiency improvement, environmental protection, and development promotion (Cooper, 2004)." A global carbon tax may be closer to reality than expected.
- Consider the impact of urban environments on energy consumption; that is, include surrounding buildings in the models to simulation the impact of shading and heat island effects.

6.3 Closing Remarks

This research, like any research, is a stepping stone on the path towards improved public building standards in China. The hope is that researchers can use the information provided recommendations for improved building standards in China, a reference of current building codes, a reference for optimization techniques, and a launch pad for new ideas for future research.

As Albert Einstein once said, “The world will not evolve past its current state of crisis by using the same thinking that created the situation.” Tackling the challenges of rising energy consumption in buildings all over the world will take ingenuity, creativity, and collaboration. We must all join forces and work together as one human race to assure our impact on the planet is minimized and our design strategies and growth tactics are sustainable for centuries to come.

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Appendix Reference

Appendix A: Schedules

- Appendix A1: Office Schedules
- Appendix A2: Hotel Schedules

Appendix B: Selected Energy Design Measures from Opt-E-Plus

- Appendix B1: Selected EDMs for the Guangzhou Office Optimization
- Appendix B2: Selected EDMs for the Guangzhou Hotel Optimization
- Appendix B3: Selected EDMs for Harbin Office Optimization
- Appendix B3: Selected EDMs for the Economic Optimization of the Harbin Hotel
- Appendix B4: Selected EDMs for Harbin Office Optimization
- Appendix B5: Selected EDMs for the Economic Optimization of the Harbin Office

Appendix C: Monthly peak Electricity Demand tables – China US Comparison

Appendix A: Schedules

Appendix A1: Office Schedules

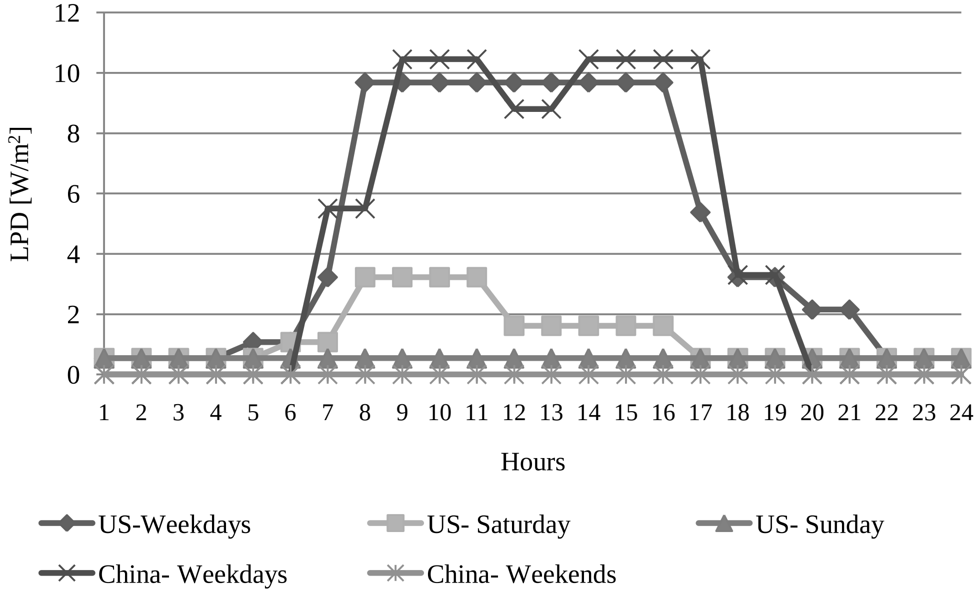


Figure 97: Office lighting power density (LPD) schedule

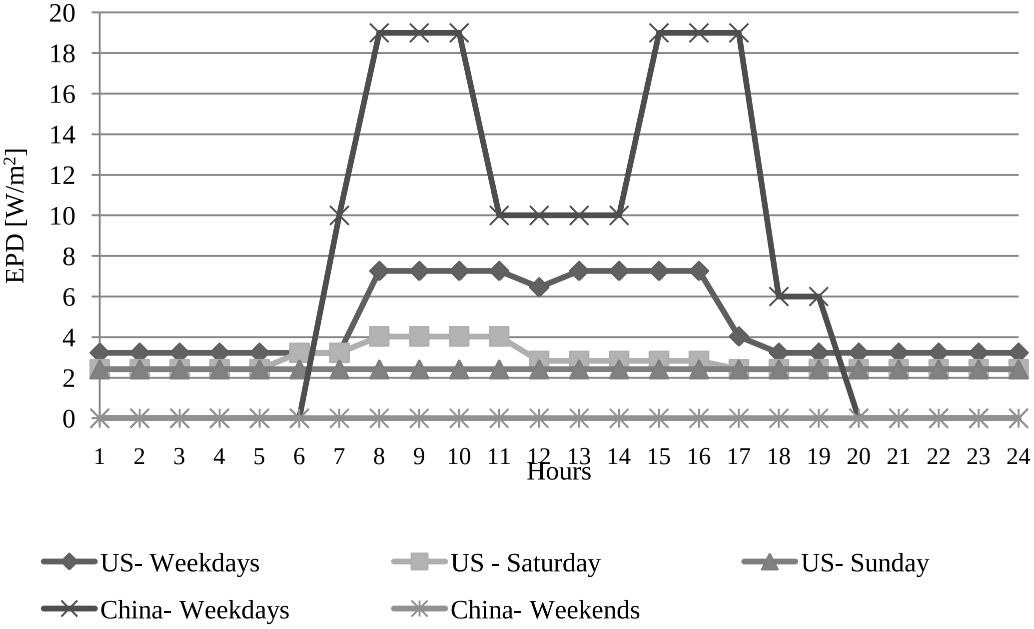


Figure 98: Office equipment power density (EPD) schedule

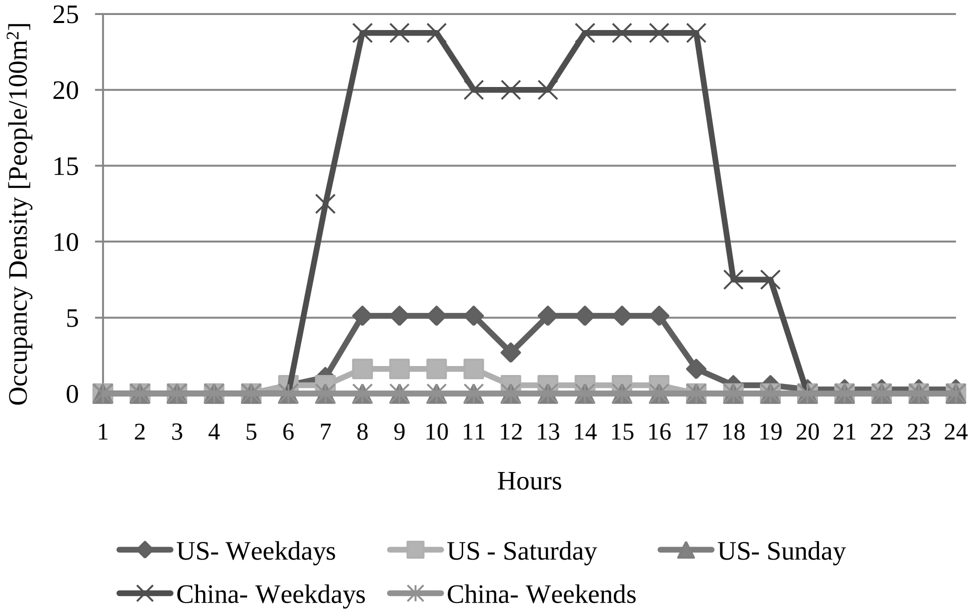


Figure 99: Office occupancy density schedule

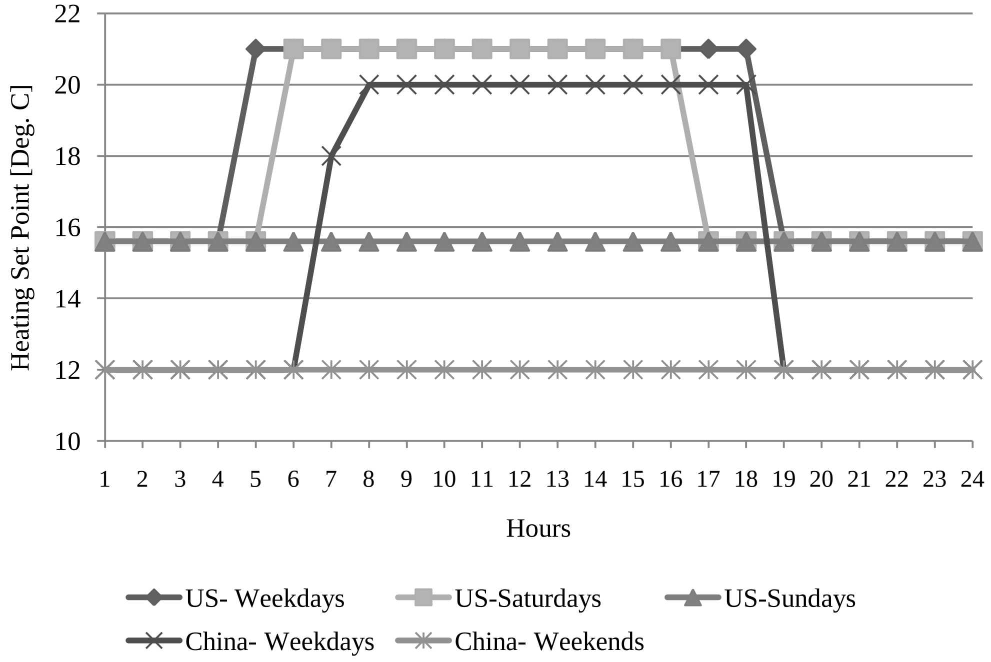


Figure 100: Office heating thermostat set point - Guangzhou climate region

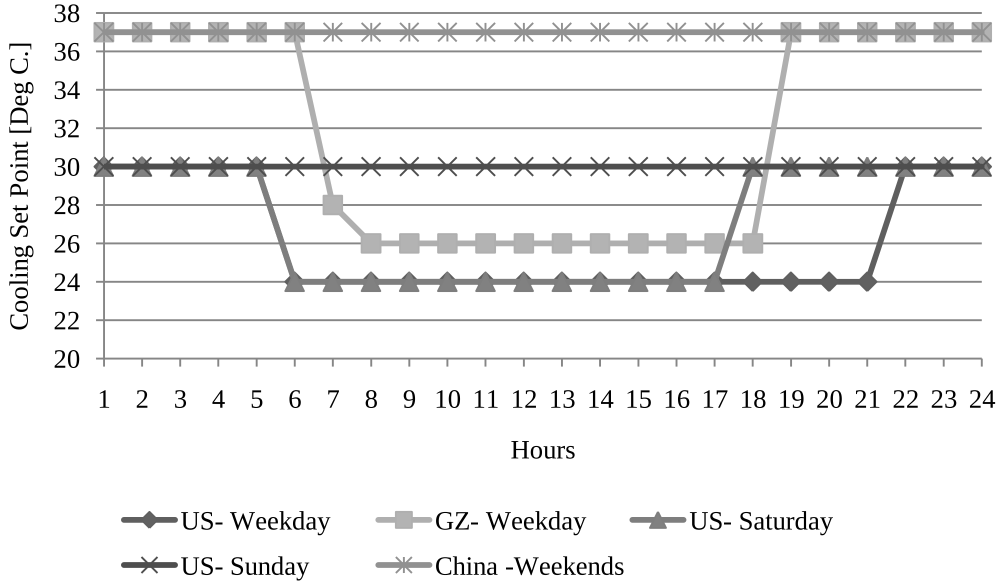


Figure 101: Office cooling thermostat set point - Guangzhou climate region

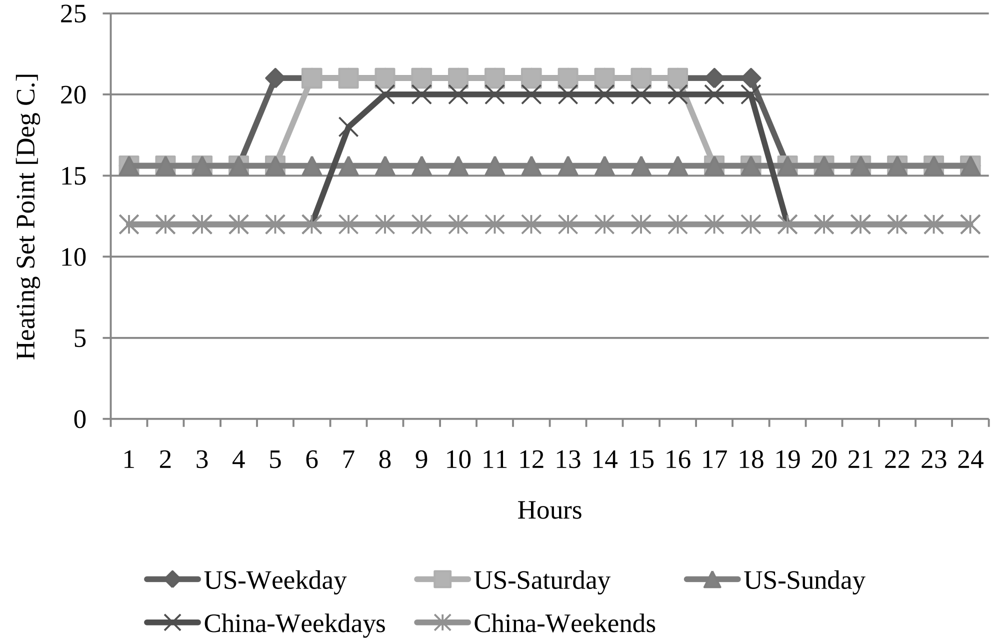


Figure 102: Office heating thermostat set point - Harbin climate region

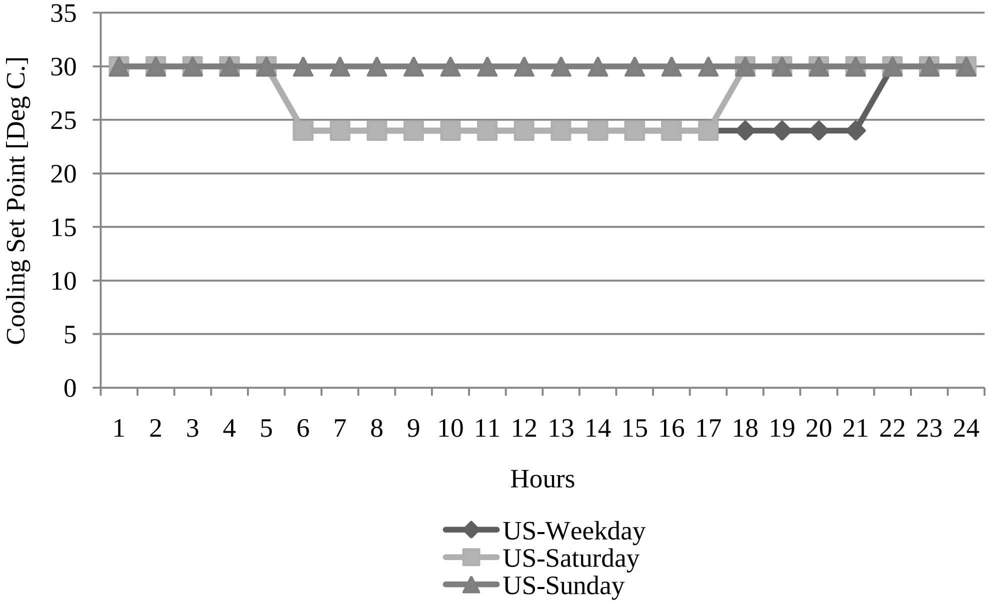


Figure 103: Office cooling thermostat set point - Harbin office

Appendix A2: Hotel Schedules

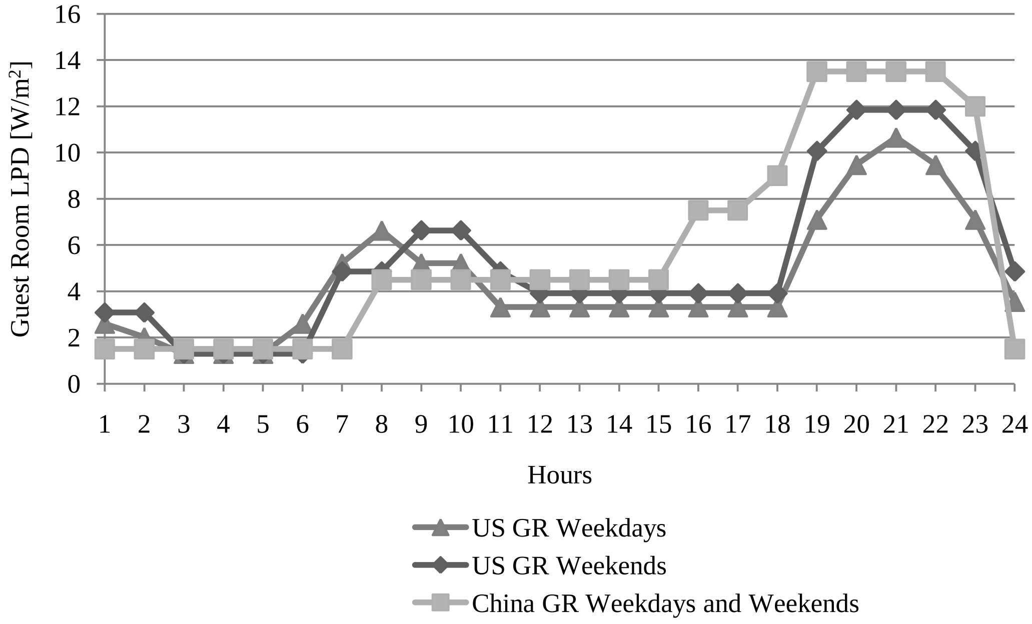


Figure 104: Hotel guest room lighting power density (LPD) schedule

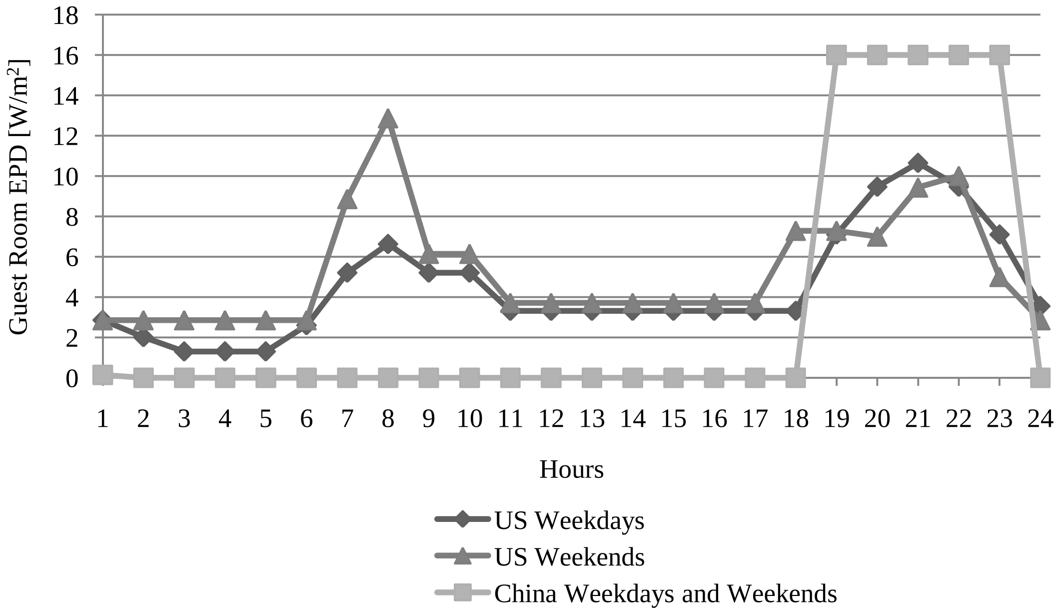


Figure 105: Hotel guest room equipment power density (EPD) schedule

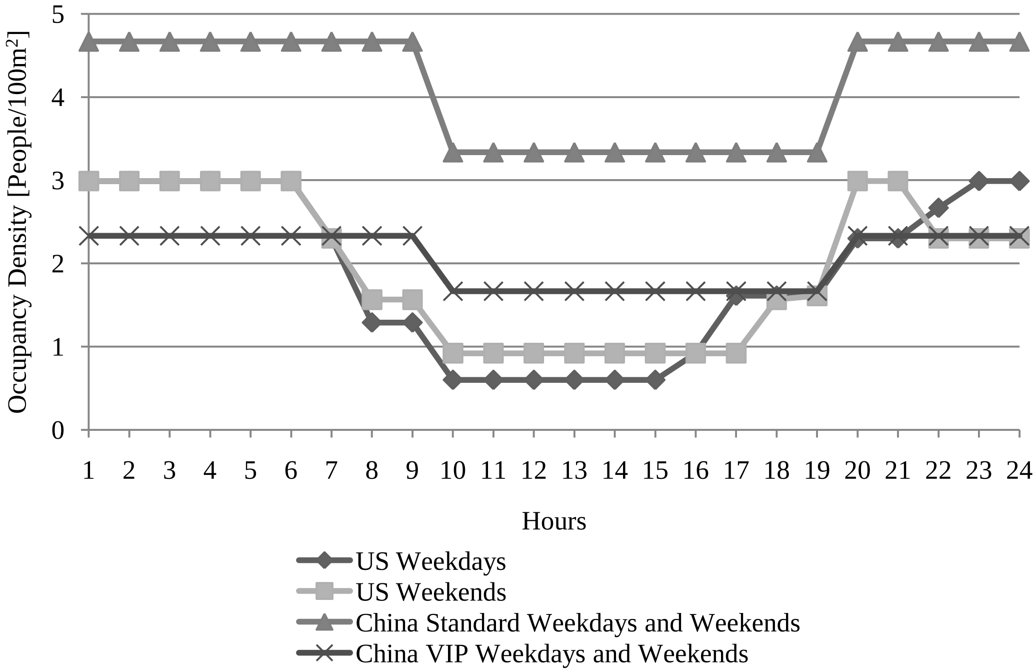


Figure 106: Hotel guest room occupancy density scheduled

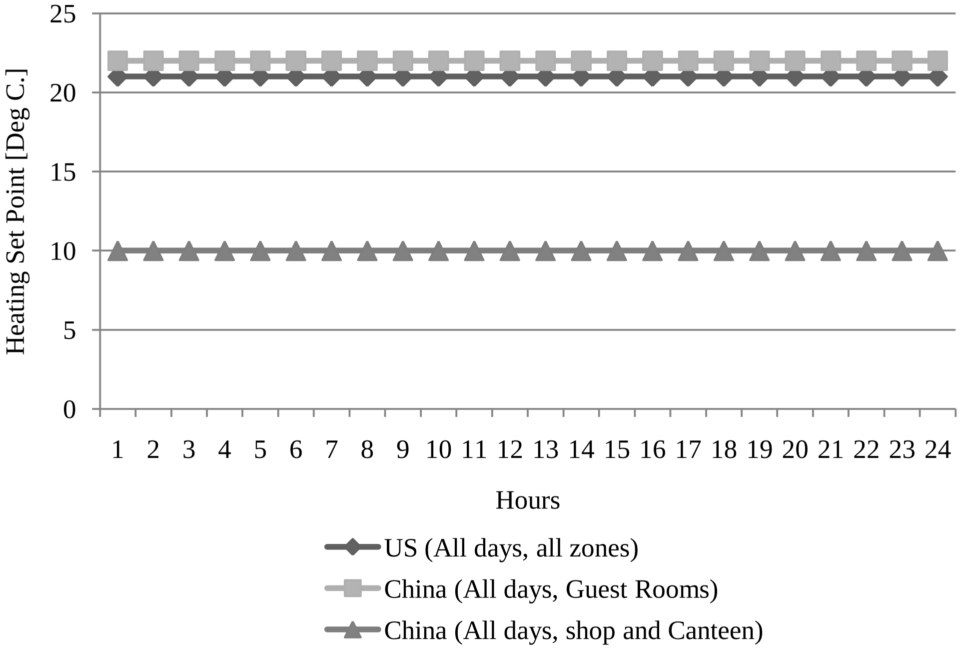


Figure 107: Hotel heating thermostat set point - Guangzhou climate region

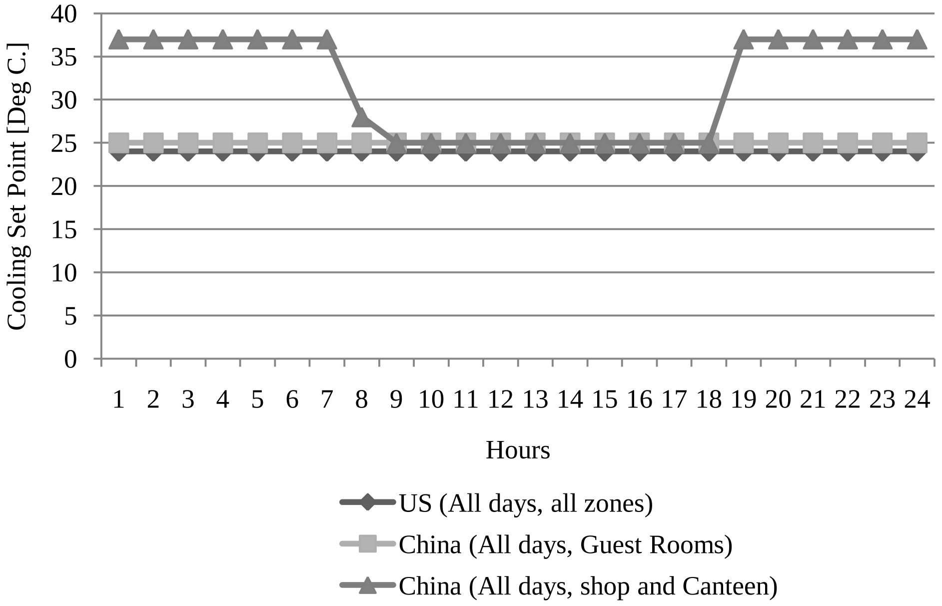


Figure 108: Hotel cooling thermostat set point - Guangzhou climate region

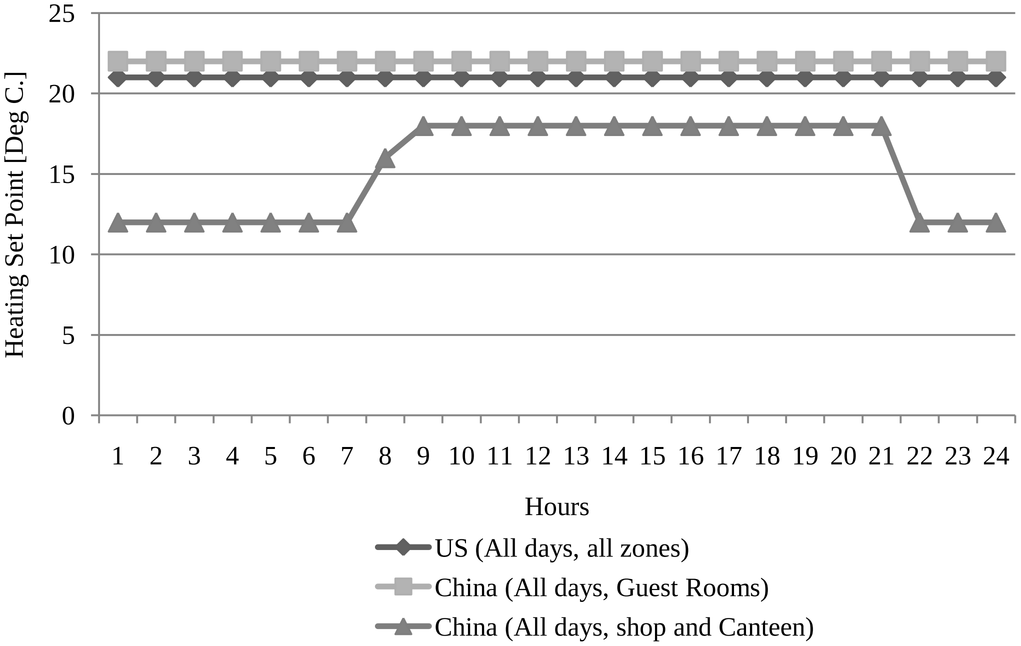


Figure 109: Hotel heating thermostat set point - Harbin climate region

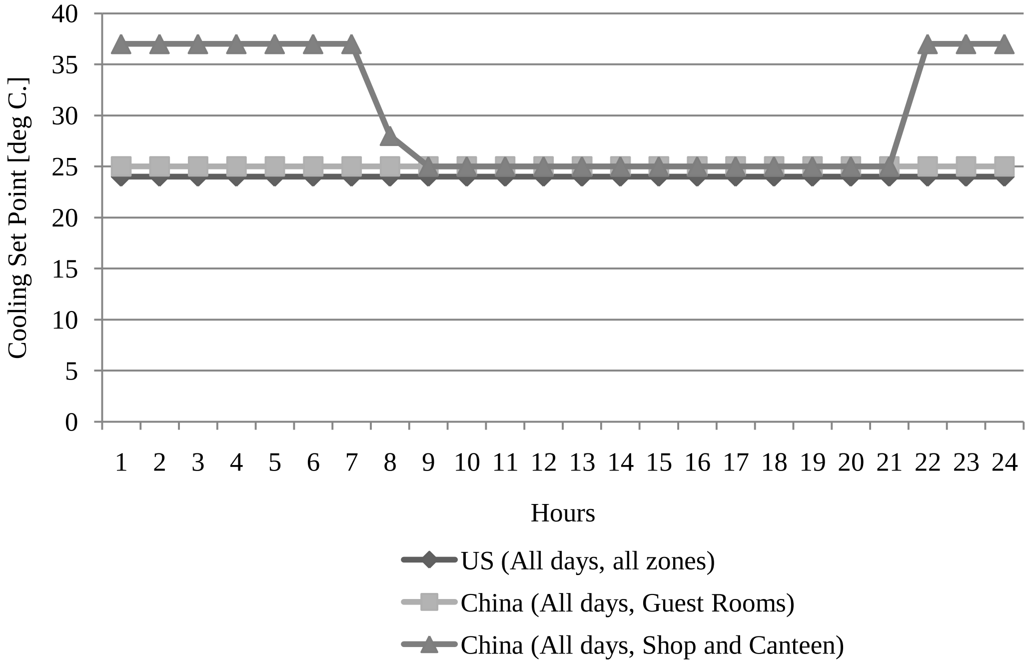


Figure 110: Hotel cooling thermostat set point - Harbin climate region

Appendix B: Selected Energy Design Measures from Opt-E-Plus

Appendix B1: Selected EDMs from the Guangzhou Office Optimization

Table 90: Selected EDMs in initial optimization - Guangzhou Office

Case	% Site Energy Savings	10% EPD Reduction	Daylight controls (400 lux)	50% WWR reduction - South façade	Overhang proj. factor 0.5 - south façade	Windows Uvalue-3.861, SHGC-0.36, VT-0.46	50% WWR reduction - East façade	50% WWR reduction - North façade	50% WWR reduction - West façade	Exterior Walls R-2.3	Exterior Walls R-6.22	Exterior Walls R-5.1	20% EPD Reduction	10% LPD Reduction	Roof R-3.3	Roof R-6.6	Skylights (4% Roof Area)	Skylights (8% Roof area)	Skylights (12% Roof area)	1.5 times ventilation rate per person	2 times ventilation rate per person	50% Roof area PV	30% Roof area PV	10% Roof area PV	20% Increased chiller COP-More efficient Fan	20% Increased COP
1	0.02			1				1		1			1			1		1		1						
2	0.04			1			1	1	1	1			1			1			1	1						
3	0.16			1			1	1	1	1			1		1				1	1						
4	1.48			1			1	1	1	1			1							1						
5	1.74			1			1	1	1	1																
6	7.39			1			1	1	1	1			1													
7	12.35		1	1			1	1	1	1			1													
8	12.59		1	1			1	1	1	1			1		1											
9	17.10	1	1	1			1	1	1	1			1		1											
10	17.72	1	1	1			1	1	1	1			1		1		1									
11	18.10	1	1	1	1		1	1	1	1			1		1		1									
12	18.18	1	1	1	1		1	1	1	1			1		1		1									
13	18.79	1	1	1	1	1	1	1	1	1			1		1		1									
14	19.18	1	1	1	1	1	1	1		1			1		1		1									
15	19.56	1	1	1	1	1		1		1			1		1		1									
16	19.62	1	1	1	1	1		1		1			1		1		1									
17	22.95	1	1	1	1	1		1		1			1		1		1						1			
18	25.17	1	1	1	1	1		1		1			1		1		1					1				
19	25.27	1	1	1	1	1		1		1			1			1	1					1				
20	29.96	1	1	1	1	1		1		1			1			1	1					1			1	
21	30.29	1	1	1	1	1		1				1	1			1	1					1			1	
22	30.35	1	1	1	1	1		1			1		1			1	1					1			1	
23	30.36	1	1	1	1	1					1		1			1	1					1			1	
Times Selected		15	17	23	13	11	13	22	12	20	2	1	22	0	12	7	14	1	2	4	0	6	1	0	4	0

Appendix B2: Selected EDMs from the Guangzhou Hotel Optimization

Table 91: Selected EDMs in initial optimization - Guangzhou Hotel

Case	% Site Energy Savings	EPD 90%	Daylighting 400lux	Shading: South 0.5	Shadting: East 0.5	Shading: West 0.5	WWR: East 0.5	WWR: East 0.8	WWR: East 1.5	WWR: East 1.2	R-15.2 Wall	R-50.0 Wall	R-37.5 Walls	WWR: north 0.5	WWR: North 0.8	1.200000 [42]	WWR: North 1.5	WWR: West 0.5	WWR: West 1.5	WWR: West 0.8	WWR: South 0.5	WWR: South 0.8	WWR: South 1.2	WWR: South 1.5	LPD 80%	LPD 90%	0 [0]	Roof R-40 (R-38.5 eff)	Roo R-19	windows: UValue_2.669	Windows: UValue_3.861	Windows: UValue_1.988	20% Increased COP-More eff Fan	20% Increased COP	More Efficient Fan	10% Increased COP-More Eff Fan	Ventilation: 2.0X's	Ventilation 1.5X's	PV 50% Roof	PV 30% Roof	PV 10% Roof
1	0.01													1						1	1					1											1				
2	0.17						1							1						1	1					1											1				
3	0.92						1				1			1							1					1											1				
4	1.56						1				1			1						1	1					1											1				
5	2.53						1				1			1				1			1					1											1				
6	3.45						1				1			1				1			1																	1			
7	7.98						1				1			1				1			1																				
8	12.27						1				1			1				1			1					1															
9	16.49						1				1			1				1			1				1																
10	25.07		1				1				1			1				1			1				1																
11	25.44		1				1				1			1				1			1				1				1												
12	26.24		1				1				1			1				1			1				1				1		1										
13	26.88		1	1			1				1			1				1			1				1				1		1										
14	28.96	1	1	1			1				1			1				1			1				1				1		1										
15	29.23	1	1	1		1	1				1			1				1			1				1				1		1										
16	29.27	1	1	1	1	1	1				1			1				1			1				1				1		1										
17	29.43	1	1	1	1	1	1				1			1				1			1				1			1			1										
18	29.63	1	1	1	1	1	1				1			1				1			1				1			1		1											
19	32.86	1	1	1	1	1	1				1			1				1			1				1			1		1				1							
20	33.41	1	1	1	1	1	1				1			1				1			1				1			1		1				1							1
21	34.53	1	1	1	1	1	1				1			1				1			1				1			1		1				1						1	
22	35.52	1	1	1	1	1	1						1	1				1			1				1			1		1				1						1	
23	35.68	1	1	1	1	1	1						1	1				1			1				1			1		1			1							1	
24	38.20	1	1	1	1	1	1						1	1				1			1				1			1		1			1						1		
25	38.35	1	1	1	1	1	1					1		1				1			1				1			1		1			1						1		
26	38.36	1	1	1	1	1		1				1		1				1			1				1			1		1			1						1		
27	38.37	1	1	1	1	1	1					1		1				1				1			1			1		1			1						1		
Times selected		14	18	15	12	13	25	1	0	0	19	3	3	27	0	0	0	23	0	3	26	1	0	0	19	6	0	11	6	10	6	0	5	4	0	0	5	1	4	3	1

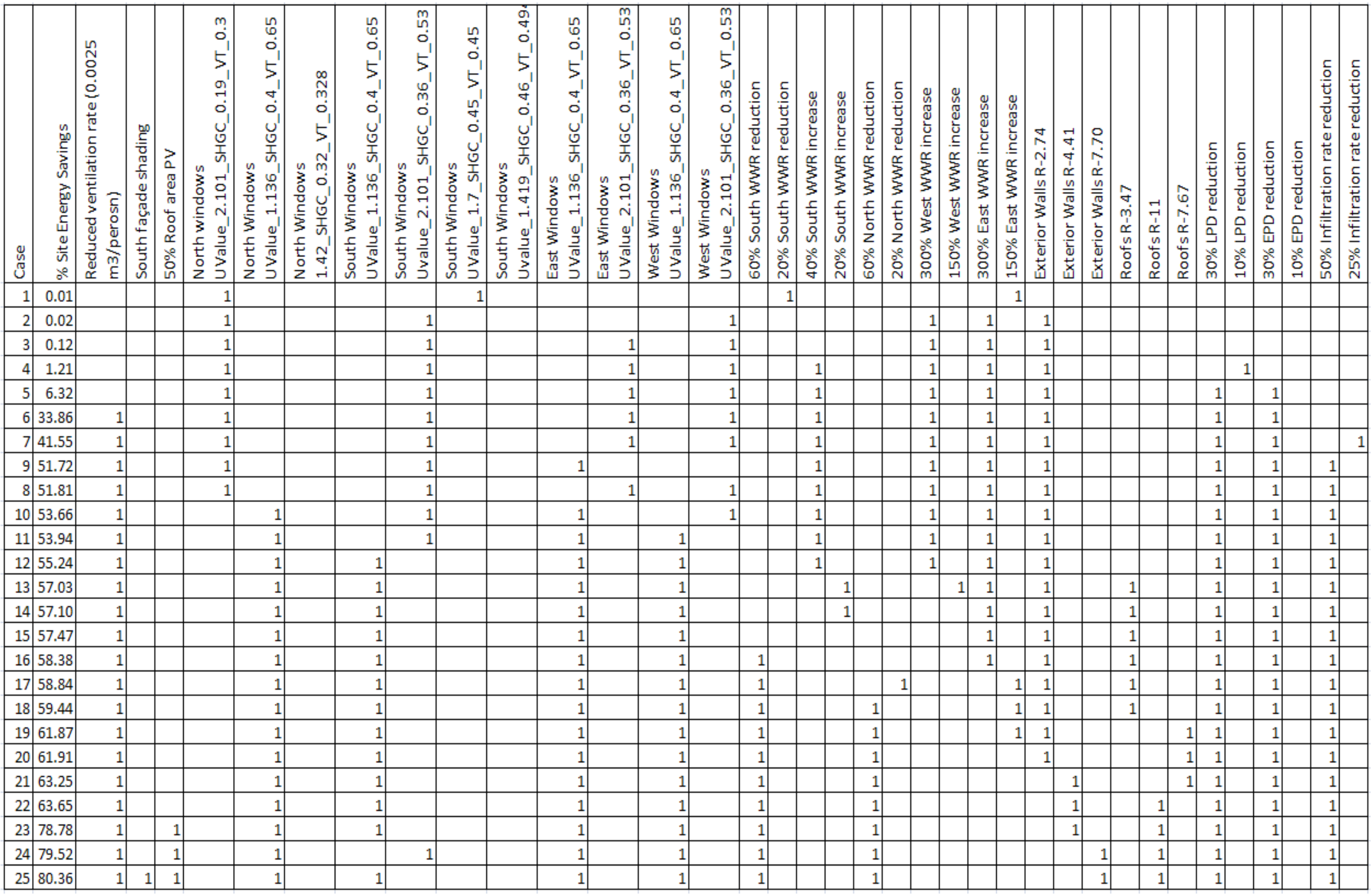
Appendix B3: Selected EDMs for Harbin Office Optimization

Table 92: Selected Energy Design Measures - Harbin Office

Case	% Site Energy Savings	Reduced ventilation rate (0.0025 m3/perosn)	South façade shading	50% Roof area PV	4% Skilight Area	North windows UValue_2.101_SHGC_0.19_VT_0.3	North Windows UValue_1.136_SHGC_0.4_VT_0.65	North Windows 1.42_SHGC_0.32_VT_0.328	South Windows UValue_1.136_SHGC_0.4_VT_0.65	South Windows Uvalue_2.101_SHGC_0.36_VT_0.53	South Windows Uvalue_1.419_SHGC_0.46_VT_0.494	South Windows UValue_1.7_SHGC_0.45_VT_0.45	East Windows UValue_2.101_SHGC_0.36_VT_0.53	East Windows UValue_1.136_SHGC_0.4_VT_0.65	West Windows UValue_2.101_SHGC_0.36_VT_0.53	West Windows UValue_1.136_SHGC_0.4_VT_0.65	140% South WWR increase	120% South WWR increase	20% South WWR reduction	40% South WWR reduction	20% North WWR reduction	60% North WWR reduction	300% East WWR increase	150% East WWR increase	300% West WWR increase	150% West WWR increase	Exterior Walls R-2.74	Exterior Walls R-7.70	Exterior Walls R-4.41	Roof R-3.47	Roof R-7.67	Roof R-11	30% EPD reduction	30% LPD reduction	Daylighting Setpoint 500lux	50% Infiltration reduction	25% Infiltration reduction
1	0.06					1			1				1		1					1					1												
2	0.06					1				1			1		1											1											
3	0.08					1				1			1		1									1		1											
4	0.12					1				1			1		1								1			1											
5	0.43					1				1			1		1								1		1												
6	0.85					1				1			1		1			1					1		1												
7	1.28					1				1			1		1		1						1		1												
8	16.11					1				1			1		1		1						1		1								1	1			
9	21.08					1				1			1		1		1						1		1								1	1	1		
10	25.27						1			1			1		1		1						1		1								1	1	1		
11	26.43						1			1				1	1		1						1		1								1	1	1		
12	30.09						1		1					1	1		1						1		1								1	1	1		
13	32.28						1		1					1		1	1						1		1								1	1	1		
14	46.04						1		1					1		1	1						1		1								1	1	1	1	
15	56.68						1		1					1		1	1						1		1		1						1	1	1	1	
16	57.62						1		1					1		1	1						1		1		1			1			1	1	1	1	
17	58.78						1		1					1		1	1						1		1		1				1		1	1	1	1	
18	74.84			1			1		1					1		1	1						1		1		1				1		1	1	1	1	
19	75.29			1			1		1					1		1	1						1		1				1		1		1	1	1	1	
20	75.43			1			1		1					1		1	1						1		1				1			1	1	1	1	1	
21	75.63			1			1		1					1		1	1						1		1			1				1	1	1	1	1	
22	75.65			1			1		1					1		1	1						1			1		1				1	1	1	1	1	

Appendix B4: Selected EDMs from the Harbin Office Optimization

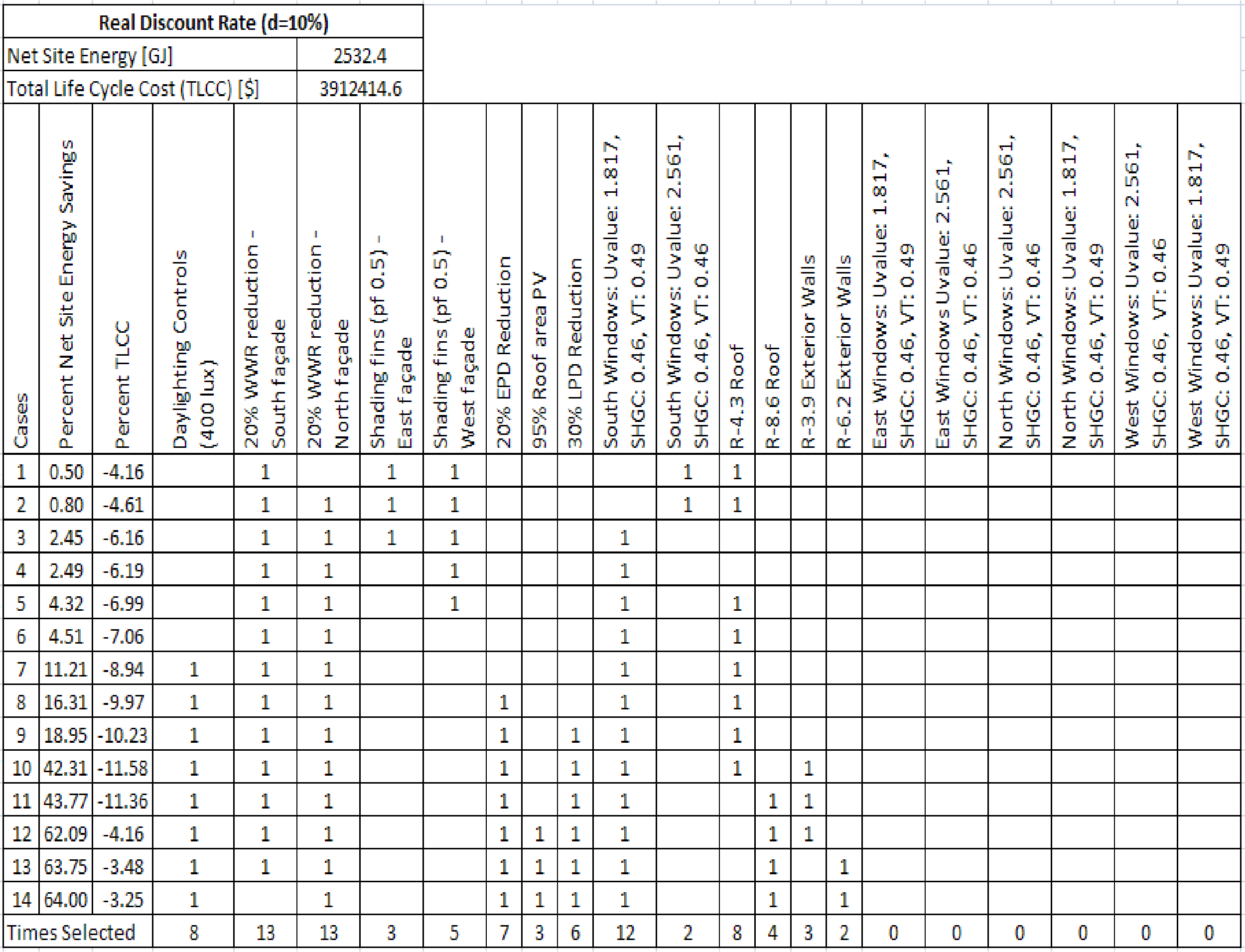
Table 93: Selected Energy Design Measures - Harbin Hotel



Case	% Site Energy Savings	Reduced ventilation rate (0.0025 m3/perosn)	South façade shading	50% Roof area PV	North windows UValue_2.101_SHGC_0.19_VT_0.3	North Windows UValue_1.136_SHGC_0.4_VT_0.65	North Windows 1.42_SHGC_0.32_VT_0.328	South Windows UValue_1.136_SHGC_0.4_VT_0.65	South Windows Uvalue_2.101_SHGC_0.36_VT_0.53	South Windows UValue_1.7_SHGC_0.45_VT_0.45	South Windows Uvalue_1.419_SHGC_0.46_VT_0.494	East Windows UValue_1.136_SHGC_0.4_VT_0.65	East Windows UValue_2.101_SHGC_0.36_VT_0.53	West Windows UValue_1.136_SHGC_0.4_VT_0.65	West Windows UValue_2.101_SHGC_0.36_VT_0.53	60% South WWR reduction	20% South WWR reduction	40% South WWR increase	20% South WWR increase	60% North WWR reduction	20% North WWR reduction	300% West WWR increase	150% West WWR increase	300% East WWR increase	150% East WWR increase	Exterior Walls R-2.74	Exterior Walls R-4.41	Exterior Walls R-7.70	Roofs R-3.47	Roofs R-11	Roofs R-7.67	30% LPD reduction	10% LPD reduction	30% EPD reduction	10% EPD reduction	50% Infiltration rate reduction	25% Infiltration rate reduction
1	0.01				1					1							1								1												
2	0.02				1				1						1							1		1		1											
3	0.12				1				1				1		1							1		1		1											
4	1.21				1				1				1		1			1				1		1		1							1				
5	6.32				1				1				1		1			1				1		1		1						1		1			
6	33.86	1			1				1				1		1			1				1		1		1						1		1			
7	41.55	1			1				1				1		1			1				1		1		1						1		1			1
9	51.72	1			1				1			1						1				1		1		1						1		1		1	
8	51.81	1			1				1				1		1			1				1		1		1						1		1		1	
10	53.66	1				1			1			1			1			1				1		1		1						1		1		1	
11	53.94	1				1			1			1		1				1				1		1		1						1		1		1	
12	55.24	1				1		1				1		1				1				1		1		1						1		1		1	
13	57.03	1				1		1				1		1					1				1	1		1			1			1		1		1	
14	57.10	1				1		1				1		1					1					1		1			1			1		1		1	
15	57.47	1				1		1				1		1										1		1			1			1		1		1	
16	58.38	1				1		1				1		1		1								1		1			1			1		1		1	
17	58.84	1				1		1				1		1		1					1				1	1			1			1		1		1	
18	59.44	1				1		1				1		1		1				1					1	1			1			1		1		1	
19	61.87	1				1		1				1		1		1				1					1	1					1	1		1		1	
20	61.91	1				1		1				1		1		1				1						1					1	1		1		1	
21	63.25	1				1		1				1		1		1				1							1				1	1		1		1	
22	63.65	1				1		1				1		1		1				1							1			1		1		1		1	
23	78.78	1		1		1		1				1		1		1				1							1			1		1		1		1	
24	79.52	1		1		1			1			1		1		1				1								1		1		1		1		1	
25	80.36	1	1	1		1		1				1		1		1				1								1		1		1		1		1	

Appendix B5: Selected EDMs from the Economic Optimization of the Harbin Office

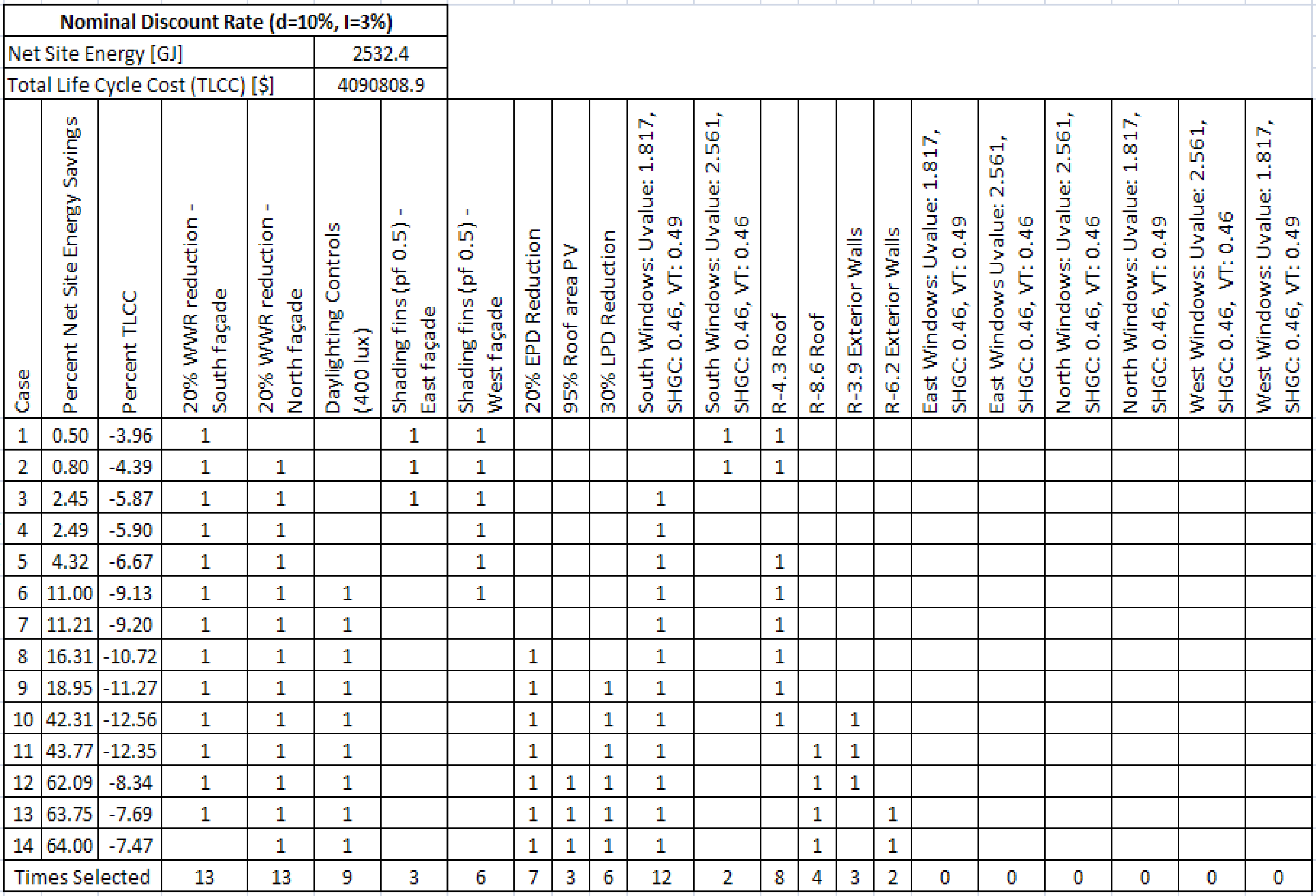
Table 94: Selected EDMs for Harbin office economic optimization (d_R=10%)



Real Discount Rate (d=10%)	
Net Site Energy [GJ]	2532.4
Total Life Cycle Cost (TLCC) [$]	3912414.6

Cases	Percent Net Site Energy Savings	Percent TLCC	Daylighting Controls (400 lux)	20% WWR reduction - South façade	20% WWR reduction - North façade	Shading fins (pf 0.5) - East façade	Shading fins (pf 0.5) - West façade	20% EPD Reduction	95% Roof area PV	30% LPD Reduction	South Windows: Uvalue: 1.817, SHGC: 0.46, VT: 0.49	South Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	R-4.3 Roof	R-8.6 Roof	R-3.9 Exterior Walls	R-6.2 Exterior Walls	East Windows: Uvalue: 1.817, SHGC: 0.46, VT: 0.49	East Windows Uvalue: 2.561, SHGC: 0.46, VT: 0.46	North Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	North Windows: Uvalue: 1.817, SHGC: 0.46, VT: 0.49	West Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	West Windows: Uvalue: 1.817, SHGC: 0.46, VT: 0.49
1	0.50	-4.16		1		1	1					1	1									
2	0.80	-4.61		1	1	1	1					1	1									
3	2.45	-6.16		1	1	1	1				1											
4	2.49	-6.19		1	1		1				1											
5	4.32	-6.99		1	1		1				1		1									
6	4.51	-7.06		1	1						1		1									
7	11.21	-8.94	1	1	1						1		1									
8	16.31	-9.97	1	1	1			1			1		1									
9	18.95	-10.23	1	1	1			1		1	1		1									
10	42.31	-11.58	1	1	1			1		1	1		1		1							
11	43.77	-11.36	1	1	1			1		1	1			1	1							
12	62.09	-4.16	1	1	1			1	1	1	1			1	1							
13	63.75	-3.48	1	1	1			1	1	1	1			1		1						
14	64.00	-3.25	1		1			1	1	1	1			1		1						
Times Selected			8	13	13	3	5	7	3	6	12	2	8	4	3	2	0	0	0	0	0	0

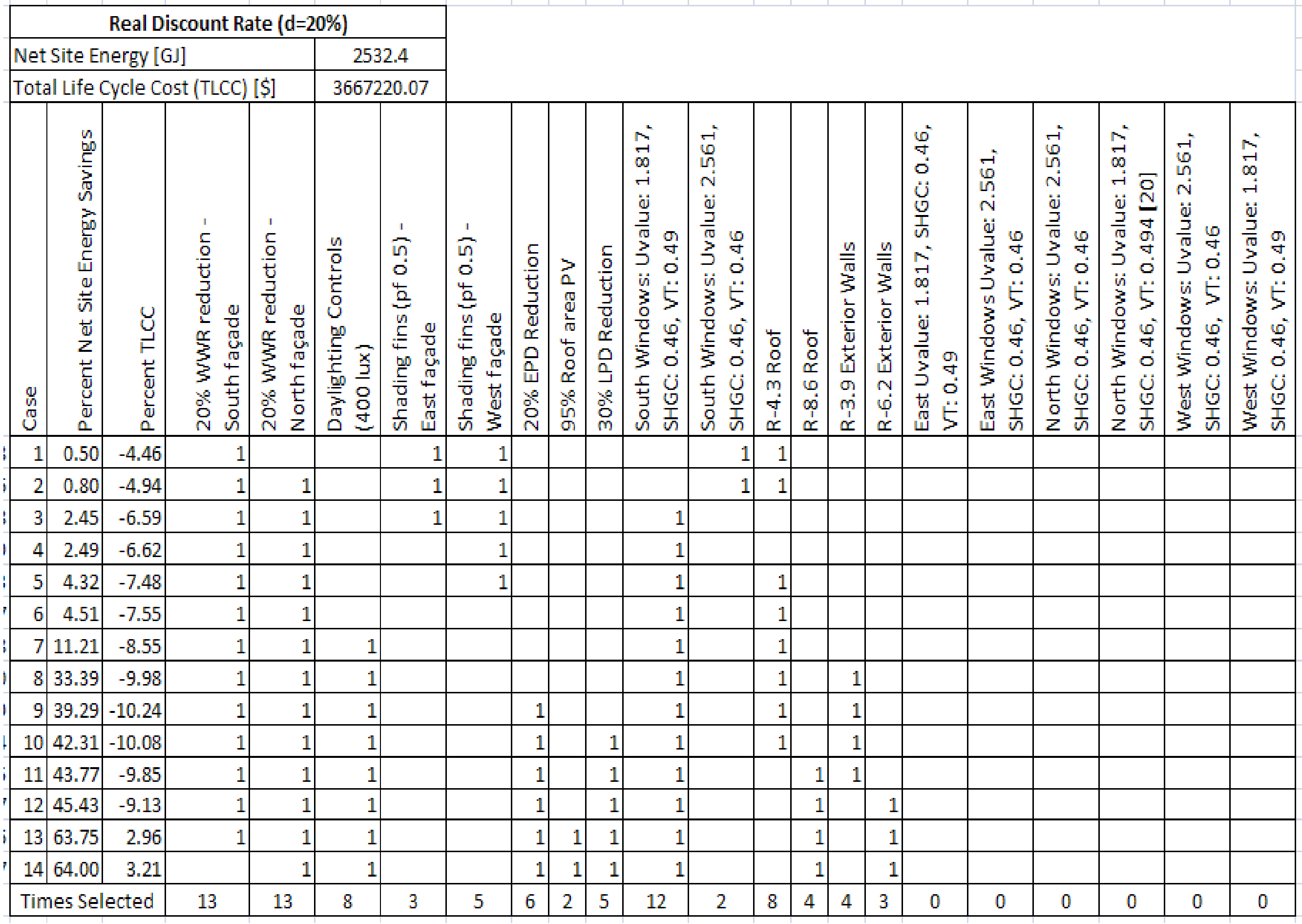
Table 95: Selected EDMs for Harbin office economic optimization (d_N=10%)



Nominal Discount Rate (d=10%, I=3%)	
Net Site Energy [GJ]	2532.4
Total Life Cycle Cost (TLCC) [$]	4090808.9

Case	Percent Net Site Energy Savings	Percent TLCC	20% WWR reduction - South façade	20% WWR reduction - North façade	Daylighting Controls (400 lux)	Shading fins (pf 0.5) - East façade	Shading fins (pf 0.5) - West façade	20% EPD Reduction	95% Roof area PV	30% LPD Reduction	South Windows: Uvalue: 1.817, SHGC: 0.46, VT: 0.49	South Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	R-4.3 Roof	R-8.6 Roof	R-3.9 Exterior Walls	R-6.2 Exterior Walls	East Windows: Uvalue: 1.817, SHGC: 0.46, VT: 0.49	East Windows Uvalue: 2.561, SHGC: 0.46, VT: 0.46	North Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	North Windows: Uvalue: 1.817, SHGC: 0.46, VT: 0.49	West Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	West Windows: Uvalue: 1.817, SHGC: 0.46, VT: 0.49
1	0.50	-3.96	1			1	1					1	1									
2	0.80	-4.39	1	1		1	1					1	1									
3	2.45	-5.87	1	1		1	1				1											
4	2.49	-5.90	1	1			1				1											
5	4.32	-6.67	1	1			1				1		1									
6	11.00	-9.13	1	1	1		1				1		1									
7	11.21	-9.20	1	1	1						1		1									
8	16.31	-10.72	1	1	1			1			1		1									
9	18.95	-11.27	1	1	1			1		1	1		1									
10	42.31	-12.56	1	1	1			1		1	1		1		1							
11	43.77	-12.35	1	1	1			1		1	1			1	1							
12	62.09	-8.34	1	1	1			1	1	1	1			1	1							
13	63.75	-7.69	1	1	1			1	1	1	1			1		1						
14	64.00	-7.47		1	1			1	1	1	1			1		1						
Times Selected			13	13	9	3	6	7	3	6	12	2	8	4	3	2	0	0	0	0	0	0

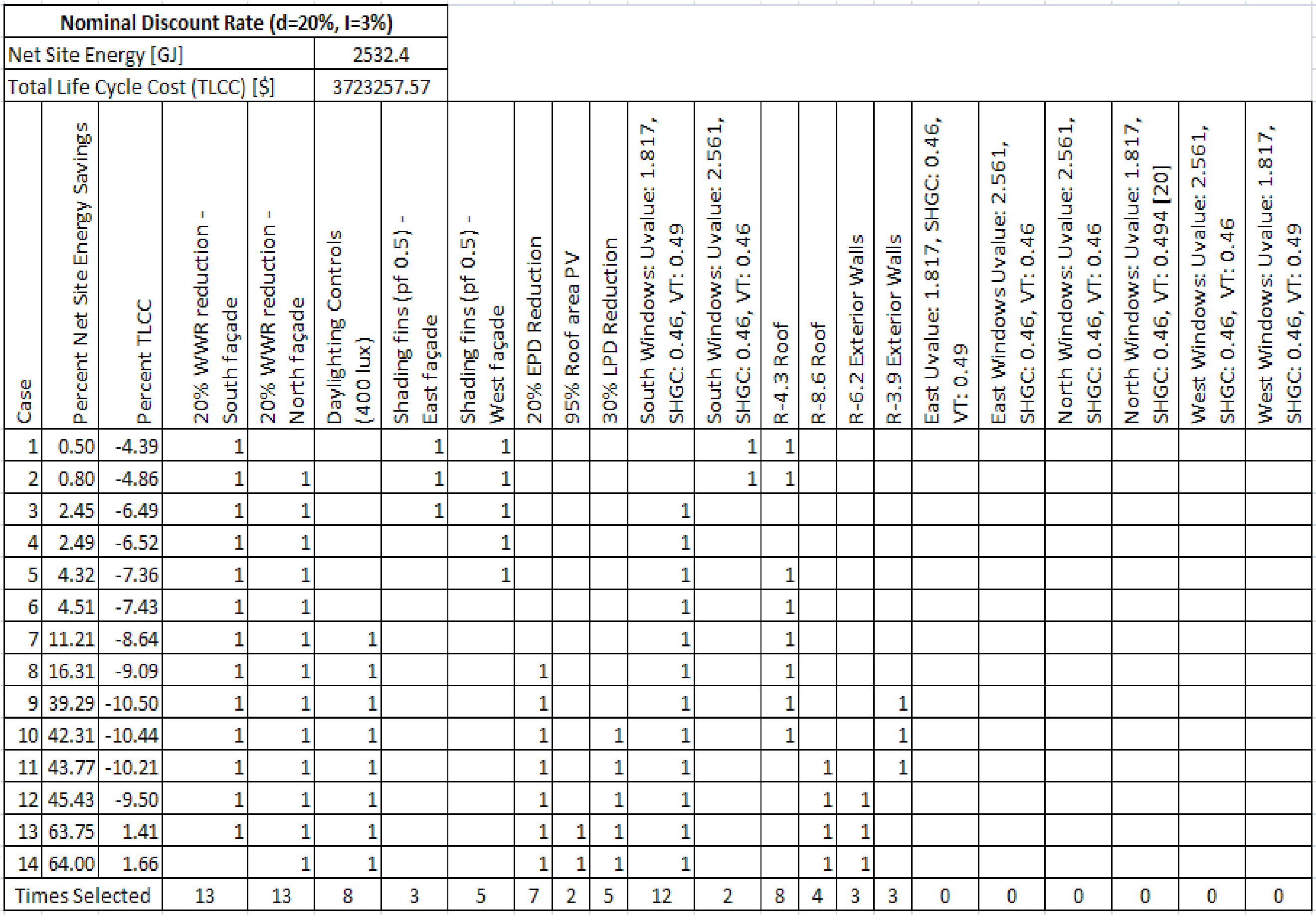
Table 96: Selected EDMs for Harbin office economic optimization (d_R=20%)



Real Discount Rate (d=20%)	
Net Site Energy [GJ]	2532.4
Total Life Cycle Cost (TLCC) [$]	3667220.07

Case	Percent Net Site Energy Savings	Percent TLCC	20% WWR reduction - South façade	20% WWR reduction - North façade	Daylighting Controls (400 lux)	Shading fins (pf 0.5) - East façade	Shading fins (pf 0.5) - West façade	20% EPD Reduction	95% Roof area PV	30% LPD Reduction	South Windows: Uvalue: 1.817, SHGC: 0.46, VT: 0.49	South Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	R-4.3 Roof	R-8.6 Roof	R-3.9 Exterior Walls	R-6.2 Exterior Walls	East Uvalue: 1.817, SHGC: 0.46, VT: 0.49	East Windows Uvalue: 2.561, SHGC: 0.46, VT: 0.46	North Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	North Windows: Uvalue: 1.817, SHGC: 0.46, VT: 0.494 [20]	West Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	West Windows: Uvalue: 1.817, SHGC: 0.46, VT: 0.49
1	0.50	-4.46	1			1	1					1	1									
2	0.80	-4.94	1	1		1	1					1	1									
3	2.45	-6.59	1	1		1	1				1											
4	2.49	-6.62	1	1			1				1											
5	4.32	-7.48	1	1			1				1		1									
6	4.51	-7.55	1	1							1		1									
7	11.21	-8.55	1	1	1						1		1									
8	33.39	-9.98	1	1	1						1		1		1							
9	39.29	-10.24	1	1	1			1			1		1		1							
10	42.31	-10.08	1	1	1			1		1	1		1		1							
11	43.77	-9.85	1	1	1			1		1	1			1	1							
12	45.43	-9.13	1	1	1			1		1	1			1		1						
13	63.75	2.96	1	1	1			1	1	1	1			1		1						
14	64.00	3.21		1	1			1	1	1	1			1		1						
Times Selected			13	13	8	3	5	6	2	5	12	2	8	4	4	3	0	0	0	0	0	0

Table 97: Selected EDMs for Harbin office economic optimization (d_N=20%)



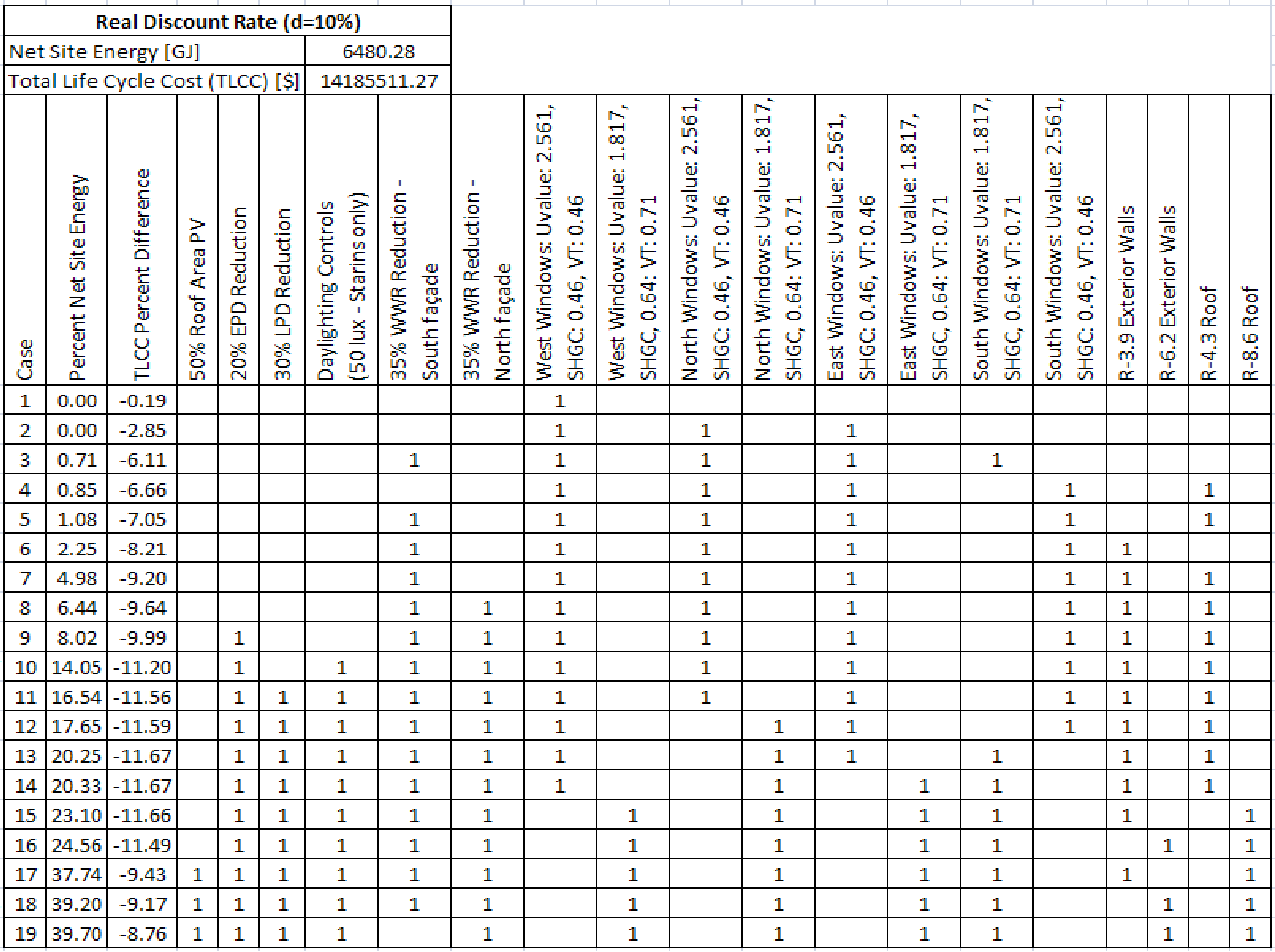
Nominal Discount Rate (d=20%, I=3%)

Net Site Energy [GJ]	2532.4
Total Life Cycle Cost (TLCC) [$]	3723257.57

Case	Percent Net Site Energy Savings	Percent TLCC	20% WWR reduction - South façade	20% WWR reduction - North façade	Daylighting Controls (400 lux)	Shading fins (pf 0.5) - East façade	Shading fins (pf 0.5) - West façade	20% EPD Reduction	95% Roof area PV	30% LPD Reduction	South Windows: Uvalue: 1.817, SHGC: 0.46, VT: 0.49	South Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	R-4.3 Roof	R-8.6 Roof	R-6.2 Exterior Walls	R-3.9 Exterior Walls	East Uvalue: 1.817, SHGC: 0.46, VT: 0.49	East Windows Uvalue: 2.561, SHGC: 0.46, VT: 0.46	North Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	North Windows: Uvalue: 1.817, SHGC: 0.46, VT: 0.494 [20]	West Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	West Windows: Uvalue: 1.817, SHGC: 0.46, VT: 0.49
1	0.50	-4.39	1			1	1					1	1									
2	0.80	-4.86	1	1		1	1					1	1									
3	2.45	-6.49	1	1		1	1				1											
4	2.49	-6.52	1	1			1				1											
5	4.32	-7.36	1	1			1				1		1									
6	4.51	-7.43	1	1							1		1									
7	11.21	-8.64	1	1	1						1		1									
8	16.31	-9.09	1	1	1			1			1		1									
9	39.29	-10.50	1	1	1			1			1		1			1						
10	42.31	-10.44	1	1	1			1		1	1		1			1						
11	43.77	-10.21	1	1	1			1		1	1			1		1						
12	45.43	-9.50	1	1	1			1		1	1			1	1							
13	63.75	1.41	1	1	1			1	1	1	1			1	1							
14	64.00	1.66		1	1			1	1	1	1			1	1							
Times Selected			13	13	8	3	5	7	2	5	12	2	8	4	3	3	0	0	0	0	0	0

Appendix B6: Selected EDMs for the Economic Optimization of the Harbin Hotel

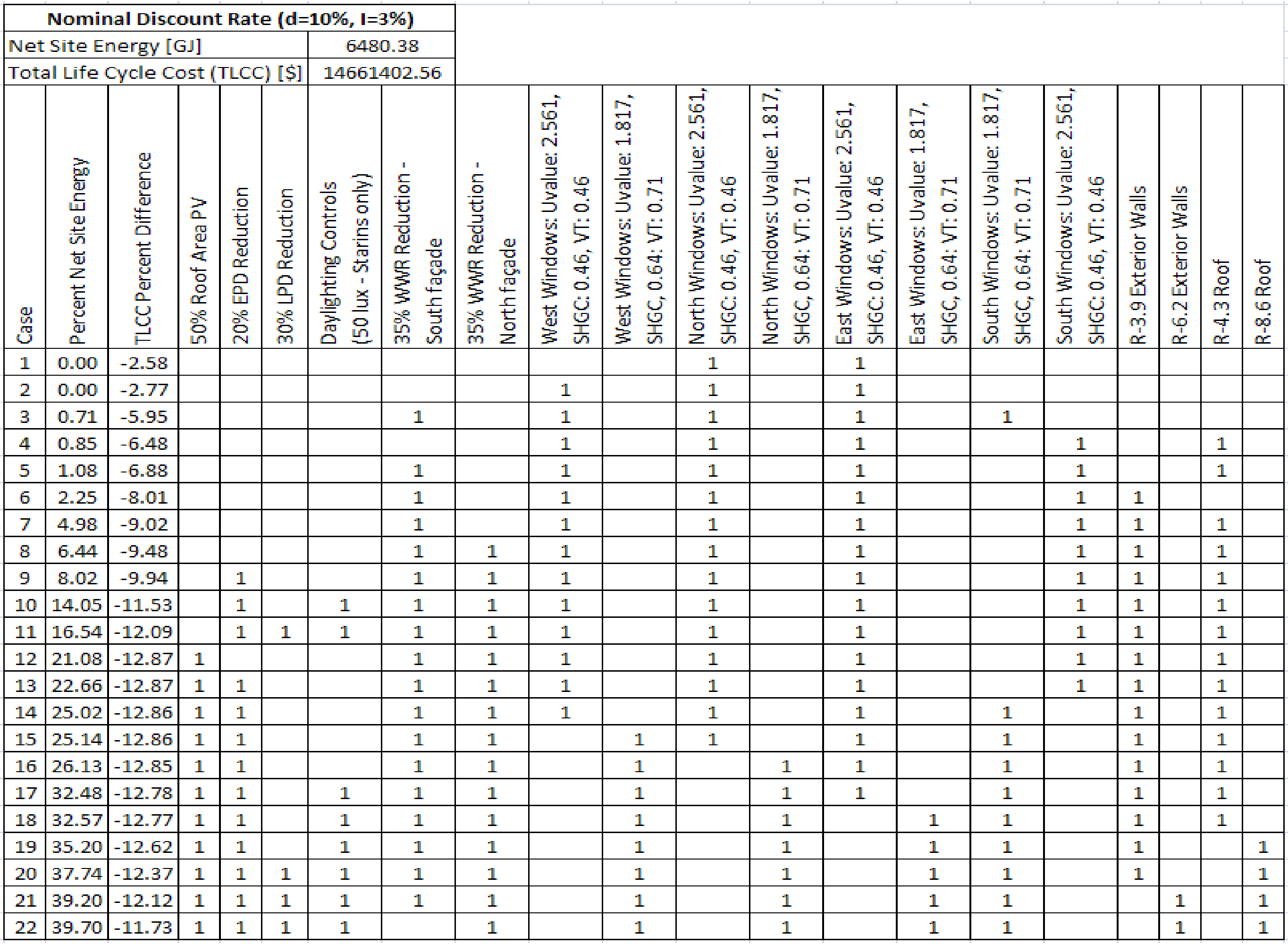
Table 98: Selected EDMs for Harbin hotel economic optimization (d_R=10%)



Real Discount Rate (d=10%)	
Net Site Energy [GJ]	6480.28
Total Life Cycle Cost (TLCC) [$]	14185511.27

Case	Percent Net Site Energy	TLCC Percent Difference	50% Roof Area PV	20% EPD Reduction	30% LPD Reduction	Daylighting Controls (50 lux - Starins only)	35% WWR Reduction - South façade	35% WWR Reduction - North façade	West Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	West Windows: Uvalue: 1.817, SHGC, 0.64: VT: 0.71	North Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	North Windows: Uvalue: 1.817, SHGC, 0.64: VT: 0.71	East Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	East Windows: Uvalue: 1.817, SHGC, 0.64: VT: 0.71	South Windows: Uvalue: 1.817, SHGC, 0.64: VT: 0.71	South Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	R-3.9 Exterior Walls	R-6.2 Exterior Walls	R-4.3 Roof	R-8.6 Roof
1	0.00	-0.19							1											
2	0.00	-2.85							1		1		1							
3	0.71	-6.11					1		1		1		1		1					
4	0.85	-6.66							1		1		1			1			1	
5	1.08	-7.05					1		1		1		1			1			1	
6	2.25	-8.21					1		1		1		1			1	1			
7	4.98	-9.20					1		1		1		1			1	1		1	
8	6.44	-9.64					1	1	1		1		1			1	1		1	
9	8.02	-9.99		1			1	1	1		1		1			1	1		1	
10	14.05	-11.20		1		1	1	1	1		1		1			1	1		1	
11	16.54	-11.56		1	1	1	1	1	1		1		1			1	1		1	
12	17.65	-11.59		1	1	1	1	1	1			1	1			1	1		1	
13	20.25	-11.67		1	1	1	1	1	1			1	1		1		1		1	
14	20.33	-11.67		1	1	1	1	1	1			1		1	1		1		1	
15	23.10	-11.66		1	1	1	1	1		1		1		1	1		1			1
16	24.56	-11.49		1	1	1	1	1		1		1		1	1			1		1
17	37.74	-9.43	1	1	1	1	1	1		1		1		1	1		1			1
18	39.20	-9.17	1	1	1	1	1	1		1		1		1	1			1		1
19	39.70	-8.76	1	1	1	1		1		1		1		1	1			1		1

Table 99: Selected EDMs for Harbin hotel economic optimization (d_N=10%)

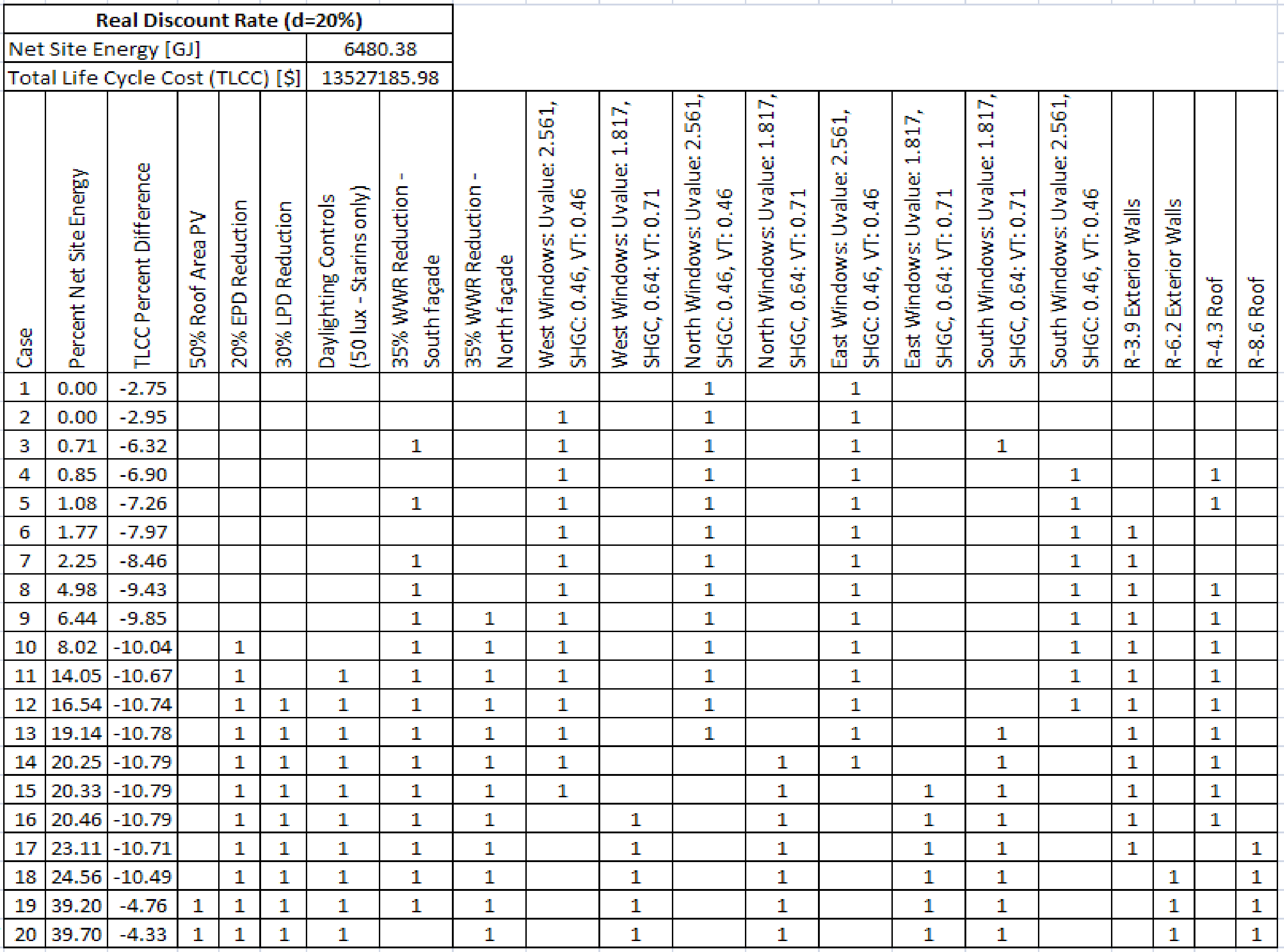


Nominal Discount Rate (d=10%, I=3%)

Net Site Energy [GJ]	6480.38
Total Life Cycle Cost (TLCC) [$]	14661402.56

Case	Percent Net Site Energy	TLCC Percent Difference	50% Roof Area PV	20% EPD Reduction	30% LPD Reduction	Daylighting Controls (50 lux - Starins only)	35% WWR Reduction - South façade	35% WWR Reduction - North façade	West Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	West Windows: Uvalue: 1.817, SHGC, 0.64: VT: 0.71	North Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	North Windows: Uvalue: 1.817, SHGC, 0.64: VT: 0.71	East Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	East Windows: Uvalue: 1.817, SHGC, 0.64: VT: 0.71	South Windows: Uvalue: 1.817, SHGC, 0.64: VT: 0.71	South Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	R-3.9 Exterior Walls	R-6.2 Exterior Walls	R-4.3 Roof	R-8.6 Roof
1	0.00	-2.58									1		1							
2	0.00	-2.77							1		1		1							
3	0.71	-5.95					1		1		1		1		1					
4	0.85	-6.48							1		1		1			1			1	
5	1.08	-6.88					1		1		1		1			1			1	
6	2.25	-8.01					1		1		1		1			1	1			
7	4.98	-9.02					1		1		1		1			1	1		1	
8	6.44	-9.48					1	1	1		1		1			1	1		1	
9	8.02	-9.94		1			1	1	1		1		1			1	1		1	
10	14.05	-11.53		1		1	1	1	1		1		1			1	1		1	
11	16.54	-12.09		1	1	1	1	1	1		1		1			1	1		1	
12	21.08	-12.87	1				1	1	1		1		1			1	1		1	
13	22.66	-12.87	1	1			1	1	1		1		1			1	1		1	
14	25.02	-12.86	1	1			1	1	1		1		1		1		1		1	
15	25.14	-12.86	1	1			1	1		1	1		1		1		1		1	
16	26.13	-12.85	1	1			1	1		1		1	1		1		1		1	
17	32.48	-12.78	1	1		1	1	1		1		1	1		1		1		1	
18	32.57	-12.77	1	1		1	1	1		1		1		1	1		1		1	
19	35.20	-12.62	1	1		1	1	1		1		1		1	1		1			1
20	37.74	-12.37	1	1	1	1	1	1		1		1		1	1		1			1
21	39.20	-12.12	1	1	1	1	1	1		1		1		1	1			1		1
22	39.70	-11.73	1	1	1	1		1		1		1		1	1			1		1

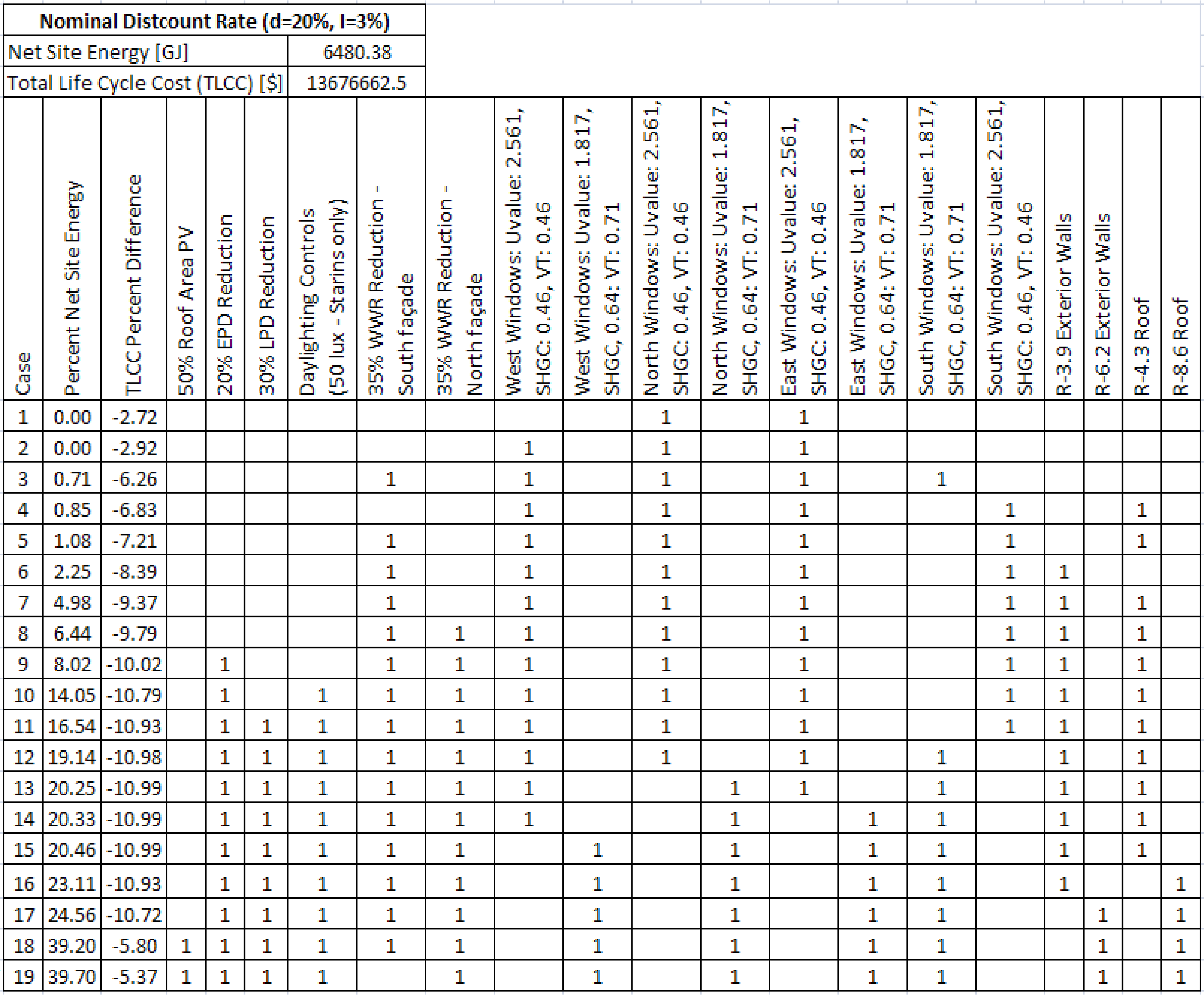
Table 100: Selected EDMs for Harbin hotel economic optimization (d_R=20%)



Real Discount Rate (d=20%)	
Net Site Energy [GJ]	6480.38
Total Life Cycle Cost (TLCC) [$]	13527185.98

Case	Percent Net Site Energy	TLCC Percent Difference	50% Roof Area PV	20% EPD Reduction	30% LPD Reduction	Daylighting Controls (50 lux - Starins only)	35% WWR Reduction - South façade	35% WWR Reduction - North façade	West Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	West Windows: Uvalue: 1.817, SHGC, 0.64: VT: 0.71	North Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	North Windows: Uvalue: 1.817, SHGC, 0.64: VT: 0.71	East Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	East Windows: Uvalue: 1.817, SHGC, 0.64: VT: 0.71	South Windows: Uvalue: 1.817, SHGC, 0.64: VT: 0.71	South Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	R-3.9 Exterior Walls	R-6.2 Exterior Walls	R-4.3 Roof	R-8.6 Roof
1	0.00	-2.75									1		1							
2	0.00	-2.95							1		1		1							
3	0.71	-6.32					1		1		1		1		1					
4	0.85	-6.90							1		1		1			1			1	
5	1.08	-7.26					1		1		1		1			1			1	
6	1.77	-7.97							1		1		1			1	1			
7	2.25	-8.46					1		1		1		1			1	1			
8	4.98	-9.43					1		1		1		1			1	1		1	
9	6.44	-9.85					1	1	1		1		1			1	1		1	
10	8.02	-10.04		1			1	1	1		1		1			1	1		1	
11	14.05	-10.67		1		1	1	1	1		1		1			1	1		1	
12	16.54	-10.74		1	1	1	1	1	1		1		1			1	1		1	
13	19.14	-10.78		1	1	1	1	1	1		1		1		1		1		1	
14	20.25	-10.79		1	1	1	1	1	1			1	1		1		1		1	
15	20.33	-10.79		1	1	1	1	1	1			1		1	1		1		1	
16	20.46	-10.79		1	1	1	1	1		1		1		1	1		1		1	
17	23.11	-10.71		1	1	1	1	1		1		1		1	1		1			1
18	24.56	-10.49		1	1	1	1	1		1		1		1	1			1		1
19	39.20	-4.76	1	1	1	1	1	1		1		1		1	1			1		1
20	39.70	-4.33	1	1	1	1		1		1		1		1	1			1		1

Table 101: Selected EDMs for Harbin hotel economic optimization (d_N=20%)



Nominal Distcount Rate (d=20%, I=3%)	
Net Site Energy [GJ]	6480.38
Total Life Cycle Cost (TLCC) [$]	13676662.5

Case	Percent Net Site Energy	TLCC Percent Difference	50% Roof Area PV	20% EPD Reduction	30% LPD Reduction	Daylighting Controls (50 lux - Starins only)	35% WWR Reduction - South façade	35% WWR Reduction - North façade	West Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	West Windows: Uvalue: 1.817, SHGC, 0.64: VT: 0.71	North Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	North Windows: Uvalue: 1.817, SHGC, 0.64: VT: 0.71	East Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	East Windows: Uvalue: 1.817, SHGC, 0.64: VT: 0.71	South Windows: Uvalue: 1.817, SHGC, 0.64: VT: 0.71	South Windows: Uvalue: 2.561, SHGC: 0.46, VT: 0.46	R-3.9 Exterior Walls	R-6.2 Exterior Walls	R-4.3 Roof	R-8.6 Roof
1	0.00	-2.72									1		1							
2	0.00	-2.92							1		1		1							
3	0.71	-6.26					1		1		1		1		1					
4	0.85	-6.83							1		1		1			1			1	
5	1.08	-7.21					1		1		1		1			1			1	
6	2.25	-8.39					1		1		1		1			1	1			
7	4.98	-9.37					1		1		1		1			1	1		1	
8	6.44	-9.79					1	1	1		1		1			1	1		1	
9	8.02	-10.02		1			1	1	1		1		1			1	1		1	
10	14.05	-10.79		1		1	1	1	1		1		1			1	1		1	
11	16.54	-10.93		1	1	1	1	1	1		1		1			1	1		1	
12	19.14	-10.98		1	1	1	1	1	1		1		1		1		1		1	
13	20.25	-10.99		1	1	1	1	1	1			1	1		1		1		1	
14	20.33	-10.99		1	1	1	1	1	1			1		1	1		1		1	
15	20.46	-10.99		1	1	1	1	1		1		1		1	1		1		1	
16	23.11	-10.93		1	1	1	1	1		1		1		1	1		1			1
17	24.56	-10.72		1	1	1	1	1		1		1		1	1			1		1
18	39.20	-5.80	1	1	1	1	1	1		1		1		1	1			1		1
19	39.70	-5.37	1	1	1	1		1		1		1		1	1			1		1

Appendix C: Monthly Peak Demand Tables – China US Comparison

Table 102: Office Monthly Peak Electricity Demand - Guangzhou Climate Region

	GZ	Houston – GZ Sched. Set pts, Loads	Houston – GZ Sched. Set pts	Houston
January	91.24	39.78	22.98	26.05
February	117.32	39.68	23.41	26.66
March	73.41	49.18	26.37	29.60
April	58.31	61.58	29.90	32.31
May	77.53	71.61	41.71	41.78
June	79.66	72.36	42.17	42.96
July	84.72	72.61	42.30	44.82
August	82.88	73.24	42.66	46.92
September	80.75	72.61	42.30	45.63
October	67.93	70.48	35.14	39.76
November	50.48	50.98	25.78	31.37
December	55.43	40.36	23.33	26.56
Average	76.64	59.54	33.17	36.20
Minimum of Months	50.48	39.68	22.98	26.05
Maximum of Months	117.32	73.24	42.66	46.92

Table 103: Office Monthly Peak Electricity Demand - Harbin Climate Region

	HB	Duluth – HB Sched. Set pts., Loads	Duluth – HB Sched. Set pts.	Duluth
January	30.13	30.70	18.81	18.08
February	30.01	30.66	18.80	17.96
March	29.71	30.64	18.78	17.96
April	29.57	54.39	27.98	29.32
May	29.45	68.97	32.54	33.89
June	29.45	77.26	35.09	36.64
July	29.45	63.34	31.55	32.26
August	29.45	65.04	32.74	33.56
September	29.45	56.28	29.84	31.94
October	29.51	43.29	27.48	28.95
November	29.77	30.65	18.79	17.96
December	30.05	30.67	18.80	17.99
Average	29.67	48.49	25.93	26.38
Minimum of Months	29.45	30.64	18.78	17.96
Maximum of Months	30.13	77.26	35.09	36.64

Table 104: Hotel Monthly Peak Electricity Demand - Guangzhou Climate Region

	GZ	Houston – GZ Sched. Set pts, Loads	Houston – GZ Sched. Set pts	Houston
January	27.17	32.90	26.88	26.74
February	28.32	33.16	27.16	26.07
March	33.66	35.41	29.08	31.26
April	35.75	36.74	30.44	33.42
May	40.08	38.59	32.30	37.11
June	39.15	38.96	32.73	36.97
July	39.62	38.92	32.62	38.09
August	39.18	38.96	32.70	37.17
September	38.04	38.42	32.24	37.13
October	36.34	37.82	31.56	34.09
November	31.92	34.98	28.84	28.71
December	27.48	32.89	26.92	26.57
Average	34.73	36.48	30.29	32.78
Minimum of Months	27.17	32.89	26.88	26.07
Maximum of Months	40.08	38.96	32.73	38.09

Table 105: Hotel Monthly Peak Electricity Demand - Harbin Hotel

	HB	Duluth – HB Sched. Set pts., Loads	Duluth – HB Sched. Set pts.	Duluth
January	22.84	33.80	33.01	34.72
February	22.88	28.34	30.35	30.79
March	24.04	24.29	28.46	25.57
April	31.95	33.20	37.28	31.76
May	32.24	33.64	37.85	33.55
June	32.49	33.97	38.24	35.92
July	31.25	33.36	37.50	32.53
August	32.13	33.65	37.89	33.74
September	28.97	32.16	36.32	29.03
October	24.43	27.57	31.71	23.99
November	22.41	30.42	31.40	31.85
December	22.66	30.95	32.56	33.01
Average	27.36	31.28	34.38	31.37
Minimum of Months	22.41	24.29	28.46	23.99
Maximum of Months	32.49	33.97	38.24	35.92