PRIORITIZING ENERGY CONSERVATION MEASURES FOR BUILDING STOCKS

SCREENING METHODOLOGY FOR PRIORITIZING ENERGY CONSERVATION MEASURES FOR OFFICE BUILDING STOCKS

By

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Abstract

As energy costs continue to escalate and awareness spreads with regard to the importance of sustainability, interest in reducing energy consumption of buildings is growing. For managers of large stocks of office buildings, the task of selecting building improvement projects is most challenging. A multitude of energy conservation measures (ECMs) are available from which to select, however financial resources are limited and in high demand. Thus, ECMs must be known to be effective and prioritized so as to provide the highest benefit for the financial resources available.

The aim of this study is to provide a screening methodology for the evaluation and prioritization of ECMs for implementation in a stock of buildings that exhibit varying characteristics and locations. Prioritization of ECMs is based on predicted energy consumption savings and financial analysis. Building stocks are reduced to a manageable set by applying archetype classification. Energy consumption predictions for representative buildings from each archetype are obtained through use of a mathematical model. Twelve ECMs pertaining to improvements in the building envelope, HVAC, and electrical systems are considered and ranked based on present value over the short, mid, and long terms.

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Chapter 1: Introduction

1.1 Global Energy Trends

The health of the environment and the sustainability of energy resources are ever growing concerns faced across the globe. As the world population continues to expand and countries further their economic development, demand for energy is escalating (United Nations Department of Economics and Social Affairs Population Division, 2009; The World Bank, 2010). Coupled with larger energy production and energy use are increases in green house gas (GHG) emissions and diminishing natural resources, both of which negatively impact the environment. There is a strong need to reduce energy consumption to correct and prevent further environmental damage and ensure energy resources are available for future generations. International recognition of the situation and the necessity for action has been made most notably through the development of the Kyoto Protocol in 1997, an agreement among industrialized countries to commit to reducing GHG emissions compared to 1990 levels (United Nations Framework Convention on Climate Change [UNFCCC], n.d.). In 2009, discussions among international leaders lead to drafting of the Copenhagen Accord, an international agreement which addresses the continuation of the Kyoto Protocol (UNFCCC, n.d.).

1.2 Energy Trends in Canada

The global situation is reflected in Canada, where energy demands are growing primarily due to population and economic growth, extreme temperatures and low energy prices (National Round Table on the Environment and the Economy & Sustainable Development Technology Canada [NRTEE & SDTC], 2009). The latest statistics available for 2007 indicate that eighty-two percent (82%) of GHG emissions are attributable to energy production and consumption in the country (Environment Canada, 2009). As part of the Government of Canada's obligations to the environment under the Kyoto Protocol, short-term and long-term commitments were made to reduce GHG emissions to twenty percent (20%) below the 2006 levels by the year 2020 and sixty to seventy percent (60-70%) below the 2006 levels by the year 2050 (Environment Canada, 2009). Finding alternatives to energy intensive practices and increasing energy efficiency to reduce demand, as well as adopting energy production methods with low environmental impact will contribute significantly to reaching these goals

(NRTEE & SDTC, 2009).

1.3 Energy Use in Canadian Office Buildings

Improving energy efficiency in non-residential buildings has great potential to curb increases in energy consumption and GHG emissions over the coming years. The National Round Table on the Environment and the Economy (2006) estimates energy efficiency can reduce carbon emissions by fifty-eight percent (58%) from the business-as-usual scenario by the year 2050; "twenty-two percent (22%) from existing building retrofits and energy management; twenty percent (20%) from integrated building systems for energy efficiency in new buildings; and sixteen percent (16%) from electrical efficiency in lighting and equipment," (NRTEE, p.23). The significance of potential reductions in this area is not surprising given that the commercial/institutional sector is one of the two fastest growing areas with respect to energy consumption, along with the transportation sector, and the most rapidly growing with respect to GHG emissions; growth rates between 1990 and 2007 were thirty-two percent (32%) and thirty-six percent (36%) for energy use and GHG emissions respectively (Natural Resources Canada [NRCan], Office of Energy Efficiency [OEE], 2010). Left unchecked, the proportions of overall secondary energy end use and GHG emissions in this sector will be much larger in the future than those most recently reported in 2007 of thirteen percent (13%) and fourteen percent (14%) respectively (NRCan, OEE, 2010).

Positive effects of energy efficiency improvements over the past two decades have been realized however are not enough to offset the coinciding growth due to increases in the number of new buildings, growing auxiliary loads, higher occupancy densities, and sub-optimal building control (NRTEE & SDTC, 2009). As is presented in Figure 1.1, activity effect (increased floor area) and service level effect (increased equipment loads) considerably outweigh the energy efficiency effect on overall energy consumption (NRCan, OEE, 2008). From this standpoint, it is clear that a more concerted effort needs to be made to reduce overall energy consumption within the commercial/institutional sector.

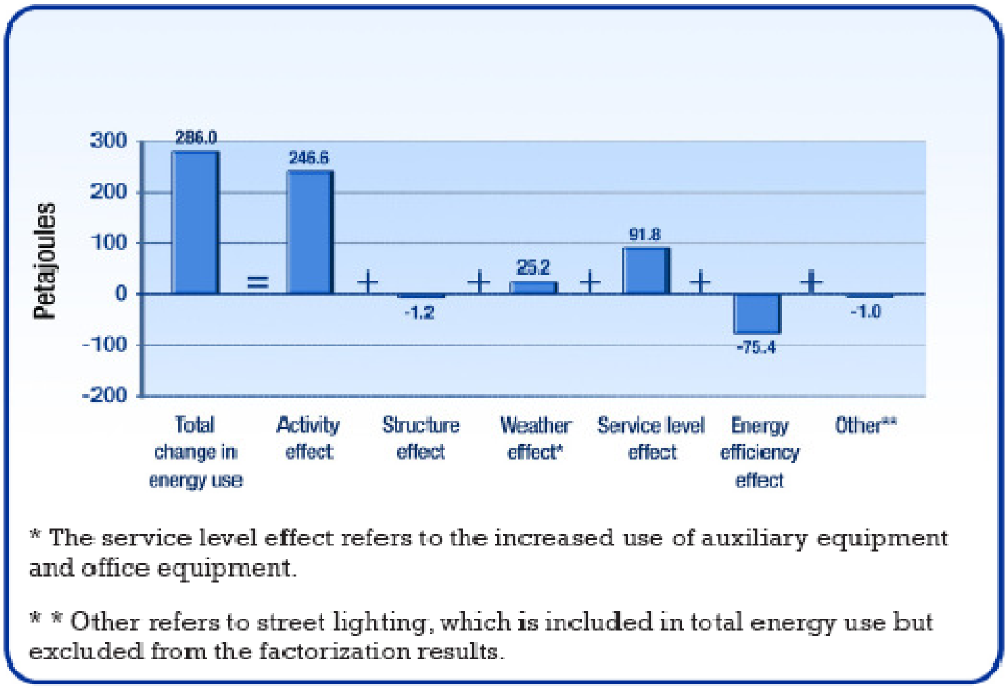

Figure 1.1: Factors affecting energy use in the commercial/institutional sector between 1990 and 2005 (NRCan, OEE, 2008, fig. 4.11)

Offices account for the largest percentage of energy use within the commercial/institutional sector (forty-one percent (41%) in 2007), which also includes retail, trade, educational services, health care and accommodations (NRCan, OEE, 2008). Although energy intensity (GJ/m^2) for offices has fluctuated, floor space between 1990 and 2007 steadily escalated by forty-four percent (44%), leading to an overall increase in energy consumption and GHG emissions (NRCan, OEE, 2010).

Numerous energy conservation measures (ECMs) are available to reduce energy consumption in office buildings, however retrofit rates remain low. In 2005, the annual rate of retrofit in commercial buildings was two percent (2%) (NRTEE & SDTC, 2009). The most predominant challenge restricting the implementation of ECMs is the lack of information available to building owners, including unawareness of current consumption levels and opportunities for savings (NRTEE & SDTC, 2009). Building owners are faced with the questions: what ECMs are applicable?; which will be the most beneficial?; and which are financial feasible? This challenge is particularly onerous when a large stock of buildings is considered, such as is the case for governments and large organizations where the number of buildings under their control can reach into the hundreds, if not thousands (International Energy Agency Annex 46, 2009).

1.4 Objective and Scope

For owners of large stocks of buildings, it is important to be able to accurately and efficiently determine applicable ECMs and prioritize the order of implementation. Many tools have been developed to aid decision makers with the challenge of prioritizing retrofit scenarios, including analysis of predicted energy consumption prior to and after the implementation of ECMs. However, the majority of available decision programs are designed to evaluate buildings on an individual basis. In addition, the level of building detail required as input becomes unmanageable for large numbers of buildings.

The objective of the work presented herein is to develop a screening methodology for office buildings, applicable to large building stocks, which presents the user with an optimal order of implementation of financially viable ECMs for a defined set of building archetypes. Centred on a mathematical model to predict energy consumption, the goals of the method are to be easy to use, efficient, timely, and accurate within a margin of error acceptable for preliminary decision making. Evaluation of the ECMs is based on overall energy savings and present value (PV) financial analysis.

The ECMs considered in the analysis address improvements in the building envelope, lighting, and HVAC systems. Although optimization of building controls is an effective means of reducing energy consumption of existing buildings, the costs associated with implementing such measures is negligible in comparison to that of the ECMs considered herein, and is presumed to have been implemented previously where applicable.

1.5 Thesis Outline

The outline of the work presented in this thesis is as follows. In the first chapter, the context of the work and a description of the problem to be addressed are defined. Chapter 2 includes a review of decision tools and energy prediction methods currently found in the literature. Potential energy conservation measures are introduced in Chapter 3. In Chapter 4, the methodology of the screening process is presented, covering the basis of the approach and the mathematical model used to predict energy consumption. The methodology is verified in

Chapter 5, with comparison of energy consumption prediction results from the mathematical model for a set of sample buildings to those obtained through simulations. The prioritization results for these buildings are also presented. Chapter 6 contains conclusions and recommendations for future work.

Chapter 2: Decision Tools and Energy Consumption Prediction Methods

The optimal selection of ECMs for buildings is a complex problem facing building owners, especially for those managing large stocks of buildings. Several decision tools are available to assist the decision maker in this situation. Energy savings resulting from the implementation of ECMs is often of primary focus in the evaluation and is required as input. As such, calculation of the predicted savings is frequently incorporated into the programs. A review of decision tools and various methods for predicting energy consumption are discussed herein.

2.1 Decision Tools for Selection of ECMs

Based on a review of current literature, several decision tools are available to assist owners faced with the task of selecting and prioritizing ECMs. Two general categories of programs are apparent: decision support tools that present the user with relevant information upon which to base decisions, and decision making tools that use algorithms to suggest optimal solutions. Within these two categories, the programs exhibit varying characteristics with respect to: scope of building elements considered, overall goals of improvements, approach to establishing existing building conditions/performance, scope of improvement scenarios, incorporation of energy consumption prediction methods, and evaluation criteria. Tools that present the user with suggestions for retrofit, classified here as decision support tools, are TOBUS and the Energy Concept Adviser. Decision making tools reviewed include: an integrated decision support model, a hybrid decision support system, and a multi-criteria assessment methodology. The OFFICE project bridges both categories, including both decision support tools and ORME, a multi-criteria rating methodology. A comparison of the decision tools reviewed is included in Table 2.1. Similar to some decision making tools, multi-criteria mathematical optimization techniques have been applied to building models to determine the ideal building characteristics, taking into account energy consumption and economic factors. This approach is also presented.

Table 2.1: Decision Tool Comparison

Name	***Building Type***	***Pre- / Post- ECM Energy Predictions***	***Evaluation Criteria***	***Decision Method***
Decision Support Tools				
TOBUS / XENIOS / EPIQR	offices / hotels / apartments	internal calculations based on audit / internal calculations	IEQ, degradation, obsolescence, energy savings	user comparison
Energy Concept Advisor	schools	user input / case studies	energy savings	user comparison
Decision Making Tools				
Intelligent Decision Support Model	offices	BEMS building mgmt system / case studies	performance indexes	decision support algorithm
Hybrid Decision Support System	offices	n/a	sustainability scores, cost	hybrid algorithm
Office Retrofit Strategies	offices	energy simulations / energy simulations	environmental, socio-cultural, economic factors	Electre III software
ORME (OFFICE Project)	offices	user input / case studies	energy savings, IEQ, environmental impact	Electre III software

2.1.1 Decision Support Tools

Developed under the Joule III project of the European Commission, TOBUS is designed to aid experts in office building audits to assess the degradation, energy performance and functional obsolescence of the building, and identify indoor environmental quality issues (Caccavelli & Gugerli, 2002). Based on building improvement needs, the user is presented with improvement scenarios including energy consumption savings determined through internal calculations and cost estimates using an internal cost database as evaluation criteria. Related programs, XENIOS (Dascalaki & Balaras, 2004) and EPIQR (Jaggs & Palmer, 2000) have been developed on the same basis for application to hotels and educational buildings respectively.

Resulting from the work of the Annex 36 project, the Energy Concept

Adviser is a tool to aid in the selection of optimal ECMs for educational buildings based on case study results (Erhorn et al., 2008). Once the building is defined and energy consumption data imported, the user is presented with a comparison of the current building to the case studies in the database to determine current performance levels and potential retrofit scenarios. The evaluation criteria presented to the user are energy savings and simple payback period based on initial cost and energy cost savings.

Annex 46 has been developed to extend the work of Annex 36 through development of the IT-Toolkit that is comprised of ten different tools used for the collection, management, and assessment of energy data, and assessing energy retrofit measures based on energy saving potential and financial analysis. The work of Annex 46 also expands the scope of the previous work to include most public buildings (International Energy Agency Annex 46, 2009; International Energy Agency Annex 46, n.d.).

2.1.2 Decision Making Tools

Doukas et al. (2009) present an intelligent decision support model to be integrated with building energy management systems (BEMS) to determine optimal energy saving measures. Based on comparison of performance indexes with standard building indexes, opportunities for improvements are recognized. A decision support algorithm utilizes historical building performance, energy saving information from a case studies database, and user-supplied cost information to determine optimal energy saving measures.

Improving building sustainability is the goal of a hybrid decision support system described by Juan et al. (2010). Sustainability scores, as calculated based on a combination of green building rating program criteria, and implementation cost, calculated from an internal database, are the basis of evaluation. A hybrid between a genetic algorithm and a best-first algorithm provides an optimal solution and alternatives that maximize the sustainability score while staying within the user's budget.

A multi-criteria assessment methodology for retrofits, mainly focused on facades, is laid out by Rey (2004). Combining environmental, socio-cultural, and economic factors, various levels of retrofit options are compared using the Electre III decision software. Pre- and post-retrofit energy consumption predictions are entered by the user.

The OFFICE project, partly funded by the European Commission under the Joule-Thermie program, falls into both of the categories defined here. The project aims to assemble an information database of global retrofit scenarios focused on passive solar and energy efficiency retrofits for various types of office buildings in various European locations (Santamouris & Dascalaki, 2002). Also within the scope of the project is the development of ORME, a ranking and rating tool for buildings and retrofit scenarios based on energy use, environmental impact, indoor environment quality, and cost (Roulet et al., 2002).

2.1.3 Multi-criteria Mathematical Optimization

Similar to decision making tools, multi-criteria optimization is used to select optimal alternatives for building improvements. This technique is applied to mathematical building models and is used in conjunction with energy simulation software tools.

Diakaki, et al. (2008) discuss the applicability of multi-criteria optimization in selecting building envelope components to improve the energy efficiency of a building. The method uses mathematical objective functions to minimize overall cost and energy consumption, and constraints that limit the selection to one alternative per component. The optimization software LINGO is used for the analysis.

Alternately, Ellis et al. (2006) and Hasan et al. (2008) present the use of multi-criteria optimization programs that are linked to text input and output simulation tools to determine optimal building solutions. Ellis et al. (2006) outline an optimization tool based on a custom optimization program linked with DOE-2 simulation software to find building solutions that minimize both cost and energy consumption. In considering design options for the construction and HVAC systems of a residential dwelling, the approach described by Hasan et al. (2008) uses the optimization program GenOpt linked with the simulation program IDA ICE 3.0 to minimize life cycle cost. In both cases, the optimization program uses search techniques to determine the input values for the simulation program based on the previous simulation results.

2.2 Energy Consumption Prediction Methods

Energy consumption is an important consideration in the assessment and selection of ECMs. In order to effectively evaluate the impact of ECMs on building performance, it is essential to determine the current energy usage in order to establish a basis for comparison. Likewise, it is necessary to predict post-retrofit energy consumption to quantify the effects of ECMs.

Estimates of current energy usage can be obtained through monitoring and evaluation of energy bills, however using this approach it is difficult to determine consumption of specific systems and building components. Evaluation of the effects of ECMs after installation is also possible, however implementation is a costly investment with regard to financing and time, making it impracticable to implement ECMs before assuring positive benefits will be realized. By predicting energy consumption using computer based tools, assessment of multiple ECMs is possible in a timely and cost effective manner.

Several energy consumption prediction methods are available to assess the energy performance of buildings. These include simplified energy calculations, energy simulation software packages, and mathematical models. These are discussed further in the following subsections.

2.2.1 Simplified Energy Calculations

Simplified energy calculation methods are based on equations using the indoor-to-outdoor temperature difference to estimate energy consumption. Usually focusing on heating and/or cooling, this method is designed to be simple enough to be carried out manually and is often used in energy audits (Al-Homoud, 2000). Examples of simplified calculation methods are the degree-day method and the bin method, and the variations of each (Al-Homoud, 2000; Knebel, 1995).

The degree-day method is a steady-state method to predict heating energy consumption based on the assumption that a building will be in a state of energy balance with the environment when the outdoor temperature is 18.3°C (65°F) and energy consumption will be proportional to the difference between the mean daily temperature and 18.3°C (Al-Homoud, 2000). This method can be applied to cases where the "building use, HVAC equipment efficiency, indoor temperature and internal gains are relatively constant," (Caneta Research Inc., 1996, p. 1). The modified degree-day method incorporates a correction factor to account for inaccuracies in the base assumption, while the variable-base degree-day method uses a calculated balance point temperature as the reference allowing for calculation of cooling as well as heating energy consumption (Al-Homoud, 2000; Knebel, 1995). Even with these updates, the application to commercial buildings is very limited (Knebel, 1995).

The bin method is applicable for estimating heating and cooling consumptions of larger buildings where energy use does not vary linearly with outdoor temperature. Energy consumption is calculated at various outdoor temperatures (bins) and then multiplied by the number of occurrences throughout the year (Al-Homoud, 2000; Caneta Research Inc., 1996; Knebel, 1995). Total annual energy consumption is the sum of the products. The modified bin method takes the calculations further by using averages rather than peak loads in the analysis, increasing the accuracy of the method (Al-Homoud, 2000).

The attractiveness of simplified energy calculations lies in the simplicity and ease of use of the methods (Jaffal et al., 2009). However, the most predominant drawback is in the inaccuracy of results (Catalina et al., 2008; Jaffal et al., 2009). Interactions of building systems are not incorporated in the calculations and generalizations of building properties (e.g. lumping all envelope U-values together) does not allow for detailed analysis of components (Jaffal et al., 2009). Building morphology and thermal inertia are also not considered (Catalina et al., 2008). While not precise, this method is useful for identifying trends in overall energy consumption (Al-Homoud, 2000).

2.2.2 Energy Simulation Software

Energy simulation software programs are designed to model the behaviour of buildings as closely as possible to accurately predict energy consumption. Buildings respond to changing weather conditions and occupant use in a nonlinear manner. In order to capture the dynamic effects of the influences and responses, calculations are performed at small time step intervals of an hour or less using inputs such as hourly weather data, occupancy and operational schedules, and part-load efficiency curves.

Simulation programs are typically broken down into three primary components: load, system, and plant (Al-Homoud, 2000; Caneta Research Inc., 1996; Sowell & Hittle, 1995). The load component determines heating and cooling loads due to heat transfer across the building envelope, ventilation requirements to maintain comfortable indoor conditions, and loads from internal systems (e.g. lighting and equipment). The most common approaches taken for determining heating and cooling loads is either through use of weighting factors or heat balancing methods. With the weighting factors approach, pre-calculated factors are used to convert the heat gain to the building spaces into cooling or heating loads on the air (Sowell & Hittle, 1995). On the other hand, the heat balance method uses detailed models of the thermal transfer processes across the building envelope to calculate loads from heat gains (Sowell & Hittle, 1995). The system module addresses the energy requirements of secondary systems, such as the ventilation including fans and pumps, for distribution of energy from the plant throughout the building. Within the plant component, the energy requirements for converting primary fuel sources into heating or cooling energy through the boiler and chiller systems are calculated. These components are linked in one of two ways, sequentially in series where one feeds the next, or simultaneously integrated with each other to account for interactions between the components (Al-Homoud, 2000; Crawley et al., 2008). In some cases, a fourth component is included in the software that gives the user opportunity to analyze the economical aspects of the building design and energy performance (Al-Homoud, 2000).

The primary advantage of energy simulation software is the ability to model large and complex buildings of various types with a high level of detail and accuracy (Al-Homoud, 2000; Caneta Research Inc., 1996; Catalina et al., 2008; Jaffal et al., 2009). They are most useful in situations where systems are highly integrated or interdependent (Pan et al., 2007). However, to gain these benefits, detailed input data is required and simulations may take an extended time to run. Owing to the complexity of the programs they are best used by experienced users and require significant time for learning, adding to the cost of their use (Al-Homoud, 2000; Caneta Research Inc., 1996; Lam et al., 1997; Signor et al., 2001; Turiel et al., 1984).

Comparisons between simulation programs proves difficult due to the lack of consistency in defining terms to describe methods and components of the various software available (Crawley et al., 2005). Hundreds of energy simulation packages have been developed over the past few decades, each with unique variations. A brief overview of four commonly used building simulation programs, BLAST (US Army Construction Engineering Research Laboratory, 1977), DOE-2 (Lawrence Berkeley National Laboratory [LBNL], 1979), EnergyPlus (LBNL, 1996), and TRNSYS (Solar Energy Laboratory, 1988), is given here.

BLAST is an energy simulation tool developed by the US Army

Construction Engineering Research Laboratory and the University of Illinois. The software is designed to perform whole building energy simulation calculations using three subprograms: space loads prediction, air system simulation, and central plant (Crawley, et al., 2005). Loads are calculated using heat balance calculations. The last release of the program was in 1998 (Crawley et al., 2005).

Developed by the US Department of Energy and Lawrence Berkeley National Laboratory, DOE-2 is a widely used program in the building industry (LBNL, 1979). This simulation software predicts hourly energy use and energy cost using four sequential subprograms: loads, system, plants, and economics (Crawley et al., 2005). Input data is taken in by the Building Description Language (BDL) processor, which also calculates the weighting factors to determine space heating and cooling loads (Crawley et al., 2005).

Deemed as the next generation of whole building simulation tools, EnergyPlus has been developed by the US Department of Energy and Lawrence Berkeley National Laboratory, using the most favourable features of BLAST and DOE-2 (Al-Homoud, 2000; Crawley et al., 2005; LBNL, 1996). The program is of a modular structure with three main components, surface heat balance manager, air heat balance manager, and building systems simulation manager, governed by a simulation manager and fed my multiple sub-modules (LBNL, 1996). By integrating the modules at each time step, more accurate prediction of space temperatures is possible, allowing for more detailed analysis of system controls, moisture transport, radiant heating and cooling systems, and inter-zone air flow (Al-Homoud, 2000; Crawley et al., 2005).

TRNSYS is another whole building simulation tool, developed by Solar Energy Laboratory at the University of Wisconsin-Madison, designed to analyze the transient behaviour of systems (Solar Energy Laboratory, 1988). The software has a modular structure and uses “types”, which can vary in scale from individual pipes or wall layers to multi-zone buildings, to define the system (Crawley et al., 2005). Energy predictions are made by simultaneous solution of systems of algebraic and differential equations that represent the whole system (Crawley et al., 2005). Loads are calculated using the heat balance method.

2.2.3 Mathematical Models

As a compromise between simplified energy calculations and complex simulation programs, mathematical models have been developed using regression analysis to provide a means of determining building energy consumption accurately and efficiently (Catalina et al., 2008).

The bases of the models are databases of building simulation results as determined by an energy simulation program. Using this set of data, regression analysis is performed to determine the coefficients of predefined equations which use building characteristic parameters as the variables. To identify the variables to be included in the equations, the influence of each on the overall energy consumption is determined through simulations, changing single parameter values at a time. Alternately, variables are selected based on building physics or by logical selection and the statistical relevance of the variables is calculated afterwards, making the model development an iterative process (Kavgic et al., 2010). Once the model is developed, it is verified by comparing results with simulations for buildings with parameter values not included in the initial database.

By joining the use of simulations with calculation methods, the mathematical models benefit from the accuracy of the dynamic simulation programs while reflecting the simplicity of use of the simplified energy calculations (Jaffal et al., 2009). Additional benefits of this energy prediction method are the simplification of input data as compared to dynamic simulations, quick estimations, minimal training time, and cost effectiveness (Catalina et al., 2008; Freire, Oliveira, & Mendes, 2008; Jaffal et al., 2009; Turiel et al., 1984). These benefits come at the cost of lower accuracy for complex buildings, use of the model limited to buildings similar in character to those in the database, a large number of simulations needed to obtain reasonable accuracy of the results, and limited ability to model new systems (Catalina et al., 2008; Jaffal et al., 2009). Linear models have been found to be inaccurate, however nonlinear models can prove to be quite precise (Catalina et al., 2008).

Numerous models have been developed using regression techniques to derive equations based purely on statistical relevance, or a combination of statistics and building physics. Some are designed to be applicable to multiple buildings as they include shape factors in the variables, while others do not and are thus limited to the single buildings used in the model development. A brief overview of a select representation of these models is included below.

Models that do not include shape factors are applicable only to a single building configuration. Examples of these are given by Lam et al. (1997), Turiel et al. (1984), Freire et al. (2008), and Chidiac et al. (2011a). Lam et al. (1997) found twelve variables to be statistically relevant for predicting load, system and plant energy consumption for a high-rise office building through a 2nd order polynomial equation. DOE 2.1E was used to create the simulation database. The model developed by Turiel et al. (1984) based on DOE 2.1 simulations uses eleven variables in an equation to predict heating and cooling energy use in an office building. The format of the equation is a summation of linear, quadratic, and cubic polynomials based on curves fitted to simulation results. Mathematical models are also useful for predicting outcomes other than energy consumption. The model developed by Freire et al. (2008) predicts indoor temperature and relative humidity for a generic building based on simulation results using PowerDomus. The first order equation uses five variables related to the building characteristics as input. Regression models have been developed in earlier stages of the current project. The model by Chidiac et al. (2011a) is a simple regression model of thirty-five variables in a 3rd order equation based on simulations run in EnergyPlus.

Models applicable to multiple building configurations are by Jaffal et al. (2009), Signor et al. (2001), Catalina et al. (2008), and Chidiac et al. (2011b). The regression model presented by Jaffal et al. (2009) is designed to predict annual energy use for a generic building type using a 2nd order polynomial equation including select interactions. Eleven variables are used in the model, which is based on simulations run in TRNSYS. Electricity consumption of office buildings is predicted in the model by Signor et al. (2001), which uses eleven variables and includes various interaction terms determined by simulations and building physics. The simulation database was created using DOE 2.1. Designed for residential buildings, the model presented by Catalina et al. (2008) predicts annual or monthly heating energy consumption through a 2nd order polynomial equation that includes all interactions of five variables. TRNSYS was used for the simulation database. The latest model developed under the current project, presented by Chidiac et al. (2011b), employs a combination of heat balance and regression analyses. Select interaction terms are included based on their statistical relevance.

2.3 Discussion

Many decision tools are available to assist in selecting optimal retrofit scenarios for buildings. Even so, none are suited to determine the priority of ECMs for large building stocks. All of the decision tools considered herein are intended to assess buildings on an individual basis. Several programs require a significant amount of data to be entered by the user, in some cases including initial and/or post-retrofit energy performance. These requirements render the programs of little use when applied to large building stocks as the time and effort necessary for their use is excessive in this situation. Basing energy savings on case study results is an alternate approach used in some programs. Although this saves time and effort, the results are not specific to the buildings being evaluated, which may lead to inaccuracies in the results.

Decision support tools present the user with information upon which to base selection of ECMs. The decision maker is aware of all criteria leading to the final decision, but is left to analyze the data and weigh conflicting factors. When a large amount of information is given this task becomes onerous. Decision making tools relieve the user of the responsibility of drawing final decisions, but do not allow for transparency of factors leading to the results or a ranking of possible alternate solutions. As well, consideration of unique or unquantifiable criteria is not possible. Multi-criteria optimization methods also do not allow for transparency of the decision making process or a ranking of results, however they do allow for solutions that are not dependent upon pre-defined alternatives. This method has been shown to work well when integrated with energy simulation software, however Diakaki et al. (2008) found that no unique solution could be found to the multi-criteria decision problem using simplified building model equations and that the problem becomes far more difficult to solve when additional goals and alternatives are included.

As seen in the review of decision tools, consideration is given to the effect of ECMs on energy consumption either through estimation within the program or from data input by the user. Simplified calculations are the easiest to implement, however do not give the accuracy needed to reliably compare ECMs. The equations also may not be detailed enough to capture the changes resulting from implementation of specific retrofits. Use of energy simulation software is the most accurate method of predicting energy consumption before and after retrofit, however the most challenging aspect in using this method is the time needed to run simulations of large stocks of buildings and the various alternatives for each. Interactions between system components are not apparent and without running alternate scenarios, little indication is given as to where improvements can be made and what savings will result (Jaffal et al., 2009). Mathematical models based on regression analysis of simulation results provide a means of efficiently and accurately determining building specific energy consumption results and give the user insight into the interactions of system variables.

As the goal of the current project is to provide a screening methodology for use in prioritizing ECMs for large building stocks, development of a tool that shows results of all ECMs and incorporates use of a mathematical model for energy predictions is desirable. This approach gives the user transparency of the decision making process while relieving the burden of the analysis. Results of the model will be specific to the buildings in the stock and also possess the accuracy of simulation results.

Chapter 3: Energy Conservation Measures (ECMs)

A wide array of energy conservation measures (ECMs) are available to building owners as a means of reducing energy consumption in office buildings. Many measures offer substantial potential for energy use reduction leading to utility cost savings, GHG emission reductions, and improvement in the indoor environmental quality (IEQ) with benefit for building owners, the environment, and occupants alike. The focus of this work is on the improvement of existing buildings, as this is the area that will have the greatest impact on the overall reduction of energy consumption and GHG emissions in the commercial/institutional sector, particularly in the short term. Some factors affecting energy consumption, such as building shape and orientation, window-to-wall ratio, inclusion of day lit areas, and layout of HVAC systems can be considered only in the design of new construction, however most ECMs are feasible for both new construction and existing building upgrades.

ECMs pertaining to improvements in the building envelope, HVAC systems, and lighting are considered in this study. Those that can be reflected readily using the variables included in the mathematical model, as is presented in Chapter 4, were chosen to be discussed in depth. Passive retrofit measures include improving the air tightness of the building envelope around perforations and reducing heat transfer through the building envelope with improvements to the thermal resistance of the roof, walls and windows. Active ECMs pertaining to the HVAC system include use of economizer controls, conversion to variable-air-volume (VAV) ventilation, installation of a heat recovery unit, and improvements in chiller and boiler efficiencies. Replacement of lighting fixtures and installation of daylighting controls are also considered in this work. In the following sections, descriptions of each of the ECMs, advantages and disadvantages, and case studies showing the potential for savings are discussed.

3.1 Building Envelope Air Tightness

Buildings that exhibit poor air tightness consume higher levels of energy and are at risk of problems such as mould growth within the building envelope, occupant discomfort, and poor indoor environmental quality (IEQ) (Anis, 2001; Emmerich et al., 2007; Fennell & Haehnel, 2005). Heat exchange between the indoor and outdoor space via infiltrating or exfiltrating air increases the heating and cooling demand of the zone, there by increasing the energy consumption of the HVAC system as it works to maintain room temperatures within heating and cooling set points (Woods et al., 1995). Replacing sealants at joints in the building envelope to restore the air tightness of the building and limit uncontrolled air movement across the building envelope is proposed as an ECM.

The air barrier, an important component of the building envelope, is used to limit air exchange between the outdoor environment and the indoor conditioned space (American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc. [ASHRAE] et al., 2004). An effective air barrier system is continuous throughout the building envelope and includes joints and seals at locations of discontinuity, namely between envelope components such as around windows and doors, penetrations for ducts, conduits, and exterior lighting, and at wall, floor, and roof interfaces (Anis, 2005; Woods et al., 1995). Window perimeters contribute substantially to uncontrolled air infiltration (Woods et al., 1995). As joints are exposed to the elements, they are most susceptible to deterioration in the form of drying, cracking, and separation from adjacent surfaces. By replacing damaged sealants, air tightness can be restored in these areas, leading to improved energy efficiency (Woods et al., 1995). Studies have also shown reduction of the peak energy demand through re-sealing of joints (Woods et al., 1995).

Increasing the air tightness of a building through the replacement of joints and sealants is an attractive retrofit. It is undisruptive to the tenants and operation of the building, relatively inexpensive, and requires low labour intensity to complete. The regular replacement of sealants is typically part of a regularly scheduled maintenance plan to prevent water penetration into the building envelope that is paid out of the operating budget. In this case, there is no additional cost to realize energy savings. In addition to preventing energy loss, increasing air tightness reduces transfer of water vapour, smoke, odours, dust, and other pollutants into the building, increasing the IEQ (Anis, 2001). The most notable drawback to this ECM is the short lifespan of the sealants. In order to maintain air tightness, replacement should be expected approximately every five years. In addition, should the air barrier be compromised in inaccessible locations within the building envelope, the expected savings from resealing of the accessible joints may not be realized.

It is commonly accepted that air infiltration can increase energy consumption of a building by up to forty percent (40%) (Air Barrier Association of America, 2009; Anis, 2005; IPCC, 2007; Orme, 2001). Examples of successful retrofits on different building types are found in the literature. The sealing of the perimeter of penetrations in the building envelope in two highrise apartment buildings in Ontario saved thirty-two percent (32%) and thirty-eight percent (38%) of overall energy use (Woods et al., 1995). Similar measures simulated for implementation in the Hellenic residential building stock showed potential overall savings of sixteen to twenty-one percent (16-21%) (Balaras et al., 2007). Chidiac et al. (2011c) show potential savings of between fifty-one to sixty-four percent (51-64%) natural gas savings due to reduced air infiltration in Canadian buildings. Jenkins et al. (2009) predict reduced heating load and increased cooling load due to reduced air infiltration in UK offices. The cooling load increase is less than the decrease in heating load, resulting in overall energy savings. Several additional studies document the importance of including an air barrier system in the building envelope design. For example, Emmerich et al. (2007) show forty percent (40%) natural gas and twenty-five percent (25%) electricity savings in a two-storey office building in a heating-dominant climate from the installation of an air barrier system. In addition, the report prepared by ConSol (2008) for the NAIOP Commercial Real Estate Development Association identifies air infiltration reduction as one of the top ECMs in multiple climate zones within the United States of America with total energy savings ranging from 4.7% to 10.3%.

3.2 Building Envelope Thermal Resistance – Opaque Constructions

A common approach to increasing building energy efficiency is to lower internal loads by reducing the thermal conductance of the building envelope (Aste et al., 2009; Balocco et al., 2008). Energy consumption of the heating and cooling systems is lessened due to lower demands as temperature variations within the building are stabilized. Thermal insulation is an important component of the building envelope in controlling heat transfer between the indoor and outdoor spaces. During cold seasons the insulation layer limits heat loss, and in hot seasons, mitigates excessive heat gain. Adding insulation to the roof or walls increases the thermal resistance of the building, leading to energy savings as well as improved thermal comfort and IEQ (Balocco et al., 2008).

3.2.1 Roof Insulation

Typically the roofs of commercial buildings are flat and easily accessible. This makes the addition of insulation to the existing construction easily achievable and straightforward. Particularly if installation or upgrading of insulation is scheduled to coincide with re-roofing, the additional effort required to improve the performance of the roof is minimal and the costs associated with the ECM are minimized (Burn & Roux, 1982). In addition to thermal benefits, re-roofing also provides the opportunity for damaged or inadequate details to be addressed. The interface between walls and the roof is a common area of air infiltration as the combined effect of wind pressure, stack effect, and HVAC fan pressure is highest at the upper building corners (Anis, 2001). With the use of proper roof details, air infiltration can be reduced, providing additional benefit to the function of the building as previously discussed. Additional insulation on the roof also has potential benefit for the roofing membrane. If placed over top, as pictured in Figure 3.1(a), the insulation protects the membrane from physical damage and ultra-violet radiation, leading to an extended service life (Burn & Roux, 1982). Additional insulation installed below the roof membrane, as shown in Figure 3.1(b), is also effective. Concerns of accelerated deterioration of the membrane due to thermal isolation above the roof deck as a result of increased insulation underneath have been found to be insignificant (Burn & Roux, 1982).

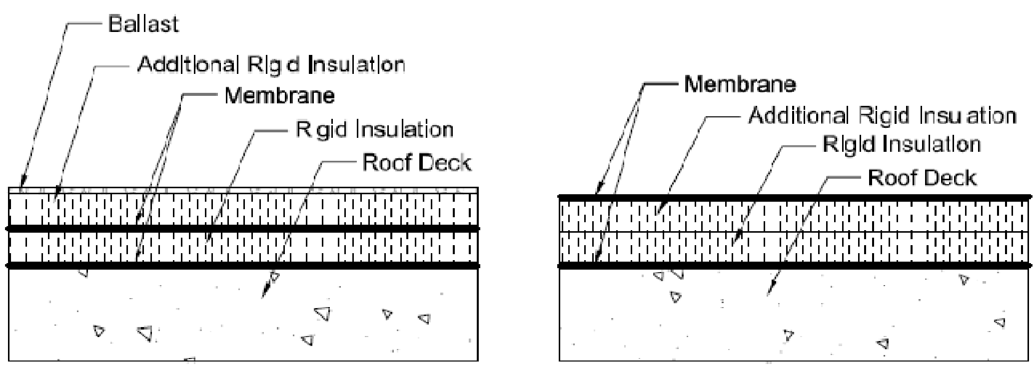

Figure 3.1: Additional roof insulation (a) above roof membrane (b) below roof membrane

The impact of increased thermal resistance of the roof system on energy consumption is highly dependent upon local climate conditions, building geometry (particularly the wall to roof area ratio), and the level of existing insulation (Kashiwagi & Moor, 1993). Research has shown an optimum level of insulation exists for each building, beyond which the energy savings diminish and do not justify the additional costs; however, the financial penalty is less for using too much insulation rather than too little (Cash, 1978; Çomaklı & Yüksel, 2003; Mahlia et al., 2007).

Few examples of building energy upgrades including increased roof insulation thickness are found in the literature. Results reported by Chidiac et al. (2011c) show potential for an average of fifteen percent (15%) overall energy savings due to roof thermal insulation upgrades in Canadian buildings. In the ConSol (2008) report, energy savings of 1.37% to 1.65% above ASHRAE 90.1-2004 standards for R-38 roofs are reported. Meanwhile, significant savings were experiences as a result of upgrading to a high-efficiency envelope as compared to ASHRAE 90.1-2004, including roof improvements, in two office buildings housing data centres in Shanghais, China (Pan et al., 2008). In many countries, roof insulation is not required, however is shown to be beneficial. Several works report on energy savings gained through introduction of roof insulation in various building types in different climatic regions. Within the Hellenic building stock, space heating energy savings as a result of roof insulation installation are given by Balaras et al. (2007) for the residential sector of two to fourteen percent (2-14%), and by Gaglia et al. (2007) for the non-residential sector of four to seven percent (4-7%). In the hot humid climate of Saudi Arabia, additional insulation on an office building roof had minimal impact as less than one percent (1%) of overall energy was saved (Iqbal & Al-Homoud, 2007).

3.2.2 Wall Insulation

Several approaches may be used to increase the thermal resistance of existing walls. Insulating options include polymer insulation blown into the wall cavity, interior spray-foam insulation, or rigid insulation applied to the building interior or exterior. The application of rigid insulation to the building exterior is the least disruptive option to building tenants, requires minimum disturbance or modification to the existing wall construction, and the location on the exterior allows for increased continuity which has the added benefit of reducing air leakage through the building envelope. As such, the use of exterior insulation is considered as the ECM in this study.

3.2.2.1 Exterior Insulation and Finishing System (EIFS)

External Insulation and Finishing System (EIFS) is an effective means of increasing the thermal resistance of existing walls (IPCC, 2007). Originating in Europe in the 1940’s, EIFS was typically installed over masonry walls for the purpose of increasing thermal comfort and decreasing rain and air penetration into buildings (Lstiburek, 2007; Williams & Lamp Williams, 1995). This construction technique has been adopted in North America, however has gained a negative reputation due to failures experienced when applied over moisture sensitive materials (Lstiburek, 2007). Improving the performance of EIFS construction has been a popular subject of research. With proper details, such as drainage within the system to control water egress, effective edge details to control water penetration, and reinforcing mesh within the outer stucco to control surface cracking, EIFS has been shown to perform effectively (Brown et al., 1997; Hens & Carmeliet, 2002; Stazi et al., 2009). In this study, EIFS is considered as a method of improving the thermal resistance of existing masonry walls. A typical cross section of a masonry wall with EIFS applied is shown in Figure 3.2.

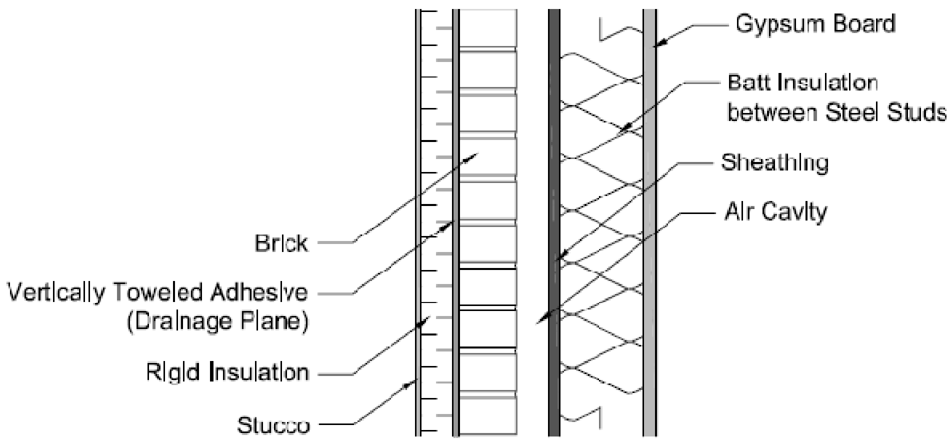

Figure 3.2: EIFS applied over an existing brick wall

There are several benefits of using EIFS as an ECM over interior insulation. The location on the outside of the building allows for a continuous insulation layer, reducing thermal bridging, while also increasing the air tightness of the building (Balocco et al., 2008; Hens & Carmeliet, 2002). Research has shown the most effective location of insulation in reducing the heat flux across the wall to be on the outer surface of the envelope (Kossecka & Kosny, 2002; Ozel & Pihtili, 2007). EIFS is also advantageous for the performance of the masonry, as the exterior insulation stabilizes temperature fluctuations within the wall, reducing hygrothermal stresses in the brick (Hens & Carmeliet, 2002). However, EIFS is not an appropriate ECM for buildings for which maintaining the appearance of the façade is important, such as for historic buildings (Jenkins et al., 2009). As the work is performed on the exterior of the building, this is a non-disruptive ECM to the operation of the building. As previously mentioned, proper design of the EIFS system is of high importance in order to gain satisfactory performance and ensure durability (Stazi et al., 2009). Strong attention must be paid to details both in the design and construction of the system, especially with regard to moisture management. EIFS is most susceptible to moisture damage due to rain penetration and condensation, as it can retain water and has low drying potential (Brown et al., 1997; Hens & Carmeliet, 2002; Lstiburek, 2007). Within the building, humidity levels may rise as a result of reduced heat gain and low air infiltration, requiring dehumidification systems to address increased latent heat gains (Hens & Carmeliet, 2002). In addition, EIFS systems require regular maintenance; cleaning is recommended every five to eight (5-8) years and repainting is recommended every ten to fifteen (10-15) years (Hens & Carmeliet, 2002).

As with roof insulation, the effectiveness of EIFS as an ECM is highly dependent upon the local climate and the existing wall characteristics. Regardless, it is known that the addition of insulation to the building envelope as a means of conserving energy is most effective in cold climates where the indoor to outdoor temperature difference is greater than in hot climates (Kashiwagi & Moor, 1993). Chidiac et al. (2011c) present results showing thirty to forty percent (30-40%) natural gas use reductions following improvement in wall and window U-values in Canadian buildings. Few examples of EIFS used as a retrofit measure are found in the literature. However, preliminary field research results from an office building in Ottawa, Ontario, Canada, show the application of EIFS on a brick building to have increased the thermal resistance of the walls five fold (Said et al., 1997). Jenkins et al. (2009) also show the potential benefit of EIFS applied to the exterior of the building in their study of interventions to improve the performance of office buildings in the UK. It was found that when used in conjunction with other fabric improvements and improved boiler efficiency, that significant heating energy savings were predicted. The benefit of increased wall insulation in general is well known. Compared to ASHRAE 90.1-2004 requirements, heating gas savings of twenty-eight percent (28%) were achieved in two office buildings in China designed using high-efficiency envelopes (Pan et al., 2008). Similarly, the report authored by Consol (2008) suggests total savings of 1.06%, 1.25%, and 0.81% for buildings in California, Maryland, and Illinois, USA respectively over the standard by using a wall with thermal resistance of R-25. The two high-efficiency libraries discussed by Cohen et al. (2007) also exhibit highly insulated envelopes with wall thermal conductance of 0.15 and 0.25 $W/m^2 \cdot K$.

3.3 High Performance Windows

Windows are important components of the building envelope with regard to energy performance and occupant comfort in the indoor environment (Citherlet et al., 2000; Larsson et al., 1999). They provide thermal insulation, solar heat gains, daylighting, overheating protection, noise reduction, and safety (Citherlet et al., 2000). Optical properties (absorptivity, transmissivity, and reflectivity) and thermal properties (thermal conductivity) affect the amount of internal heat gain and heat transfer through the windows due to radiation (Chaiyapinunt et al., 2005; Koçlar Oral, 2000). The temperature fluctuations of the indoor environment in turn influence the heating and cooling demands and energy consumption of the HVAC system. Lighting energy consumption is also affected by the amount of daylight the windows provide to the indoor space, especially in buildings with daylighting controls (Citherlet et al., 2000).

Windows are often the thermally weakest surface of the building envelope due to the high conductivity of glass, which makes it a poor insulator. However performance improvements have been great over the past few decades; use of multiple glazings, infill gases, and glass coatings has contributed to improved energy efficiency of windows (IPCC, 2007). With the use of multiple layers of glazing, air, which is less conductive than glass, can be trapped within the window to increase the overall thermal resistance (Aydin, 2000). The insulative properties are additive with the introduction of additional glazing layers. Further improvements are achievable with the use of inert gas instead of air between the glazings. Argon, krypton, and xenon are used for this purpose. The thermal conductance and molecular weight of the gas are inversely hyperbolically related, thus as the molecular weight rises, the thermal conductivity drops dramatically (Weir & Muneer, 1998). Although krypton and xenon are heavier, and therefore more thermally resistive, argon is most commonly used for gas-filled windows as it accounts for a higher percentage in the composition of air, and thus requires less energy to extract and provides a higher yield in the separation process (Weir & Muneer, 1998). Sealed glazing units will experience leakage of the inert gas over time. Reduction in the volume of gas between the glazing panes will reduce the thermal resistance of the unit, however leakage rates are estimated to be one percent (1%) at most per year and a window will remain thermally effective even if the volume of gas is reduced to eighty percent of the original volume (International Association of Certified Home Inspectors, 2011).

Spectrally selective coatings are another method used to control heat transfer through glazing surfaces. Low emissivity (low-E) coatings exhibit low spectral transmittance in the long-wavelength (infrared or thermal) range, while allowing short-wavelength (solar) transmittance (ASHRAE, 2009b; Chaiyapinunt et al., 2005; Karlsson et al., 2001). Due to the low absorptivity, low emissivity, and high thermal reflectance of the coating, radiated heat from interior surfaces is reflected back into the room, preventing heat loss (ASHRAE, 2009b). Two types of low-E coatings are available, distinguished by the range of allowable solar transmittance. In cold climates, solar heat gain is beneficial for off-setting heating demands, thus, coatings allowing the full range of solar transmittance are recommended (ASHRAE, 2009b). Low-E coatings also have the advantage of warming the surface of the glazing, increasing occupant comfort close to the window and reducing the occurrence of condensation on the glazing surface during the cold season (ASHRAE, 2009b). Conversely, in hot climates solar heat gain is disadvantageous against cooling demand. Coatings with solar transmissivity limited to the range visible by the human eye are recommended to limit heat gain while maintaining visual light penetration for daylighting (ASHRAE, 2009b).

Replacing poor insulative windows with those of higher performance is a well known ECM with substantial potential. Although window costs have not escalated significantly with the advancements in technologies available, the replacement of windows is a costly investment (IPCC, 2007). However, if window upgrades are scheduled to coincide with planned maintenance or repair, the base cost of replacement is no longer associated with the retrofit, and only the incremental cost to achieve higher energy savings should be considered in the evaluation of the ECM. The disturbance of the work to the operation of the building during retrofit should also be taken into consideration in the planning. Window replacement is considered as an ECM only for buildings with window units, not curtain walls, as the cost of curtain wall replacement is extraordinarily prohibitive.

3.3.1 Double Glazed, Low-E, Argon-Filled Windows

Double glazed windows offer significantly improved performance over single glazed windows in terms of thermal resistance and occupant comfort. A sample profile of a double-glazed window is shown in Figure 3.3. Considering single glazing, thermal resistance is provided solely by the glass pane; without a coating, heat transfer and internal heat gains will be high. As has been discussed, double glazed windows with inert gas infill and low-E coating exhibit higher thermal resistance and lower radiative heat transfer. Estimates found in the literature estimate argon adds twenty percent (20%) insulation to the assembly (Kaklauskas et al., 2006), and low-E coatings reduce heat loss in cold climates up to forty percent (40%) in combination with air filled cavities, and even more with gas filled cavities (Weir & Muneer, 1998). Overall estimates of energy consumption savings as a result of replacing single glazed windows with double glazed, low-E, argon filled windows is highly dependent upon the local weather conditions, window-to-wall area ratio, orientation and shading, and heating and cooling loads.

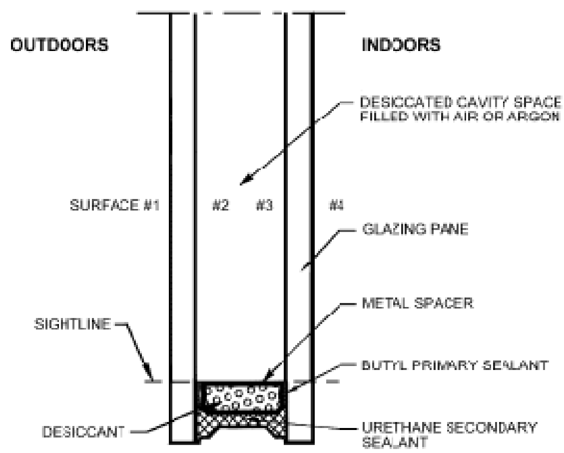

Figure *3.3*: Double glazed window cross section (ASHRAE, 2009a, fig. 1)

Case studies of highly efficient buildings presented by Xu et al. (2007) and Cohen et al. (2007) include the use of high efficiency glazing assemblies in order to achieve overall energy efficiency. Xu et al. describe a demonstration building located in Beijing, China designed with technologies from the United States of America including double pane, low-E windows. Cohen et al. compare two university library buildings in the UK and Sweden with highly insulated envelopes including windows with U-values of 1.2 and 1.9 W/m^2·K respectively. Contributions of the windows to energy savings were not available in either study. Chidiac et al. (2011c) show between twenty to forty percent (20-40%) natural gas savings by upgrading to double glazed high efficiency windows. Balaras et al. (2007) and Gaglia et al. (2007) estimate overall energy savings resulting from the replacement of single glazed windows with double glazed for the residential and non-residential sectors in Greece of fourteen to twenty percent (14-20%) and ten to twelve percent (10-12%) respectively. The effectiveness of low-E coatings is outlined by Córdoba et al. (1998) in an investigation of different glazing options for office buildings in Madrid, Spain. Low-E coatings were found to reduce heating capacity up to thirty-two percent (32%) in comparison with tinted glass due to lower U-values; design cooling capacity was reduced by thirty percent (30%); and electricity savings of up to twelve percent (12%) with a reduction in peak load of twenty-two percent (22%) were simulated.

3.3.2 Triple Glazed, Low-E, Argon-Filled Windows

The energy performance of windows can be further increased with the addition of a second air cavity, as in triple glazed windows, which exhibit a higher thermal resistance than double glazed with similar characteristics. The cross section of a triple glazed window is shown in Figure 3.4. As with double glazed windows, the thermal resistance can be further improved with replacement of the air with inert gas within the inter-pane spaces and the use of low-E coating on one or more of the glazing surfaces. The use of low-E coated glass is particularly advantageous as it has been shown that the performance of uncoated triple glazed windows is below that of coated double glazed windows (Karlsson et al., 2001). Without the low-E coating, the investment in the use of triple glazed windows is unjustified. Although triple glazed windows provide higher thermal resistance, and thus higher energy savings for heating and cooling, they are more expensive than double glazed windows and are often not economically favourable, especially when considered for window replacement in existing buildings. These windows are much heavier than double glazed, and require a stronger frame and increased labour intensity during installation, which also influences the higher cost (Weir & Muneer, 1998).

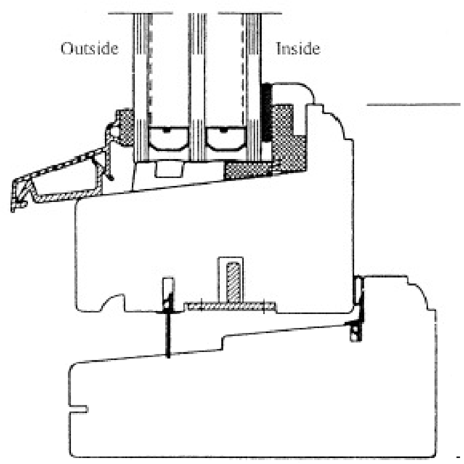

Figure 3.4: Triple glazed window cross section (Larsson et al., 1999, fig. 1)

As with all windows, the energy performance of triple glazed windows is highly dependent upon the local climate, building use, window-to-wall ratio, and solar exposure. Illustrations of the potential of triple glazed, high efficiency windows are found in the published literature. As part of a comprehensive energy retrofit of the Empire State Building in New York, NY, USA, existing double glazed windows were rebuilt to include a third glazing pane, a low-E film, and argon/krypton gas fill (Schneider & Rode, 2010). Energy savings in combination with lighting, ventilation controls, and chiller upgrades are projected to save 38% of overall energy use within the building. Reuse of existing materials reduced upfront costs, doubled energy savings, and avoided material waste. Larsson et al. (1999) and Bülow-Hübe (1998) both evaluate triple glazed, krypton filled, low-E windows in the Swedish climate. Larsson et al. use test cells to investigate the conductive and convection thermal performance of the windows. Findings showed a large temperature difference between the inner and outer surfaces, but thermal bridging at spacers caused localized decreases in the temperature difference. Bülow-Hübe studied the effect of glazing type and size on the annual heating and cooling demand of offices. Results indicate the U-value significantly affects heating demand, while cooling energy is influenced little. Using simulations, Jenkins et al. (2009) identify the benefit of using triple glazed windows as a part of an intervention strategy to reduce energy consumption in UK office buildings. Coupled with other fabric interventions and boiler upgrade, significant heating savings are predicted.

3.4 Ventilation System

Commercial buildings are typically equipped with a central ventilation system through which conditioned air is delivered to the building zones in order to control indoor air temperature and IEQ. Depending on the heating design approach, ventilation systems may provide heating and cooling, or only cooling to the occupied zones (ASHRAE, 2008a). The temperature of the supply air is varied through the use of cooling and/or heating coils within the air handling unit (AHU) in response to the thermal demands of the zones. In order to maintain acceptable IEQ, fresh outdoor air is required to be delivered to the occupied areas of the building. Standards such as ASHRAE prescribe the minimum air intake based on the occupancy of the space (Cho & Liu, 2009a).

The majority of the energy supplied to the ventilation system is consumed through conditioning of the supply air. Technologies and control methods are available to limit unnecessary heating or cooling and to prevent energy loss. Three ECMs with regard to ventilation are considered herein: use of economizer controls, conversion to variable air volume (VAV) ventilation, and installation of exhaust air heat recovery. These ECMs are discussed in detail in the following sections.

3.4.1 Economizer Control

In addition to satisfying IEQ requirements, the introduction of outside air can be advantageous in minimizing the amount of air conditioning necessary to satisfy heating and cooling demands. Economizer controls manage the proportion of fresh outdoor air intake into the building such that when outdoor conditions are favourable, a greater proportion of fresh air is supplied to the system, reducing the need for mechanical cooling or heating (ASHRAE, 2008a; Brambley et al., 1998; Cho & Liu, 2009a; Fisk et al., 2005; Krakow et al., 2000; Mathews et al., 2002; Taylor, 2000). The benefit of these controls is commonly referred to as “free cooling”. Two types of economizer systems are available: temperature controlled and enthalpy controlled (Brambley et al., 1998; Liu et al., 1997). Temperature controlled economizers use dry-bulb temperature sensors to compare the outdoor intake and indoor return air temperature. In cooling mode, if the outdoor air temperature is lower than the return air temperature, the economizer will open the outdoor air damper to allow the maximum volume of outside air into the ventilation system. Otherwise, if the outdoor temperature is higher, the damper is set to allow only the minimum required air volume in for IEQ purposes

(Brambley et al., 1998; Mathews et al., 2002; Taylor, 2000). The inverse is true in heating mode; the maximum volume of outdoor air will be allowed into the building when the outdoor temperature is greater than that of the return air and the minimum will be drawn in when the outdoor temperature is lower. Enthalpy economizers operate on the same principle, but also take into account the relative humidity or wet-bulb temperature of the outside air (Liu et al., 1997). Enthalpy economizers require more sensors, but generally save more energy than temperature economizers since they are better equipped to determine the suitability of the outdoor air using the additional reading of the air moisture content (Liu et al., 1997).

As described, the primary advantage of utilizing economizer controls in a ventilation system is the reduction in energy consumption due to use of suitable outdoor air for indoor air conditioning. Additionally, as a result of higher fresh air content, IEQ may be improved in mild weather (ASHRAE, 2008f). Studies have shown reduced rates of absenteeism associated with buildings using economizers which is often neglected in the economic analysis, suggesting economizers have been under valued (Fisk et al., 2005). In single-duct HVAC systems, little heating penalty is incurred when economizers are introduced; however the same is untrue for dual-duct systems. In circumstances where the heating air flow is higher than the cooling air flow in a dual duct setup, the heating energy consumption will rise when additional cooler outdoor air is introduced (Chidiac et al., 2011a; Krakow et al., 2000). By implementing an additional condition within the economizer control algorithm with regard to the ratio of the heating and cooling air flows, the heating penalty can be eliminated (Krakow et al., 2000). Another design condition to be aware of when introducing economizers is the synchronization of the exhaust relief damper with the outdoor air intake damper to provide proper exhaust of the extra air (ASHRAE, 2008f). If insufficient relief air flow is provided when the economizer fully opens the outdoor air damper, the net result can be an over-pressurization of the building (Taylor, 2000). Potential side effects of inadequate pressure relief are incomplete closure of exterior doors and air whistling through exterior and elevator doors. In tall buildings, over-pressurization of the building can lead to reduced supply air rates (Taylor, 2000).

Energy savings as a result of implementing economizer controls are strongly linked to the local climate conditions, occupancy schedule, and demand control algorithm (Brandemuehl & Braun, 1999; Krakow et al., 2000). As such, energy performance is highly variable between locations and use of an energy simulation tool is required for predicting energy consumption on a local basis. In general, economizer controls are most beneficial in shoulder seasons when the outdoor temperature fluctuates above and below the indoor temperature setpoints and in moderate climates. System characteristics that are more energy efficient with respect to fan power include use of a linear control algorithm for the dampers, a two-coupled as opposed to a three-coupled damper strategy between the outdoor air, return and relief dampers, and constant ventilation pressure (Krakow et al., 2000). Demand controlled ventilation systems including economizers also consume less energy than set minimum controlled systems (Krakow et al., 2000).

Economizer controls have become common within the building industry, thus many examples of reduced energy consumption resulting from their use are documented. In the design of a data centre in China, use of enthalpy economizer controls provided air-side free cooling saving 9.44% of electricity consumption compared to ASHRAE 90.1-2004 (Pan et al., 2008). An increase in gas consumption of 17.3% was also realized, however due to the magnitude of electrical energy consumption compared to gas, significant overall savings were obtained, making free cooling the most attractive of the ECMs implemented. Cho et al. (2009a) present a case study of an office building complex in Nebraska, USA where economizer controls were used within a VAV system resulting in cooling energy savings of eight percent (8%). Energy savings of two thousand US dollars ($2,000US) and savings due to reduced absenteeism of between six and sixteen thousand US dollars ($6,000-$16,000US) due to economizer control implementation were approximated for a building in Washington, DC, USA (Fisk et al., 2005). Liu et al. (1997) discuss the use of economizer controls in a dual-duct ventilation system in Texas, USA; with use of an advanced algorithm, heating penalty was avoided and the economizer controls function as good as a conventional system without an economizer system. Branemuehl and Braun (1999) used simulations to determine the benefit of economizers in multiple buildings in various climates within the United States of America. Results were highly varied dependent upon weather and building characteristics, but showed significant savings are possible for both heating and cooling when used in combination with demand controlled ventilation. Successful applications of economizer systems are also given for multiple building types by Mathews et al. (2002) for a conference centre in South Africa; by Mathews et al. (2001) for a university building in South Africa; and by Callaway et al. (1999) for a civic centre retrofit.

3.4.2 Variable Air Volume (VAV)

Building ventilation systems fall into one of two categories: constant volume or variable air volume. Constant volume (CV) systems vary the temperature of a constant volume of supply air to meet zone demands, whereas variable-air-volume (VAV) systems maintain a relatively steady air temperature while varying the quantity of air delivered to each zone to offset heating or cooling loads (ASHRAE, 2008a). With CV systems, supply air with a temperature set to meet the need of the zone with the highest cooling (or lowest heating) demand is delivered equally to all zones. Reheat coils at the zone level increase the air temperature for zones with less cooling (or greater heating) demand to avoid over-cooling of the space (ASHRAE, 2008a; Cho & Liu, 2009b). In VAV systems, variable frequency drives on the fans adjust the overall volume of air supplied to the network, while modulating dampers in each terminal box control the proportion of air fed to the zone based on the local heating or cooling requirements (ASHRAE, 2008a; Cho & Liu, 2009a). Schematics of constant volume and variable-air-volume ventilation systems are included in Figure 3.5 and Figure 3.6 respectively.

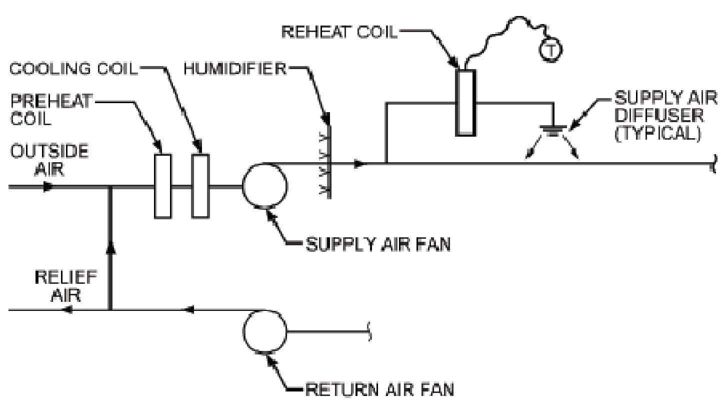

Figure 3.5: Constant volume ventilation system (ASHRAE, 2008a, fig. 9)

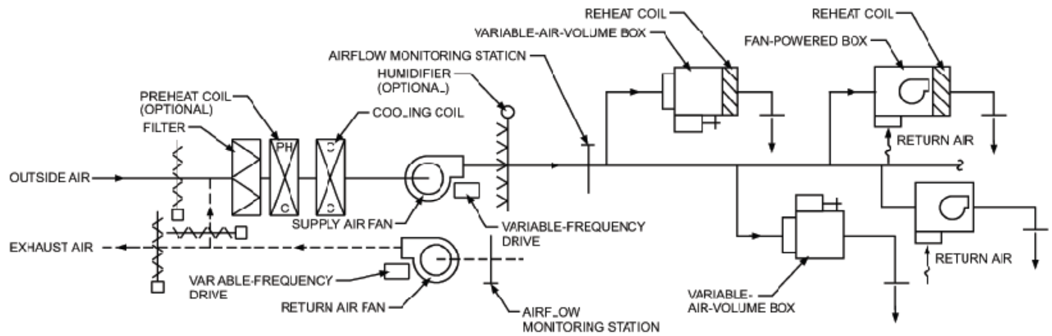

Figure 3.6: Variable-air-volume ventilation system (ASHRAE, 2008a, fig. 10)

Introduced in the 1960's, VAV ventilation has proven to be the more energy efficient of the two designs (Aynur et al., 2009; Inoue & Matsumoto, 1979). Considerably less energy is consumed in VAV systems compared to their CV counterparts, particularly when loads throughout the building vary, allowing for significant air volume reductions (ASHRAE, 2008a; Gaglia et al., 2007). As a result of reduced air volume passing through the system, less fan and air conditioning energy is required (Cho & Liu, 2009b; Kukla, 1997; Linder & Dorgan, 1997; Schwaller, 2003; Wendes, 1994). As well, with the proportion of air for each zone controlled by dampers, reduction or elimination of reheat coils is possible, thus saving energy by minimizing simultaneous heating and cooling of the supply air (Linder & Dorgan, 1997). Since it is rare for all zones to reach maximum load conditions simultaneously, cooling and heating equipment can be resized to meet the maximum coincidental load of all the zones as opposed to the sum of the maximum loads for each zone, leading to additional savings (ASHRAE, 2008a; Linder & Dorgan, 1997; Wendes, 1994). Further energy consumption reductions are possible when the supply air temperature is varied with the seasons (Engdahl & Johansson, 2004; Hartman, 2003). Studies have shown the use of an optimal supply air temperature to provide considerable savings in overall energy requirements (Engdahl & Johansson, 2004; Hartman, 2003).

Many older buildings are equipped with CV ventilation systems that consume significantly more energy than VAV systems. Conversion from CV to VAV is possible with the replacement of fixed drive fan motors with variable frequency drives, and installation of VAV terminal units within each zone (Cho &

Liu, 2009b). In addition to the potential for considerable energy use reductions, greater control of space comfort is gained, as zone conditions can be controlled on an individual basis (Linder & Dorgan, 1997; Schwaller, 2003). VAV ventilation installation is an attractive retrofit, however requires increased attention by knowledgeable persons during design, operation and maintenance (Cappellin, 1997; Linder & Dorgan, 1997). Improper design, control, or operation can lead to serious consequences including wild temperature and humidity swings in the conditioned space, noisy terminal boxes due to pressure loss causing dampers to flutter, frequent breakdowns, and high utility costs (Cappellin, 1997; Linder & Dorgan, 1997). Moreover, sufficient supply of outdoor air, air movement, and humidity control in all zones are of concern in VAV systems. In zones with high occupancy and low heating/cooling load, the restriction of airflow to the zone may result in inadequate outdoor air delivery, lack of air movement, or lack of humidity control (ASHRAE, 2008a; Cavique & Goncalves, 2009; Linder & Dorgan, 1997). With use of proper controls with minimum airflow settings, mixing fan terminal boxes, and humidity sensors, proper conditions can be managed (Kukla, 1997; Utterson & Sauer Jr., 1998).

High energy savings are possible through conversion of CV ventilation systems to VAV; however, actual savings depend on local climate, building use, and relative demands between zones. Estimates of savings found in the literature vary widely from twenty to more than fifty percent (20-50+ %) of energy used by the ventilation system (Ardehali & Smith, 1996; Cappellin, 1997). Case studies of full and partial conversion to VAV systems are found in the literature with positive results. Johnson (1985) presents the conversion of a CV ventilation system to VAV with the installation of variable speed fan drives in an office in Michigan, USA. Energy savings of 46.5% and 53.9% are reported for the two AHUs respectively. Cho and Liu (2009b) authored a paper in which a the central fans in the CV system were refit with variable speed fan motors, but otherwise left unchanged in an office complex in Nebraska, USA. By optimizing the supply air volume using the fan speed setpoint that more closely matched needed air requirements, reheat consumption was reduced by forty-four percent (44%), fan power was reduced by sixty percent (60%) in interior zones and seventy-five percent (75%) in exterior zones, and overall electricity and gas consumptions were reduced twenty-three (23%) and nineteen percent (19%) respectively. Predicted electrical energy savings are presented by Chidiac et al. (2011c) for Canadian office buildings of thirty to forty percent (30-40%) following conversion to VAV ventilation. Simulation results for an office building in Saudi

Arabia predicted energy savings of thirteen percent (13%) by installing variable frequency drives for the ventilation fans (Iqbal & Al-Homoud, 2007). The successful conversion of a civic centre in California, USA to VAV ventilation is highlighted by Callaway et al. (1999). Results from the replacement of fan motors with variable frequency drives and replacement of mixing boxes showed HVAC energy consumption dropped steadily during construction and overall the project exceeded the ten year payback initially estimated. Similarly, several buildings of a large laboratory campus in Illinois, USA were converted to VAV systems with the result of an estimated fifteen percent (15%) savings in HVAC energy consumption (Doyle et al., 1993). VAV system implementation in an air craft hanger in Vancouver, British Columbia, Canada saved twenty-five percent (25%) electricity and thirty-two percent (32%) gas (O'Donnell, 1998).

3.4.3 Exhaust Air Heat Recovery

In building ventilation systems, a portion of the return air, equal to the outdoor air intake volume, is exhausted to the outdoors in order to maintain constant building pressurization. The energy used to condition the air is lost when the exhaust air leaves the building at a temperature and humidity level similar to the indoor space. This is a source of significant energy loss in the overall operation of a building (Jenkins et al., 2009). When a temperature or humidity differential exists between the indoor and outdoor air, energy losses may be partially recovered using an air-to-air energy recovery heat exchanger based on the principle that heat or moisture will migrate from mediums of high to low temperature or humidity (ASHRAE, 2008b). Energy recovery units facilitate energy transfer between the outdoor intake and exhaust airstreams, lowering the enthalpy of incoming air in the summer and raising it in the winter (ASHRAE, 2008b; Besant & Simonson, 2000; Dieckmann et al., 2003; Yau, 2008). As a result of the preconditioning of outdoor air, energy consumption of the mechanical air conditioning system is reduced.

Sensible heat alone or both sensible and latent heat can be exchanged between the incoming and outgoing airstreams using heat recovery ventilators (HRVs) or energy recovery ventilators (ERVs) respectively (ASHRAE, 2008b). In HRVs, the two airstreams are separated by impermeable heat conducting materials, whereas in ERVs, vapour permeable heat conductive membranes are used to allow for latent, as well as sensible, heat transfer (ASHRAE, 2008b). A variety of both types of energy recovery units applicable to building ventilation systems are available. Various types of HRVs include plate exchangers, air-to-air cross flow exchangers, heat pipes, run-around loops, and thermosiphons. ERVs encompass plate exchangers with a vapour pervious membrane, rotary enthalpy wheels, and twin-tower enthalpy recovery loops (ASHRAE, 2008b). Select examples of these units are shown in Figure 3.7.

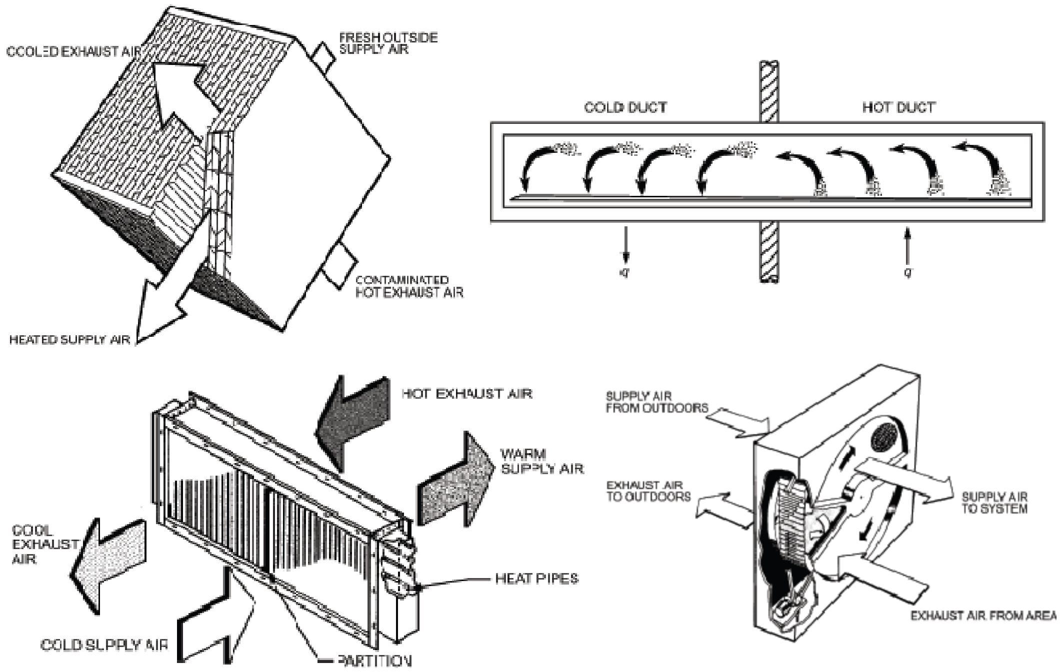

Figure 3.7: Heat exchangers: (a) fixed plate (b) thermosiphon (c) heat pipe (d) rotary enthalpy wheel (AHRAE, 2008b, fig. 4, 6, 10, & 15b)

Several factors influence the energy savings of an energy recovery heat exchanger. The effectiveness of energy recovery varies between the types of exchangers as it depends on the airflow direction and pattern of the supply and exhaust airstreams (ASHRAE, 2008b). Parallel-flow exchangers have a theoretical maximum effectiveness of fifty percent (50%), cross-flow units operate between fifty to seventy percent (50-70%) effectiveness for single pass, sixty to eighty-five percent (60-85%) effectiveness for multiple pass, and counter-flow exchangers have potential to operate close to one hundred percent (100%) effectiveness, although typical performance is lower (ASHRAE, 2008b). Infiltration and leakage between the two airstreams can reduce the effectiveness of the exchanger, as does accumulation of frost or condensation within the unit (ASHRAE, 2008b; Besant & Simonson, 2000; Roulet et al., 2001). Bypassing the heat exchanger, pre-heating the incoming air, or reducing the effectiveness of the unit by adjusting airflows are approaches used to prevent frosting (ASHRAE, 2008b). Removal of condensate through regular cleaning is required to restore effectiveness and prevent mould growth (ASHRAE, 2008b; Dieckmann et al., 2003; Yau, 2008). The heat exchanger must also be bypassed during economizer cycles in order to be able to take advantage of air conditioning using fresh air when conditions are favourable and in shoulder seasons to avoid over-heating of the building (ASHRAE, 2008b; Besant & Simonson, 2000; Fauchoux et al., 2007). When assessing the potential energy savings of an ERV, the negative effect of latent energy transfer in the opposite direction of the sensible energy exchange must also be considered as this will reduce the amount of energy recovered (ASHRAE, 2008b; Fauchoux et al., 2007). Due to the high variability of humidity, energy predictions are best made with simulations using hour weather data to determine the most suitable choice of heat exchanger (Besant & Simonson, 2000). Additional energy may also be required to overcome the pressure drop across the unit due to increased resistance in the air flow (ASHRAE, 2008b; Roulet et al., 2001).

The primary benefit of HRVs and ERVs is the reduction of energy consumption of the mechanical systems and reduction of peak auxiliary energy rates (Besant & Simonson, 2000). However, energy recovery is also important in maintaining IEQ while controlling energy costs and reducing overall energy consumption (ASHRAE, 2008b; Besant & Simonson, 2000). Studies show buildings with energy recovery units have improved occupant satisfaction than those without (Fauchoux et al., 2007). Installing energy recovery units is an attractive ECM as they are mostly passive devices that require little maintenance, are reliable, and have a low operating cost (ASHRAE, 2008b; Besant & Simonson, 2000; Yau, 2008). Even in devices with moving parts such as rotary enthalpy wheels, advancements in the technology have decreased the wear of the device and the amount of maintenance required (Dieckmann et al., 2003). Heat exchangers are most easily installed when the supply and exhaust ducts of a building are situated close to one another, however, run-around heat exchangers, heat pipes and thermosiphons use a refrigerant in a piping system as the heat transfer mechanism and are not restricted by the proximity of the ducts (Sonmor & Lagana, 2009).

The value of energy savings resulting from implementation of energy recovery heat exchangers is highly variable as it is dependent upon local climate variations, outdoor air requirements of the building, exchanger efficiency, and HVAC operation and economizer schedules (Besant & Simonson, 2000; Dieckmann et al., 2003; Roulet et al., 2001). Research shows a wide range of potential savings, from one third to ninety percent (90%) of HVAC energy use, reported in the literature (Dieckmann et al., 2003; Jaffal et al., 2009). As building air tightness and envelope thermal resistance increase, the potential for energy recovery in the ventilation network becomes considerable (Jenkins et al., 2009). Case studies demonstrating the potential for offsetting energy consumption using heat recovery are published. An exemplary case of heat recovery implemented as part of an ECM package in an office building in Montreal, Quebec, Canada is presented by Sonmor (2009). Using a custom gravity-actuated thermosiphon in conjunction with heat recovery between the ventilation and air conditioning condensers, both systems are capable of recovering enough energy to heat the fresh air for the winter season. In combination with boiler, lighting, and control upgrades, savings of 60% natural gas and 12% electricity were realized despite increased building occupancy. Chidiac et al. (2011c) show implementation of heat recovery in Canadian office buildings to lead to up to ten percent (10%) natural gas savings. Jenkins et al. (2009) determined heat recovery has significant potential to reduce energy consumption in the UK commercial building stock; simulations showed the possibility for forty-six percent (46%) GHG emissions savings through widespread implementation of ventilation heat recovery. In the USA-China demonstration office building, an air-to-air heat exchanger was used to control air conditioning loads and, in conjunction with other retrofits, contributed to sixty percent (60%) annual energy savings over ASHRAE 90.1-2004 (Xu et al., 2007). Significant savings beyond ASHRAE 90.1-1999 standards were also realized for a public works centre in Illinois, USA. The performance of energy recovery units and contaminate control demand sensors lead to ventilation energy savings in excess of thirty-two percent (32%) above the standard (Mesik & Howery, 2009). In addition, HRVs were shown to be effective in retail applications. The cooling capacity in a JC Penny store in Louisiana, USA was reduced eighteen percent (18%) as a result of heat recovery, experienced seven percent (7%) annual energy savings and a seventeen percent (17%) reduction in annual peak demand (Smith, 1999).

3.5 Lighting

Interior lighting is an important factor in offices with regard to functionality of the space and occupant comfort; it also constitutes a substantial portion of overall energy consumption within buildings. According to Natural Resources Canada, Office of Energy Efficiency (2010), in the Canadian commercial building sector, lighting accounted for ten percent (10%) of overall energy use in 2007, and has consistently been one of the top three uses of energy in commercial buildings over the past twenty years. Estimates of lighting energy use in North American commercial buildings found in the literature are even higher, between twenty-five to forty percent (25-40%) (Enermodal Engineering Limited, 2002; Ihm et al., 2009). Improvements in lighting systems are a well recognized ECMs as there is strong potential to reduce electrical utility costs while at the same time enhance occupant comfort (NRCan, 2005). In most office buildings the lighting level is higher than necessary. Implementing lighting retrofits allows for the opportunity to correct levels of illuminance, which increases energy savings and provides a better work environment. Work by Newsham and Birt (2010) shows lighting levels can be reduced up to 40% without causing occupant discomfort.

Two approaches effective in reducing the amount of electricity required for lighting are most prominent: increase the efficiency of the equipment to lower the amount of energy required for a given luminance level, or limit the duration during which the lighting system is in use through controls (Mahdavi et al., 2008; NRCan, 2005; Zmeureanu & Peragine, 1999). Advances in lighting technology are continuously being made to improve the efficiency of lighting systems (IPCC, 2007). With proper selection of equipment, replacement of entire luminaires, or select components, can lead to lower electricity usage. Installation of intelligent lighting controls is also effective in achieving energy savings. Sensors are available to detect occupancy and lighting levels within the zone such that controls can dim or turn off lights when not required.

The ECMs pertaining to lighting addressed in this work include replacement of inefficient lighting components with improved efficiency models, and installation of daylight sensors with controls that reduce artificial lighting use when natural daylight is available. Electricity savings up to eighty to ninety percent (80-90%) of lighting energy use compared to conventional practice have been estimated using these two methods (Bodart & De Herde, 2002; IPCC, 2007).

In predicting energy savings, the interaction of lighting with building HVAC systems must be taken in to consideration. Conventional, inefficient lights generate a considerable amount of heat when in use whereas modern lamps operate at cooler temperatures. The reduction in heating load is beneficial toward decreasing air conditioning cost in the cooling season, however leads to increased heating demand during the heating season (Bodart & De Herde, 2002; Enermodal Engineering Limited, 2002; NRCan, 2005; Todesco, 2005; Zmeureanu & Peragine, 1999). In Canadian climates where the heating season is typically dominant, the increase in heating demand will be greater than the reduction in cooling load. The disruption to office workers must also be considered for lighting retrofits as the refurbishment work is completed in the occupied space (NRCan, 2005).

3.5.1 Energy Efficient Luminaires

Luminaires are generally comprised of lamps, ballasts, housing, a diffuser, internal wiring and sockets (NRCan, 2005). Various types of each component are available, with varying energy efficiencies. The selection of lamps and ballasts are the primary influences of the overall efficiency of the assembly. Lamps are rated based on their luminous efficacy (luminous output per unit of energy, measured in lumens per watt), while the energy efficiency of ballasts is given as a ballast factor based on the relative performance compared with a reference ballast (NRCan, OEE, Energy Innovators Initiative, 2007). Luminaries found in typical North American commercial building exhibit little variation; fixtures with T12 fluorescent lamps with electromagnetic ballasts, similar to the one shown in, are very common. This type of lamp and ballast are inefficient compared with newer lighting technologies, and replacement with higher efficiency components can lead to significant lighting energy reductions in buildings (Todesco, 2005).

Continual improvement has been experienced toward higher efficiency technologies with regard to lighting systems (IPCC, 2007). The latest available lamps have higher luminous output and improved luminous efficiency (lm/W) compared to older versions. T12 lamps are very common in commercial buildings however are considerably less efficient than currently available fluorescent lamps. Newer T8 lamps, shown in Figure 3.8 and Figure 3.9, exhibit lower wattage and higher lumen output, longer lamp life, less lumen depreciation over time, and greater colour rendering index (CRI) (Marbek Resource Consultants Ltd., 2004; NRCan, 2005; NRCan, OEE, Energy Innovators

Initiative, 2007; Sonmor & Lagana, 2009). Electromagnetic ballasts, which are highly inefficient, are being phased out and replaced with efficient electronic ballasts (NRCan, OEE, Energy Innovators Initiative, 2007). Three levels of efficiency are available for ballasts that allow for control of lighting levels: low ballast factor (LBF) (0.7-0.8), normal ballast factor (NBF) (0.85-0.95), and high ballast factor (HBF) (1.05-1.15) (NRCan, OEE, Energy Innovators Initiative, 2007). Ballasts also vary based on the method used to start the lamps, options being instant start (IS), rapid start (RS), and program start (PS), with IS and PS the most efficient (NRCan, OEE, Energy Innovators Initiative, 2007). In addition, notable benefits of electronic ballasts are the elimination of lamp flicker, longer life expectancy, and the fact they do not leak tar as electromagnetic ballasts do (NRCan, OEE, Energy Innovators Initiative, 2007).

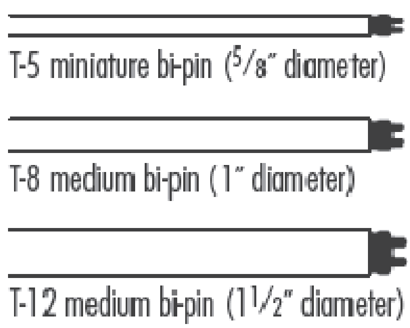

Figure 3.8: Fluorescent lamp size comparison (Enermodal Engineering, 2005, p. 81

Figure 3.9: T-8 Lamps (NRC: OEE: Energy Innovators Initiative, 2007, fig. 1)

Energy efficiency improvements in lighting systems can be accomplished by either replacing the entire luminaire or components thereof, using newer lamps and ballasts. Replacing whole fixtures in buildings in which light placement is flexible allows for the most energy efficient components with higher luminance to be used. In this case, the required lighting level can be maintained without over illuminating the workspace by reducing the number of luminaires (Marbek Resource Consultants Ltd., 2004). In buildings with fixed grid ceilings, adjusting the number of fixtures may not be feasible; however using fewer lamps per fixture and LBF ballasts, the lighting levels in the space can be kept constant while energy consumption is reduced (Fenerty-McKibbon & Khare, 2005). This option also reduces initial investment costs as existing fixtures can be reused.

Published estimates of lighting energy savings resulting from the energy efficiency improvements of luminaires are significant, between thirty to fifty percent (30-50%) (Bodart & De Herde, 2002; Fenerty-McKibbon & Khare, 2005; Marbek Resource Consultants Ltd., 2004). Studies estimate that only thirty percent of commercial buildings in North America use the more efficient T8 fluorescent lamps and electronic ballasts, thus there is great potential for energy savings due to lighting efficiency improvements to be made (Todesco, 2005). Many case studies are found in the literature that demonstrate the energy saving potential of this refurbishment. Replacement of existing T12 lamps and electromagnetic ballasts with T8 lamps and LBF ballasts in a twenty-five storey office building netted $100,000 in annual energy savings and a five year payback at an electricity rate of $0.05 per kWh (NRCan, OEE, Energy Innovators Initiative, 2007). U-tube fluorescent lamps and electromagnetic ballasts were interchanged with T8 lamps and electronic ballasts in a Toronto, Ontario, Canada office building at a cost of $2.5 million, resulting in saving of $1 million annually in energy costs, at a thirty percent (30%) internal rate of return (IRR) (NRCan, 2005). Select Canada Post buildings were retrofit in a re-lamping project under which T12 lamps were replaced with T8 lamps and new controls (Fenerty-McKibbon & Khare, 2005). For a large building, lighting demand was reduced by twenty-eight percent (28%), energy consumption was reduced by twenty-three percent (23%), and working conditions were improved. Positive results were also experienced for several smaller Canada Post projects, saving $35,000 per year in electricity costs. Xu et al. (2007) report savings of fifty-eight percent (58%) energy savings in a China study building using United States of America energy efficient technologies, mostly as a result of lighting and cooling system technologies. Eighty percent of the lamps installed were T8, the remaining T12; digital dimming and occupancy sensors were also utilized. T12 lamps and electromagnetic ballasts were substituted with T8 lamps and electronic ballasts in several other cases. Callaway et al. (1999) present the case of a civic centre retrofit, saving 2.6 million kWh per year; Iqbal (2007) report average monthly savings of four and a half percent (4.5%) in an office in Saudi Arabia; the ConSol (2008) report predicts savings up to 5.73% in US office buildings; and sixty percent savings are shown to be feasible for Hellenic commercial and residential buildings (Balaras et al., 2007; Gaglia et al., 2007).

3.5.2 Daylight Sensor Lighting Controls

It is well known that exposure to natural daylight is beneficial for human health and wellbeing (Li & Lam, 2001). Employees tend to be more productive, efficient, and have lower rates of absenteeism when they are exposed to daylight in the workplace (Enermodal Engineering Limited, 2002; Heschong, 2002; Ihm et al., 2009; Marbek Resource Consultants Ltd., 2004). Utilizing daylight for interior lighting purposes is also beneficial as an ECM, and has been a widely used approach in building design in the past for reducing energy demands (Heschong, 2002). Significant energy savings can be realized when daylight is taken into account in controlling auxiliary lighting levels to maintain a set level of illumination (Bodart & De Herde, 2002; Enermodal Engineering Limited, 2002; Ihm et al., 2009; Jennings et al., 1999; Li & Lam, 2001; Marbek Resource Consultants Ltd., 2004; NRCan, OEE, Energy Innovators Initiative, 2002b; Onaygil & Güler, 2003). In order to take full advantage of daylighting, factors such as shading, orientation, and window glazing type, shape and size must be considered during the planning stages of the building design (Bodart & De Herde, 2002; Ihm et al., 2009; IPCC, 2007; Li & Lam, 2001). Nonetheless, sizeable lighting energy reductions can also be experienced in existing buildings by utilizing available daylight.

Target lighting levels, measured in lux (lumen/area), are determined from recommendations based on building use. For office areas where high contrast is needed for tasks such as reading and writing, the Illuminating Engineering Society of North America (IESNA) recommends the lighting level to be 500 lux (NRCan, 2005). Light sensors, such as those shown in Figure 3.10, are used to detect the illumination of the space; when the measured illuminance exceeds the set level, controls are signalled to limit auxiliary lighting such that the setting is matched (Jennings et al., 1999; NRCan, OEE, Energy Innovators Initiative, 2002b; NRCan, 2005; Onaygil & Güler, 2003).

Figure 3.10: Dual-technology occupancy sensors (NRCan, OEE, Energy Innovators Initiative, 2002b, fig. 1)

Three types of controls are used for adjusting lighting levels: on/off, staged, or dimming controls (Enermodal Engineering Limited, 2002). Dimming controls are the most favourable choice for offices as dramatic changes in the lighting level are avoided and they allow for the closest match of the target lighting level (Enermodal Engineering Limited, 2002). For dimming of fluorescent lights to be possible, dimmable ballasts must be used (Enermodal Engineering Limited, 2002). These ballasts can be up to three times more expensive than on/off ballasts, however allow for increased precision in lighting control as the output luminance varies on a continuous scale (Marbek Resource Consultants Ltd., 2004; Rensselaer Polytechnic Institute Lighting Research Center, 2009). For this reason, non-dimmable ballasts are used in interior zones where daylighting is minimal, and dimmable ballasts are installed only in the perimeter zones where daylight will be present (NRCan, OEE, Energy Innovators Initiative, 2007). Other consideration to take into account to maximize the benefit of daylighting controls are: the light transmittance of the fenestration, light reflectance of interior surfaces, proper lighting zoning in order to avoid under illumination in areas lacking windows, and office layout (Ihm et al., 2009; Jennings et al., 1999; Love, 1994; Torcellini et al., 2004). Additional design effort is required to ensure the system functions as intended (Jennings et al., 1999; Love, 1994).

There are many factors that influence savings in overall energy consumption as a result of implementing daylighting controls: sky cloud coverage, fenestration properties, lighting schedules, use of occupancy sensors in the lighting control strategy, and the influence on building heating and cooling demand due to heating load reduction (Bodart & De Herde, 2002; Franzetti et al., 2004; Ihm et al., 2009; Jennings et al., 1999). A review of the literature shows great potential for daylight controls as an ECM; estimates range between thirty to eighty percent (30-80%) savings of lighting energy consumption (Enermodal Engineering Limited, 2002; Ihm et al., 2009; IPCC, 2007; Mahdavi et al., 2008). Case studies illustrating these savings are given in several works.

Jennings et al. (1999) present finding of an office lighting control test project which showed savings due to daylight dimming alone of twenty-six percent (26%) and energy savings of forty to forty-four percent (40-44%) when dimming was used in combination with occupancy sensors. A study of the various influences on lighting energy reductions in an office in Istanbul, Turkey revealed use of daylighting and occupancy sensors to control artificial lighting saved twenty-one percent (21%) of lighting energy use in winter, thirty-five percent (35%) in spring, and forty-five percent (45%) in summer; lighting energy reductions of thirty-five percent (35%), thirty-three percent (33%), and sixteen percent (16%) were recorded on clear, mixed, and overcast days (Onaygil & Güler, 2003). Overall thirty percent (30%) reduction in annual lighting energy use was found. Incorporating daylighting and occupancy sensor controls in a small office with twenty-four, two T8 lamp fixtures produced annual energy savings of $200 at an electricity rate of $0.07/kWh; with an installation cost of $550, the payback period was 2.85 years (NRCan, OEE, Energy Innovators Initiative, 2002b). Bülow-Hübe et al. (1998) present simulation predictions of the influence of dimming artificial lighting in a test room. Lighting energy savings of 10 kWh/m^2/yr, or forty-seven percent (47%), cooling energy savings of 6 kWh/m^2/yr, and an increase in heating energy use of 4 kWh/m^2/yr were given. Additional examples of successful use of daylighting controls are found in Pan et al. (2008), Li and Lam (2001), Cohen et al. (2007) and Xu et al. (2007).

3.6 Cooling and Heating System Efficiency

The energy consumption of building cooling and heating systems is determined by two primary factors: the building heating and cooling demands, and the efficiency of the systems. In order to reduce chiller and boiler energy use, loads can be lessened through ECMs such as those discussed to this point, or alternatively, the efficiency of the equipment can be improved such that the energy input required for a given work load is reduced. Efficiency improvements can be achieved through control adjustment or refurbishment of existing machinery, or replacement with higher efficiency models. Refurbishment of existing equipment is often less expensive, especially when equipment sizes are large or accessibility is limited (Burkhart, 2004). However, the ability to take advantage of existing equipment upgrades is highly dependent upon the type and condition of the existing machinery, and thus must be evaluated on a case-by-case basis. Due to the general nature of ECM recommendations in this work, equipment replacement is focused on as a means to upgrade heating and cooling plant efficiencies.

Technological advances allow for increasingly more efficient systems to be developed. Replacement of existing chillers or boilers is advantageous not only with regard to upgrading to the most energy efficient equipment available, but also allows opportunity for equipment resizing. Chiller and boiler systems typically run most efficiently at full capacity and run less efficiently at part-loads. In this respect, accurate sizing of equipment is of significant importance so that full load capacity is reached more frequently. As ECMs are implemented, the heating and/or cooling demand profiles of buildings change and may allow for downsizing of system components to allow for operation at the highest efficiency possible. By pairing energy efficiency improvements of these systems with other ECMs, energy conservation efforts are maximized (Todesco, 2005).

3.6.1 Chiller COP

Chillers can be classified into two categories: vapour-compression refrigeration cycle or absorption-cycle (ASHRAE, 2008d). As compressorized chillers exhibit higher efficiency, they will be the focus of discussion. A compressor, condenser, evaporator, and chiller are the basic components of a compressorized chiller; other ancillary devices such as pumps, heat rejection equipment and heat exchangers may also be included (ASHRAE, 2008d; ASHRAE, 2008g). A schematic of a simplified compressorized chiller is shown in Figure 3.11.

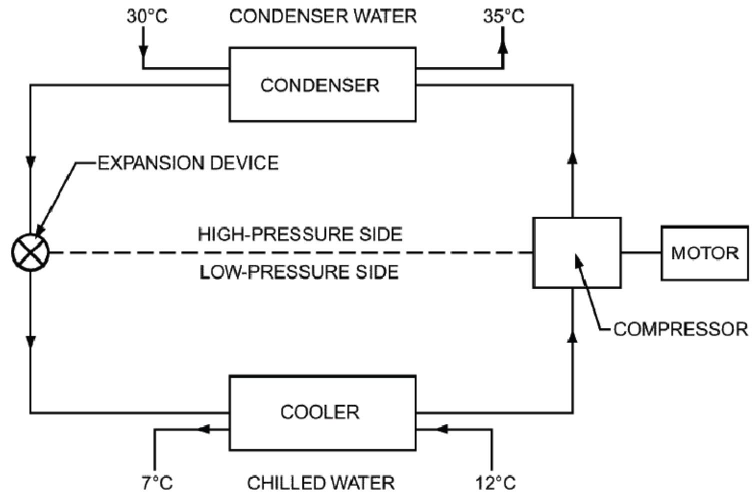

Figure 3.11: Liquid chiller equipment diagram (ASHRAE, 2008g, fig. 1)

In this system, a refrigerant in the gaseous state is compressed to create a pressure differential between the condenser and evaporator. Hot, high-pressure gas is fed to the condenser where heat is transferred to a cooling medium, causing the refrigerant to condense. The refrigerant then flows to the evaporator via the expansion relief valve where heat is absorbed by the refrigerant from the cooling circulation loop to cool the water delivered to the AHU (ASHRAE, 2008e). Many variations of this system are possible; variables include refrigerant type, compressor type (reciprocal, rotary, or centrifugal) and drive (electric motors, natural gas-, diesel-, or oil-fired internal combustion engines, combustion turbines, or steam turbines), condenser heat rejection method (air- or water-cooled), and variable or constant speed equipment (chiller, condenser, pumps and/or cooling tower fans) (ASHRAE, 2008d). Due to the numerous permutations of these variables, selection of chillers is usually performed using a manufacturer's computer program based on design criteria, two of which are full- and part-load efficiency (ASHRAE, 2008g).

Chiller efficiency is commonly stated as input energy required per ton of cooling (kW/ton) or as a coefficient of performance (COP). COP is calculated by converting tons of cooling into kilowatts, reducing the fraction to a unit less number, then taking the inverse. Overall efficiency of a chiller is influenced by many factors including individual component efficiencies and capacities, evaporating and condensing temperatures and pressures, condenser temperature differential, chilled water flow rate, compressor and fan power, and sequencing and staging controls (Burkhart, 2004; Yu & Chan, 2007). Centrifugal chillers are the most efficient of the three vapour-compressorized chillers available (NRCan, OEE, Energy Innovators Initiative, 2002a). Efficiency curves for full and part-load performance ratios are shown in Figure 3.12 for an air-cooled, centrifugal chiller with a variable speed condenser fan operated at a range of outdoor temperatures. As is seen in the chart, chillers experience peak efficiency at part-load conditions and declining efficiency when chiller load decreases (Yu & Chan, 2007). Due to the number of variables involved, chiller plants hold flexibility in the design, making several approaches possible for improving the COP.

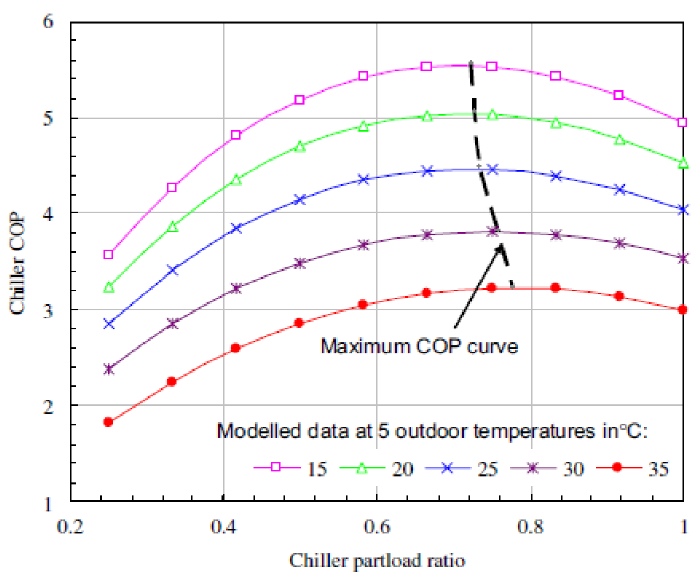

Figure 3.12: Chiller part load performance curves at specified condensing pressure and outdoor temperature (Yu & Chan, 2006, fig. 9)

Chiller improvement measures include decreasing condenser inlet water temperature, increasing evaporator setpoint, using variable speed controls on all components (chiller, condenser, pumps and/or cooling tower fans), and ensuring valves operate to avoid mixing of inlet and outlet water. Chillers with these characteristics are desirable in order to achieve high efficiency performance under typical operating conditions. Decreasing the condenser inlet water temperature and increasing the chiller leaving water temperature serve to enhance the refrigeration cycle efficiency and lowers the compressor head leading to compressor energy savings (ASHRAE, 2008g; Burkhart, 2004; Crowther &

Furlong, 2004; Dubov, 2005; Song, Akashi, & Yee, 2008). This is feasible when the system is not operating at full-load and the heat rejection equipment has reserve capacity (Crowther & Furlong, 2004). When applied to chillers with variable speed drives during operation at part-load ratio of 0.8 or less, savings of two to three percent (2-3%) per degree Fahrenheit increase in leaving chilled water temperature, up to ten percent (10%), can be realized (Burkhart, 2004). The use of variable speed drives and controls allow for capacities to be reduced to match part-load demands, resulting in lower motor, fan, and pump energy consumption (ASHRAE, 2008g; Crowther & Furlong, 2004; Hartman, 2001; Yu & Chan, 2007). Significant energy savings are possible with this approach; Burkhart (2004) reports savings up to 30% using variable speed drives. However, initial investment can be costly and detailed operating strategies are needed to control the plant (Burkhart, 2004; Hartman, 2001; Yu & Chan, 2007). There remains some debate around the optimization of chiller sequencing. In plants where cooling towers and pumps are staged on and off when the matching chiller is taken on or off-line, it is generally recommended that chillers are loaded to full capacity before another is engaged (Avery, 2001; Crowther & Furlong, 2004; Yu & Chan, 2007). However, in an all-variable speed plant where cooling towers and pumps are permitted to operate independently of the corresponding chiller, excess heat rejection capacity is gained and it is more beneficial to operate the minimum number of chiller required to meet the load at the optimum part-load efficiency (Hartman, 2001). The excess energy required to run the fans and pumps is over shadowed by the energy savings due to optimum COP operation of chillers and lower condenser temperature. Hartman (2001) reports energy savings of twenty-eight percent (28%) in an all-variable chiller plant with optimized controls compared to a fully optimized conventional constant speed plant.

In addition to the energy efficiency advantage of centrifugal chillers, this type of compressor has the ability to vary capacity to match a wide range of load conditions, thus minimizing the number of starts (ASHRAE, 2008g). This, along with the absence of contacting parts, contributes to the reduced wear centrifugal compressor experience compared to other designs (ASHRAE, 2008e; ASHRAE, 2008g). Chiller replacement in general can be environmentally advantageous by allowing for upgrade to non-ozone-depleting refrigerants (Burkhart, 2004). There are many benefits associated with chiller upgrading, however it is a costly capital investment that must be carefully considered (Burkhart, 2004). Included in the decision making, consideration should be given to training of operations staff to ensure competency in operating the new plant (Hartman, 2001).

Similar to many other ECMs, the potential for energy savings resulting from replacement of inefficient chillers with those of higher efficiency is extremely variable as it is dependent upon the efficiency of the existing plant, local weather, building operational and occupancy schedules (Crowther & Furlong, 2004). Nonetheless, it is well known that large reductions in cooling energy use are feasible due to the significant improvement of chiller efficiencies over the past number of years (Todesco, 2005). Examples of various types of chiller improvements showing the possibility of savings are found in the published literature. In an effort to curb escalating utility costs, the absorption chiller in the Royal Bank building in Halifax, Nova Scotia, Canada was replaced with two centrifugal chillers with 0.6 kW/ton efficiency; net annual utility costs were reduced by $35,000 (NRCan, OEE, Energy Innovators Initiative, 2002a). Callaway et al. (1999) present the retrofit of a civic centre in which the chiller capacity was reduced and efficiency improved along with conversion from CV to VAV ventilation, lighting improvements, and DDC control installation. Two 1,930 kW, 0.83 kW/ton and a 700 kW, 0.68 kW/ton chillers were replaced with two 1,400 kW, 0.55 kW/ton chiller and the temperature differential was also increased. Total retrofit savings were estimated at 5.8 million kW per year, or $532,600 USD annual savings. Centrifugal chiller replacement saved 2.0 MW per year in various Canada Post facilities (Fenerty-McKibbon & Khare, 2005). In a Chicago office, the 0.75 kW/ton CFC chiller was replaced with a 0.5 kW/ton chiller of the same size. The new chiller, operated with variable speed pumps and lower chilled water and condenser flow rates, resulted in annual electricity savings of 7.6% (Todesco, 2005). Improvements in cooling plant energy efficiency above ASHRAE 90.1-2004 to an energy efficiency ratio of 12.0, were predicted to result in savings of 1.52%, 0.39%, 0.24% in California, USA, Maryland, USA, and Illinois, USA respectively (ConSol, 2008). Although the percentage of savings is low, the overall magnitude of energy conserved is notable.

3.6.2 Boiler Efficiency

In Canada, space heating accounts for over half of building energy consumption within the commercial/institutional sector (NRCan, OEE, 2008). As such, selecting a boiler with a high efficiency is of importance in minimizing energy usage and utility costs. Many types of boilers with varying characteristics and a range of efficiencies are available. As described in the ASHRAE Handbook: HVAC Equipment and Systems, boilers can vary based on "working pressure and temperature, fuel used, material of construction, type of draft (natural or mechanical), and whether they are condensing or non-condensing," (ASHRAE, 2008c, p. 31.1). Generally, hot water boilers are rated up to a maximum of eighty percent (80%) efficiency, mid-efficiency boilers at eighty-three to eighty-six percent (83-86%), and condensing boilers between eighty-eight to ninety-five percent (88-95%) efficiency (ASHRAE, 2008c; Durkin, 2006).

In order to achieve the highest efficiency, condensing of exit flue gas is required in the boiler operation to recover the excess heat lost through the exhaust (Che et al., 2004; Durkin, 2006; IPCC, 2007). As seen in Figure 3.13, the efficiency of boilers operating in the condensing range is greater than that of non-condensing boilers. The discontinuity in the graph shows the dew point temperature at which flue gases condense and latent heat is recovered (Che et al., 2004; Durkin, 2006). The temperature at which condensation can first occur varies between 56-60°C based on the percentage of hydrogen in the fuel and the oxygen/carbon dioxide ratio in the flue gases (ASHRAE, 2008c; Che et al., 2004). The efficiency of condensing boilers improves when operated at lower return water temperature and increased temperature difference between return water and flow pipe temperatures (ASHRAE, 2008c; Che et al., 2004). Condensing boilers also exhibit superior efficiency at part-load capacity and during non-condensing operation compared to non-condensing boilers due to sensible heat recovery and the use of high-turndown modulating burners typical of this equipment (ASHRAE, 2008c; Durkin, 2006).

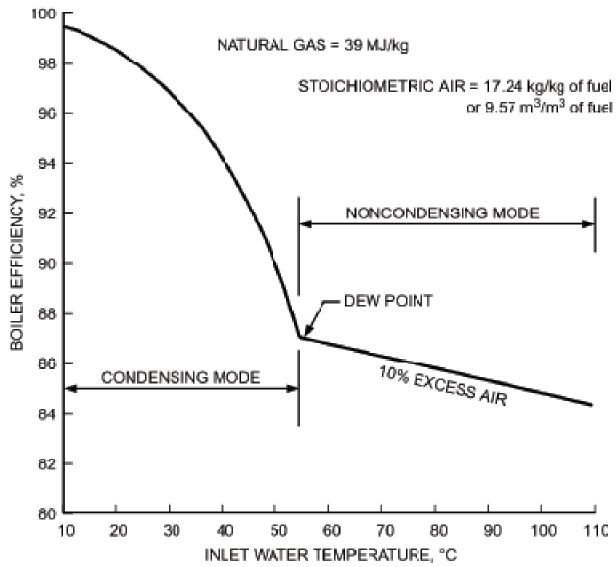

Figure 3.13: Effect of inlet water temperature on boiler efficiency (ASHRAE, 2008c, fig. 6)

There are several advantages of condensing boilers beyond the benefit of reduced energy consumption. As a result of the condensation of flue gases, the environmental impact of pollutants is lessened when they are partially or fully dissolved in the condensed water (Che et al., 2004). The ability of condensing boilers to modulate output temperatures lower than non-condensing boilers when heating demand decreases reduces the occurrence of start/stop penalties. The reduced frequency of temperature fluctuations can aid in extending the service life of the boiler, although this is a relatively new technology and long term performance is not well known (ASHRAE, 2008c; Durkin, 2006). The system components other than the boiler itself do not need to be changed to convert existing heating systems to condensing operation, which makes the boiler replacement straightforward (Che et al., 2004). In addition, with regard to operations, the use of hot water in the distribution system, as opposed to steam, reduces the risk of personal injury if leaks occur in the pipes (Durkin, 2006), and constant monitoring is unnecessary due to the low operating pressure (Desmarais & Jean-Louis, 2005). The penalty of this ECM is in the cost of the boiler. Due to the corrosive nature of the condensate, stainless steel or aluminum are used as the material for the body of the boiler. These are expensive materials, as is reflected in the cost that is estimated to be one to three times higher than non-condensing boilers (Durkin, 2006; Marbek Resource Consultants Ltd., 2004).

Estimates of the savings resulting from use of condensing boilers are varied as it is dependent upon the heating load profile of the building and the local climate conditions. The actual efficiency is also dependent upon the presence of sufficient secondary heating demand within the building (e.g. domestic hot water heating) for the recovered excess heat to be utilized (Che et al., 2004). General predictions of energy savings presented in the literature range between ten to thirty-three percent (10-33%) (Che et al., 2004; Marbek Resource Consultants Ltd., 2004). Specific case studies also show positive results. In a Montreal college, the aged hot water and steam boilers were replaced with condensing hot water and steam boilers, including steam-to-water heat recovery and a stack economizer (Desmarais & Jean-Louis, 2005). The reliability and efficiency of the heating system were improved, leading to savings of $85,000 in annual energy costs and $15,000 in annual maintenance costs with a thirteen year payback. Upgrades to condensing boilers also contributed to savings for a Montreal office building when included in conjunction with other ECMs (Sonmor & Lagana, 2009). Similarly, Canada Post reduced utility costs by replacing boilers in many of their facilities (Fenerty-McKibbon & Khare, 2005). Potential savings of 3.61% to 8.78% above ASHRAE 90.1-2004 as a result of improving boiler efficiency from 0.78 to 0.9 are report by Consol for various cities in the United States of America (ConSol, 2008). As well, Chidiac et al. (2011c) predict possible savings of twenty-two percent (22%) natural gas savings by increasing boiler efficiency. Balaras et al. (2007) and Gaglia et al. (2007) predict space heating energy consumption reductions of twenty-one percent (21%) for both commercial and residential building with replacement of inefficient gas boilers within the Hellenic building stock.

3.7 Discussion

As discussed, several methods are available for improving the efficiency of energy use within commercial buildings with respect to various components. Many of the approaches reviewed have potential to result in sizeable energy savings and GHG emission reductions, as well as improvement in IEQ. However, despite the availability of technologies, building retrofit rates remain low, mainly due to a lack of awareness on the part of building owners and managers (NRTEE & SDTC, 2009). To be able to make informed decisions, building owners need to know what the technologies are, how they work, the value of potential benefits, and the initial investment costs. The information provided in this work was obtained through research of scholarly journals, which are accessible by experts and those in academia and are not readily available to the public or many of those working within the building industry. Without this knowledge, optimal selection of ECMs that will result in the best return on investment cannot be realized. The screening methodology presented in this work is intended to fill the knowledge gap between building owners and experts with regard to the available technologies that can be implemented to result in significant energy savings.

Chapter 4: Screening Methodology of ECMs

4.1 Introduction

ECMs may be considered for implementation in buildings for a number of reasons, to reduce operational costs, lower energy consumption, reduce GHG emissions, or improve occupant comfort, however the path to achieving these goals is not always apparent. The effect of some ECMs may be easily predicted, while others affect multiple, integrated systems in a building and cannot be easily foreseen. Several factors must be considered in the evaluation of energy retrofits, such as the local climate, building layout, construction and use, HVAC systems, and interactions between building systems. The financial viability of ECMs must also factor into the decision making process to determine the benefit of the ECM as compared to alternate investment opportunities.

Considering ECMs for individual or small groups of simple buildings, the selection and prioritization process may be straight-forward and involve only a few criteria or factors. In this case, making comparisons with a database of case study results from similar buildings using a decision support tool may be satisfactory. However, in evaluating alternatives for large groups or more complex buildings, it is necessary to use a decision making tool for the evaluation of alternatives, primarily due to the large volume of data and time required for assessment. In light of the absence of an appropriate decision tool applicable to large stocks of buildings, the screening methodology presented herein is developed for the purpose of validating and prioritizing the implementation of ECMs for large stocks of office buildings. This approach is intended to be user-friendly, timely in its use, require a reduced data set, and exhibit accuracy that is acceptable for preliminary decision making needs.

To efficiently evaluate large building stocks, the concept of archetyping is used to reduce the number of buildings included in the evaluation (Chidiac et al., 2011a; Chidiac et al., 2011b). Representative buildings from each archetype are chosen, for which pre- and post-ECM energy consumption is predicted using a mathematical model, utilizing a limited set of building characteristics as input. Evaluation and ranking of pre-selected ECMs is based on cost analysis, including savings resulting from energy consumption and cost of implementation. The steps in the screening methodology are presented in detail in this chapter.

4.2 Representative Buildings – Archetypes

In dealing with large building stocks, the greatest challenge to overcome is collecting and managing large volumes of data. For government building stocks, the number of buildings can range from hundreds, up to thousands of buildings (International Energy Agency Annex 46, 2009). It is unrealistic to perform analyses on each individual building due to the volume of data and time required. Also, complete information for every building may not be available.

To simplify the problem, it is useful to group buildings of similar type together. Buildings that exhibit similar attributes have been shown to have similar energy use and be affected by the application of ECMs in the same way (Chidiac et al., 2011b; Dascalaki & Santamouris, 2002). The set of common characteristics that define a group is referred to as an archetype. From each archetype, a representative building is selected for evaluation. The results of the representative building will generally be applicable to all buildings within the archetype. With this approach, a building stock comprised of numerous buildings can be reduced to a manageable set.

Archetypes may be defined on common characteristics such as building age, size, type of construction, envelope material properties, HVAC component types and efficiencies, building use, occupancy schedule, etc. The archetype definition may be very narrow or broad depending upon the purpose of the categorization. The use of archetypes has been shown to be successful in the work performed under the OFFICE project, which uses building typologies to define building sets from which one representative building is chosen for analysis (Dascalaki & Santamouris, 2002).

The archetypes used in this work are presented in Table 4.1. Buildings have been classified based on building size, construction type, and HVAC equipment characteristics. The archetypes were broadened to reflect constructions common to the era and are representative of the prevailing code requirements.

Table 4.1: Building Archetypes

Characteristic	*Archetype 1: Pre-1950*	*Archetype 2: 1950 - 1975*	*Archetype 3: Post-1975*
Building Envelope			
Infiltration Rate (ach)	1.0	0.75	0.5
Roof			
U-Value ($W/m^2 \cdot K$)	1.25	0.90	0.46
Solar Absorptance	0.8	0.8	0.8
Wall U-value ($W/m^2 \cdot K$)			
Brick/Concrete	1.25	0.87	0.60
Curtain Wall	n/a	0.40	0.40
Windows			
Type	Single Glazed	Double Glazed	Double Glazed, Argon, Low-E
U-Value ($W/m^2 \cdot K$)	6.0	2.7	1.5
Solar Transmittance	0.775	0.837	0.63
Solar Reflectance (Front/Back)	0.071/0.071	0.075/0.075	0.19/0.22
Distribution System			
Economizer	No	No	Yes
VAV Turndown Ratio	1.0	1.0	0.65
Heat Recovery	No	No	Yes
Electrical Systems			
Lighting (W/m^2)	26	17.8	9.3
Daylighting	No	No	No
Chiller COP	1.8	2.5	5.2
Natural Gas System			
Boiler Efficiency	0.75	0.75	0.85
Heating Schedule	No Setback	No Setback	No Setback
Occupancy Characteristic			
Work Days per Week	5	5	5
Daily Schedule	05:00-23:00	05:00-23:00	05:00-23:00
System Schedule	Off Evenings	Off Evenings	Off Evenings

4.3 Energy Consumption Prediction Mathematical Model

Evaluation of ECMs is centred on the effect each has on building energy consumption. Pre- and post-ECM energy use is predicted to give a quantifiable basis for the analysis and ranking of ECMs. To obtain accurate results from the decision tool, energy consumption must be predicted based on the specific characteristics of the building under consideration. As discussed in Chapter 2, there are several methods of predicting building energy use. The most efficient and practical approach for use within the decision making tool, where multiple ECMs are evaluated for multiple buildings, is to employ a mathematical model. With this method of energy prediction, results are obtained speedily and reflect similar accuracy to that of the energy simulation program used for development of the mathematical model.

The model developed for the current project is based on energy balance and statistical analysis of energy simulation results. Separate equations predicting monthly energy use of the boilers, chillers, domestic hot water heating system, equipment, fans, lighting, and chilled water loop, condenser water loop, and hot water loop pumps are summed to determine the total energy consumption of a building. Coefficient sets have been developed for several major Canadian cities, allowing the tool to be useful for buildings located across the country. These and other aspects of the energy consumption prediction mathematical model are discussed in further detail in the following sections.

4.3.1 Variables

A notable advantage of using a mathematical model for energy consumption prediction is the reduced amount of data required as input. The current model uses a set of twenty-four variables reflecting building characteristics including geometrical parameters, surface constructions and material properties, internal loads, HVAC system equipment and efficiencies, occupancy density and schedules. The variables are listed in Table 4.2 along with the associated units of input. The ranges of variable values used in development of the mathematical model are also included as reference.

Table 4.2: Mathematical Model Input Variables

Variables	***Units***	***Reference Variable Range***	
		Low	***High***
Number of Storeys		2	25
Average Area per Floor	m^2	1500	7500
Number of Basements		0	2
Aspect Ratio/ Orientation		2:1 N/S;2:1 E/W; 1:1	
Occupancy Density	m^2/person	50	25
Occupancy Schedule	hours/day	10	18
Weekends	days	No	Yes
Equipment Load	W/m^2	25	55
Lighting Load	W/m^2	5	26
Daylighting		No	Yes
Heating Setback		No	Yes
Economizer		No	Yes
Heat Recovery		No	Yes
VAV Ratio		0.3	1
Fan Pressure Rise	Pa	300	1500
Infiltration Rate		0.2	1
Roof U-value	$W/m^2 \cdot K$	0.2	0.6
Roof Solar Absorptance		0.18	0.8
Wall U-value	$W/m^2 \cdot K$	0.2	0.8
% Fenestration		20	100
Fenestration U-value	$W/m^2 \cdot K$	0.87	3.2
Fenestration Solar Heat Gain Coefficient		0.47	0.76
Chiller COP		1.5	12
Boiler Efficiency		0.75	0.96

The majority of the variables are self explanatory by the variable name, however those that require further explanation are described here. “Weekends” identifies if weekend days are included in the occupancy schedule with “No” and “Yes” indicating a five and seven day work week respectively. “Heating setback” indicates if a setback is used in the heating thermostat settings; if used, a setback to 18°C is assumed.

4.3.2 Equations

Separate equations have been developed to predict the energy consumption of various building energy end uses on a monthly basis. These energy end uses include: boilers, chillers, domestic hot water (DHW), equipment, fans, lights, and chilled water loop supply (CWLSP), condenser water loop supply (CNWLSP), and hot water loop supply pumps (HWLSP). Boilers are assumed to be natural gas fuelled, while the other components are electricity based. The format of all equations is consistent between months, however the coefficients have been found to vary. Total annual energy consumption is found by summing the monthly predictions for each end use.

The equations are developed based on a combination of regression analysis and heat conservation principles. The general format of the equations is as shown in Equation 4.1. The energy prediction, and heat gain and loss, and pump and air flow rate equations are shown as a function of multiple variables in Appendix A.

$$\text{Energy Consumption} \approx \Sigma_1^i \, (1/\eta*(c_0 + c_1*x_1 + \ldots + c_n*x_n + c_{n+1}*x_1^2 + c_{n+2}*x_1x_2 + \ldots b_{2n}*x_n^2 + b_{2n+1}*x_1^3 + b_{2n+2}*x_1^2x_2 + \ldots + b_{2n}*x_n^3)) \tag{4.1}$$

where:

c = coefficients

i = energy consumption component

n = number of variables

x = variable

η = efficiency

A set of design buildings was established for development of the mathematical model. The group includes 2, 10 and 18 storey buildings with floor areas of 1500 m^2, 4500 m^2, and 7500 m^2. The energy prediction equations are developed for this specific set of design buildings, then adjusted using factors based on the number of storeys and floor area to predict the consumption of buildings of different sizes. Buildings are separated into low-rise and mid- to high-rise groups. Low-rise buildings are classified as having less than five storeys, and mid- to high-rise buildings are those of five to twenty-three storeys. For low-rise buildings other than those for which equations have been specifically developed, the results of the closest matching low-rise building are proportioned according to the number of storeys and area per floor. For mid- to high-rise buildings, linear interpolation between the results of the four closest matching buildings is carried out to adjust for the number of storeys and area per floor.

4.3.3 Climate Coefficients

Building energy consumption is dependent upon the local climate, which varies with location. To predict the energy use of buildings in different locations, sets of coefficients unique to various cities across Canada, have been developed to be applied to the mathematical model. The coefficients reflect the impact of the local climatic conditions. Table 4.3 lists the cities for which sets of coefficients have been developed.

Table 4.3: Cities Included in Mathematical Model

Province/Territory	***City***
Alberta	Edmonton
British Columbia	Vancouver
Manitoba	Winnipeg
Nova Scotia	Halifax
Nunavut	Iqaluit
Ontario	Ottawa Toronto Windsor
Quebec	Montreal Quebec City

4.3.4 ECMs

The mathematical model is capable of predicting the effect of ECMs that can be reflected in a change of one or more of the variables included in the input data set. Implementation of ECMs is carried out in the model by changing the variable values associated with the ECM under consideration. As described in Chapter 3, twelve ECMs pertaining to the building envelope, HVAC and lighting, and heating systems are considered in the current study. The ECMs and the values associated with each are presented in Table 4.4.

Table 4.4: Energy Conservation Measures (ECMs)

ECM Description		*ECM Value*
Building Envelope		
01-AT	Reduce Air Infiltration	0.3
02-RI	Insulate Roof (W/m^2·°C)	0.33
03-WI	Install EIFS (W/m^2·°C)	0.34
04-WD	Install Double Glazed, Argon, Low-E Windows (W/m^2·°C)	1.5
05-WT	Install Triple Glazed, Argon, Low-E Windows (W/m^2·°C)	0.78
Electrical Systems		
06-EC	Include an Economizer	Yes
07-VA	Introduce/ Reduce VAV Ratio	0.3
08-HR	Include Heat Recovery Unit	Yes
09-LI	Upgrade Lighting to T8 (W/m^2)	5.6
10-DL	Include Daylighting	Yes
11-CH	Improve Chiller COP	6.5
Natural Gas System		
12-BO	Improve Heating Efficiency	0.96

4.3.5 Limitations

In addition to the general limitations of mathematical models discussed previously in Chapter 2, the mathematical model developed under the current project also has specific limitations to its use.

The model is applicable to office buildings of similar construction and use to those included in the EnergyPlus simulations to develop the model equations. All floors are presumed to have equal areas; HVAC systems are assumed to be properly sized to meet the energy demand of the building; chillers are assumed to be centrifugal, water-chilled, electrically powered; and boilers are assumed to be hot-water, natural gas powered (Chidiac et al., 2011a). Heating is assumed to be provided via air ventilation with hot water reheat coils in the terminal boxes.

4.4 Evaluation of ECMs

There are various bases on which to evaluate the impact of ECMs to determine effectiveness. Criteria may include energy savings, GHG emission reductions, or financial measures such as present value (PV), payback period

(PB), or internal rate of return (IRR). The selection of which criteria to base decisions on is dependent upon the perspective of the decision maker. For example, building owners are typically concerned about the cost of utilities and return on investment. Governments, on the other hand, are interested in both the energy and utility cost savings of their own building stocks, but also the total and peak energy demands on infrastructure and the environmental benefits of reductions in GHG emissions. The five bases for analysis noted above are discussed in the following subsections. The current scope of this project is limited to evaluation of ECMs based on energy and present value (PV) criteria.

4.4.1 Energy Savings

The energy saving potential of ECMs is a good preliminary measure to gauge the effectiveness of retrofits evaluated, as energy savings is used in the calculation of all other evaluation criteria. By considering the magnitude of energy conserved, ECMs with little effect on building energy use can be discarded from the analysis at an early stage and a preliminary ranking of the remaining ECMs can be determined. In the screening, ECMs showing an energy savings of less than five percent (5%) are not considered in the ranking of ECMs. In addition, the quantity of energy savings is one of the factors considered in the evaluation of buildings for green building programs such as the Canadian Green Building Council's Leadership in Energy and Environmental Design (LEED) certification programs (Canadian Green Building Council, 2009).

4.4.2 GHG Emissions

The reduction of GHG emissions resulting from implementation of ECMs is an indicator of reduced environmental impact due to energy conservation. Once the amount of energy conserved as a result of an ECM is known, the impact on GHG emissions can be determined through use of emission conversion factors. Emission factors give "average emission rates of a given GHG for a given source," (UNFCCC, n.d.). They are dependent upon the type of energy used (i.e. electricity, natural gas, or oil), and the efficiency and method of energy production (IPCC, 2007). Inclusion of GHG emission data in the decision tool is beyond the scope of the current work and is suggested for future study.

4.4.3 Financial Evaluation Criteria

For many building owners and managers, ECMs are primarily of interest with regard to potential for reduced building operational costs. Particularly as energy costs continue to escalate, ECMs are becoming increasingly attractive investment options as implementation costs are offset by the increased value of energy savings (Karlsson et al., 2001). For a comprehensive assessment of the feasibility of ECMs, several costs must be taken into account. Costs associated with ECMs include energy cost savings, cost of implementation (i.e. materials, labour, and equipment), interest paid on capital loan, difference in maintenance costs, costs due to loss of production during implementation, and training costs. The financial methods of analysis considered herein take these costs into account. For cases where work is scheduled to be undertaken for reasons such as maintenance, failure or scheduled replacement, the cost difference between the scheduled work and an ECM should be considered as part of the feasibility analysis, as opposed to the total installation cost, as the costs associated with the scheduled work will be incurred regardless if an ECM is introduced (Karlsson et al., 2001).

Present value (PV), payback period (PB), and internal rate of return (IRR) methods provide different criteria for the assessment of ECMs and vary in complexity of the calculations and ease of comparison between projects of differing scales. The PV method determines the present day value of all future costs and benefits, which are easily computed using present worth factors. Using this method it is difficult to compare projects that vary in size objectively as only the absolute savings or losses are considered, not the relative benefit from the cost of the investment. PB analysis gives the length of time needed to recover investment costs. Using the discounted payback period, the calculation becomes complex, which requires the use of numerical methods or a computer program to solve. The method does not explicitly take into account expected service life of the ECM. The user must be aware that if the payback period is longer than the lifespan of the project, the investment will never be recovered. IRR analysis provides an interest rate at which all costs and benefits are equal at the present time. The resulting rate of return facilitates comparison of various sizes of projects, however, as the number of costs/savings considered increases the calculation becomes difficult and must be solved using numerical methods or a computer program.

For the analysis of different projects to be comparable, a common time period must be used for all ECMs. This is achieved by defining a study period over which all costs are considered. If the lifespan of the project is shorter than the study period, the project is repeated. If the project lifespan exceeds the study period, or if the study period is not an even multiple of the project lifespan, a residual value must be added at the end of the study period to represent the remaining usefulness of the project past the end of the study period (Fraser et al., 2000).

To overcome the complexity of PB and IRR analysis, a simplified approach has been adopted for use in the decision tool. Three study periods of one, five, and ten years have been set, at which time the present value is calculated for all effective ECMs. ECMs showing positive PV at these time periods have payback periods equal to or less than the study period. Using a minimum acceptable rate of return (MARR) as the interest rate by which future costs/savings are brought to the present, positive PV indicates the ECM is more favourable than an alternate investment opportunity that provides a return equal to the MARR.

Several parameters must be defined for any of the three methods to be used. Assumptions made in the financial evaluations for this work include the following:

1. Annual energy use trends of individual buildings are unknown, thus the annual energy use of a building is assumed to remain constant.

2. Energy savings resulting from an ECM are presumed constant year after year.

3. Historically, energy costs have increased. Growth factors, assumed to be constant, are applied to the costs of electricity and natural gas to reflect this trend.

4. As the capital investment required for the implementation of ECMs is typically large and outside the means of an annual operating budget, it is presumed that a loan will be taken out. The cost of borrowing is accounted for using a fixed interest rate over the borrowing period.

4.4.3.1 Present Values (PV)

Using present value (PV) analysis, the present worth of all savings and costs over a set time period are found taking into account the time value of money (Fraser et al., 2000). Positive PV of savings indicates a favourable investment, while a negative value signifies a poor investment choice. The PV of savings related to an ECM is given in the expression shown in Equation 4.2. The first two terms represent the present value of electricity and natural gas utility cost savings respectively using an inflation adjusted interest rate. The third term of the PV expression is the cost of implementation, including the cost of borrowing a capital loan. The third term represents the difference in maintenance cost between the existing and replacement technology. The fourth and fifth terms of the PV equation account for the cost of training staff on the operation and maintenance of the new equipment/technology and loss of production during ECM implementation (Chidiac et al., 2011a; Fraser et al., 2000).

$$PV_{savings} = C_e*\partial EC_e*(P/A,g_e,i_f,N) + C_g*\partial EC_g*(P/A,g_g,i_f,N) - CI*(A/P,i_L,M)*(P/A,i_f,M) + \partial MC(P/A,i_f,N) - TC - LOP + SV(P/F, i_f,N) \quad (4.2)$$

where:

$(A/P,i,N)$ = Capital recovery factor: $[i(1+i)^N]/[(i+1)^N-1]$

$(P/A,i,N)$ = Series present worth factor: $[(i+1)^N-1]/[i(1+i)^N]$

$(P/A,g,i,N)$ = Geometric growth series present worth factor: $[(i°+1)^N-1]/[i°(1+i°)^N]*(1/(1+g))$

C_e = Electricity costs ($/kWh)

C_g = Natural gas costs ($/kWh)

CI = Cost of implementation ($)

f = Inflation rate

g_e = Growth rate of electricity costs

g_g = Growth rate of natural gas costs

i_f = Inflation adjusted interest rate based on MARR: $[(1+i)/(1+f)-1]$

i_L = Interest rate of loan

LOP = Loss of production ($)

N = Study period (years)

M	=	Amortization period of loan (years)
MARR	=	Minimum acceptable rate of return (%)
∂EC_e	=	Annual electrical savings (kWh)
∂EC_e	=	Annual natural gas savings (kWh)
∂MC	=	Annual maintenance cost difference (assumed constant) ($)
TC	=	Staff training cost ($)
SV	=	Salvage Value ($)

4.4.3.2 Payback Periods (PB)

The payback period (PB) method is a commonly used tool to assess the financial viability of a project as it is easily understood and incorporated into the financial planning of a company. The payback period is defined as the length of time in years needed to recoup investment costs (Fraser et al., 2000). The attractiveness of the investment increases with shorter payback periods. The two versions of the payback period method are the simple and discount payback periods. The simple payback period is calculated by dividing the cost of investment by the annual savings. This method assumes an interest rate of zero percent. This is a very simplistic method often used to give a preliminary estimate of the actual payback period. The calculation of the discount payback period uses an actual interest rate to give an accurate value of when the initial investment will be recovered (Fraser et al., 2000).

Similar to the PV analysis, the PB analysis method accounts for all costs and savings associated with an ECM. Equations for the present value of costs and savings are presented in Equations 4.3 and 4.4 respectively. The payback period is calculated to be the year at which the present value of savings is equal to the present value of costs.

$$PV_{costs} = CI*(A/P,i_L,M)*(P/A,i_f,M) + TC + LOP - SV(P/F, i_f,N) \quad (4.3)$$

$$PV_{savings} = C_e*\partial EC_e*(P/A,g_e,i_f,N) + C_g*\partial EC_g*(P/A,g_g,i_f,N) + \partial MC(P/A,i_f,N) \quad (4.4)$$

4.4.3.3 Internal Rate of Return (IRR)

An alternate method of analysis for comparing two investment opportunities is using the internal rate of return (IRR) of a project. The IRR is the interest rate at which the credits and debits of a project are equal (Fraser et al., 2000). Comparing the IRR to a minimum acceptable rate of return (MARR), the favourability of the project is determined. Projects with an IRR greater than the MARR give greater return than other investment opportunities and are favoured. All cash flows for the project must be compared within the same time frame, either at present value or as an annuity. The difficulty in applying the IRR comparison is in the calculation of the interest rate. Similar to the PB analysis, as the number of cash flows increases the complexity of the calculation increases. Computer programs are necessary to solve for the IRR. The equations for the present value of costs and savings used for the IRR analysis are the same as given for the PB method above.

4.5 Discussion

The screening methodology provide a simplified method of quantifying and analyzing the effect of a set of ECMs on a building stock comprised of multiple office buildings of various types, sizes, and eras. Energy consumption predictions are made based on a small set of input variables that can be entered directly into the energy prediction model if known, or if unknown, set to match the typical constructions of defined archetypes. Use of the mathematical model equations for energy prediction allows for insight into the influence and interactions of variables. Based on the difference in energy consumptions, the prioritization of effective ECMs is determined for each building, and for all buildings overall based on energy consumption and present value at one, five, and ten years after implementation.

Overall, the screening methodology is effective, easy to use, and provides energy predictions with a level of accuracy acceptable for preliminary decision making. Its development meets the need of building owners and managers of a tool that is capable of prioritizing the implementation of ECMs in a large building stock and presents the results in a clear manner.

Chapter 5: Evaluation/Verification of the Methodology

5.1 Introduction

Demonstration of use of the screening methodology and validation of the results is carried out in an experimental program. Theoretical buildings are defined following the archetypes introduced in the previous chapter and are used as samples to demonstrate application of the screening methodology to a large stock of office buildings. The sample buildings have been evaluated in three cities across Canada with unique climates: Edmonton, Alberta, Ottawa, Ontario, and Vancouver, British Columbia.

Each building has been simulated in each of the three cities using EnergyPlus simulation software without ECMs to determine the pre-ECM base energy consumption. Simulations were subsequently run with ECMs applied individually to determine the effect of each on energy use. Results are compared to show the potential of each ECM, and are also used to validate the energy predictions obtained from the mathematical model.

The screening methodology has been applied to the set of sample buildings in Edmonton, Ottawa, and Vancouver. Results obtained include ranking of the ECMs based on total energy consumption and present value at one, five, and ten years. To allow for the financial analyses, estimates of the cost of implementation of each ECM in each building are obtained from RS Means Costworks (Reed Construction Data, 2011) and suppliers' quotes.

5.2 Sample Buildings

Five unique buildings have been defined to demonstrate application of the screening methodology. Primary variations between the buildings include differences in the number of storeys, floor area, and cladding type. Building A is a two-storey, 3,000 m^2 brick clad building. Building B is 10 storeys with two below-grade levels, 18,000 m^2, brick clad. Building C is 10 storeys with two below-grade levels, 54,000 m^2 with curtain wall cladding. Building D is 18 storeys with two below-grade levels, 90,000 m^2 with brick cladding. Building E is 18 storeys with two below-grade levels, 150,000 m^2 with curtain wall cladding. All buildings are assumed to have a 2:1 aspect ratio and be oriented in the North-South direction.

The three archetypes introduced in the previous chapter are adopted in the design of the five buildings: pre-1950, 1950-1975, and post-1975. The archetypes reflect common constructions and HVAC system characteristics reflected in codes and standards of practice that were current at the time of construction. As brick construction was uncommon for high-rise building after 1975, Buildings B and D are excluded from the post-1975 archetype. Similarly, curtain wall cladding did not appear prior to 1950, and thus Buildings C and E are excluded from the pre-1950 archetype. Building specific characteristics for the five sample buildings are shown in Table 5.1 and Table 5.2. The full definitions of the five buildings including characteristics defined by the archetypes are presented in Appendix B, Table B.1 through Table B.7.

Table 5.1: Buildings A - C Characteristics

Characteristic	***Building A***	***Building B***	***Building C***
General Information			
Number of Floors	2 above grade	10 above grade + 2 below	10 above grade + 2 below
Gross Area (m^2)	3,000	18,000	54,000
Gross Volume (m^3)	11,250	63,750	191,250
Building Envelope			
Walls	Brick/ Concrete Block	Brick/ Concrete Block	Metal Curtain Wall
Roof	Built-up Metal	Built-up Metal	Built-up Metal
Windows to Wall (%)	0.5	0.2	0.8
Distribution System			
Description	Combined AHU and Pumps	Combined AHU and Pumps	Combined AHU and Pumps
Fan Pressure Rise (Pa)	300	300	300
Electrical Systems			
Equip. Load (W/m^2)	40	40	40
Chiller Type	Centrifugal	Centrifugal	Centrifugal
Natural Gas System			
Boiler Fuel	Natural Gas	Natural Gas	Natural Gas
Type	Hot Water	Hot Water	Hot Water
Service Hot Water Fuel	Electricity	Electricity	Electricity
Occupancy Characteristic			
Occupancy Schedule	18 hr, 5 day/wk	18 hr, 5 day/wk	18 hr, 5 day/wk
Density (m^2/person)	25	25	25

Table 5.2: Building D & E Characteristics

Characteristic	***Building D***	***Building E***
General Information		
Number of Floors	18 above grade + 2 below	18 above grade + 2 below
Gross Area (m^2)	90,000	150,000
Gross Volume (m^3)	317,250	528,750
Building Envelope		
Walls	Brick/ Concrete Block	Metal Curtain Wall
Roof	Built-up Concrete	Built-up Metal
Windows to Wall (%)	0.5	0.8
Distribution System		
Description	Combined AHU and Pumps	Combined AHU and Pumps
Fan Pressure Rise (Pa)	300	300
Electrical Systems		
Equip. Load (W/m^2)	40	40
Chiller Type	Centrifugal	Centrifugal
Natural Gas System		
Boiler Fuel	Natural Gas	Natural Gas
Type	Hot Water	Hot Water
Service Hot Water Fuel	Electricity	Electricity
Occupancy Characteristic		
Occupancy Schedule	18 hr, 5 day/wk	18 hr, 5 day/wk
Density (m^2/person)	25	25

Sizing of HVAC equipment was determined for the base buildings (no ECM applied) in each of the three cities from EnergyPlus simulations that allowed automatic sizing of the boiler, chiller, and fans. For subsequent simulations, the sized for these components were fixed at the original size with exception for simulations of ECMs involving replacement of the chiller and boiler. The chiller and boiler capacities are shown in Table 5.3 and Table 5.4.

Table 5.3: Sample Building Chiller Capacities

		Chiller Capacity (kW)		
Building	***Era***	***Edmonton***	***Ottawa***	***Vancouver***
A	1950	342	407	335
	1975	306	355	300
	2000	250	289	246
B	1950	1,969	2,278	1,935
	1975	1,783	2,017	1,750
C	1975	5,241	5,934	5,149
	2000	4,477	5,012	4,410
D	1950	8,907	10,549	8,797
	1975	8,013	9,299	7,909
E	1975	14,062	16,145	13,843
	2000	12,051	13,677	11,896

Table 5.4: Sample Building Boiler Capacities

		Boiler Capacity (kW)		
Building	***Era***	***Edmonton***	***Ottawa***	***Vancouver***
A	1950	1,153	1,203	1,070
	1975	1,005	1,049	959
	2000	819	846	788
B	1950	6,518	6,844	6,250
	1975	5,914	6,073	5,677
C	1975	17,356	17,807	16,680
	2000	14,807	15,012	14,316
D	1950	29,074	30,825	27,929
	1975	26,188	27,207	25,223
E	1975	46,152	47,615	44,364
	2000	39,508	40,270	38,218

The mathematical model input variables for the sample buildings are summarized in Table 5.5 through Table 5.7.

Table 5.5: Mathematical Model Input Variables (Archetype 1: Pre-1950)

	Archetype 1: Pre-1950		
	Building A	***Building B***	***Building D***
Number of Storeys	2	10	18
Average Area per Floor	1500	1500	4500
Number of Basements	0	2	2
Aspect Ratio/ Orientation	L1	L1	L1
Occupancy Density (m^2/pers)	25	25	25
Occupancy Schedule (hrs)	18	18	18
Weekends	0	0	0
Equipment Load (W/m^2)	40	40	40
Lighting Load (W/m^2)	26	26	26
Day Lighting	0	0	0
Heating Setback	0	0	0
Economizer	0	0	0
Heat Recovery	0	0	0
VAV Ratio	1	1	1
Fan Pressure Rise (Pa)	300	300	300
Infiltration Rate (ACH)	1	1	1
Roof U-value ($W/m^2{\cdot}K$)	1.25	1.25	1.25
Roof Solar Absorptance	0.8	0.8	0.8
Wall U-value ($W/m^2{\cdot}K$)	1.25	1.25	1.25
% Fenestration	50	50	50
Fenestration U-value ($W/m^2{\cdot}K$)	5.979	5.979	5.979
Fenestration Solar Heat Gain Coefficient	0.818	0.818	0.818
Chiller COP	1.8	1.8	1.8
Boiler Efficiency	0.75	0.75	0.75

Table 5.6: Mathematical Model Input Variables (Archetype 2: 1950 - 1975)

	Archetype 2: 1950 – 1975				
	Bldg A	***Bldg B***	***Bldg C***	***Bldg D***	***Bldg E***
Number of Storeys	2	10	10	18	18
Average Area per Floor	1500	1500	4500	4500	7500
Number of Basements	0	2	2	2	2
Aspect Ratio/ Orientation	L1	L1	L1	L1	L1
Occupancy Density (m^2/pers)	25	25	25	25	25
Occupancy Schedule (hrs)	18	18	18	18	18
Weekends	0	0	0	0	0
Equipment Load (W/m^2)	40	40	40	40	40
Lighting Load (W/m^2)	17.8	17.8	17.8	17.8	17.8
Day Lighting	0	0	0	0	0
Heating Setback	0	0	0	0	0
Economizer	0	0	0	0	0
Heat Recovery	0	0	0	0	0
VAV Ratio	1	1	1	1	1
Fan Pressure Rise (Pa)	300	300	300	300	300
Infiltration Rate (ACH)	0.75	0.75	0.75	0.75	0.75
Roof U-value ($W/m^2 \cdot K$)	0.9	0.9	0.9	0.9	0.9
Roof Solar Absorptance	0.8	0.8	0.8	0.8	0.8
Wall U-value ($W/m^2 \cdot K$)	0.87	0.87	0.4	0.87	0.4
% Fenestration	50	50	80	50	80
Fenestration U-value ($W/m^2 \cdot K$)	2.716	2.716	2.716	2.716	2.716
Fenestration Solar Heat Gain Coefficient	0.764	0.764	0.764	0.764	0.764
Chiller COP	2.5	2.5	2.5	2.5	2.5
Boiler Efficiency	0.75	0.75	0.75	0.75	0.75

Table 5.7: Mathematical Model Input Variables (Archetype 3: Post-1975)

	Archetype 3: Post-1975		
	Building A	***Building C***	***Building E***
Number of Storeys	2	10	18
Average Area per Floor	1500	4500	7500
Number of Basements	0	2	2
Aspect Ratio/ Orientation	L1	L1	L1
Occupancy Density (m^2/pers)	25	25	25
Occupancy Schedule (hrs)	18	18	18
Weekends	0	0	0
Equipment Load (W/m^2)	40	40	40
Lighting Load (W/m^2)	9.3	9.3	9.3
Day Lighting	0	0	0
Heating Setback	0	0	0
Economizer	1	1	1
Heat Recovery	1	1	1
VAV Ratio	0.65	0.65	0.65
Fan Pressure Rise (Pa)	300	300	300
Infiltration Rate (ACH)	0.5	0.5	0.5
Roof U-value ($W/m^2 \cdot K$)	0.46	0.46	0.46
Roof Solar Absorptance	0.8	0.8	0.8
Wall U-value ($W/m^2 \cdot K$)	0.6	0.4	0.04
% Fenestration	50	80	80
Fenestration U-value ($W/m^2 \cdot K$)	1.512	1.512	1.512
Fenestration Solar Heat Gain Coefficient	0.597	0.597	0.597
Chiller COP	5.2	5.2	5.2
Boiler Efficiency	0.85	0.85	0.85

5.3 Energy Saving Potential of ECMs – Energy Simulation Results

The energy saving potential of the ECMs considered in the tool is demonstrated using comparison of pre- and post-ECM building energy simulation results. Energy simulations of all sample buildings were simulated using the EnergyPlus simulation software. The pre-ECM energy consumption results are presented as reference in Figure 5.1. The results for each ECM, for all buildings, simulated in Edmonton, Ottawa, and Vancouver are presented and discussed below.

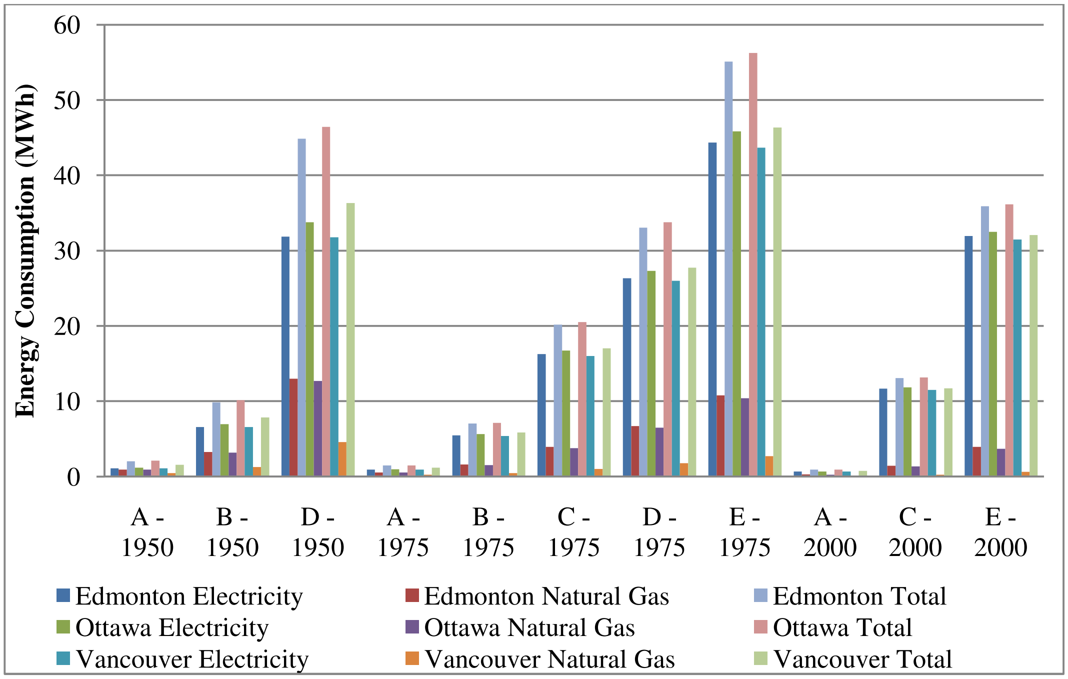

Figure 5.1: Pre-ECM Energy Consumption of Sample Buildings

5.3.1 Building Envelope Air Tightness

Increasing the air tightness of the building envelope is an effective ECM for all buildings, as shown in Figure 5.2. Natural gas savings range from 34-95%, with the greatest saving experienced in larger, older buildings, which have higher surface area and higher air leakage than their smaller, newer counterparts. Electricity energy consumption was not affected. Overall savings were between 2-20% of the total energy consumption, depending on the proportion of natural gas to total energy use. These savings are in the same range as those reported in the literature.

The difference between the effect of air infiltration reduction on heating and cooling energy use can be explained by the variance in the indoor-to-outdoor pressure differential during the heating and cooling seasons. Internal pressure of buildings is higher during the heating season, compared to the cooling season, as warmer air is less dense than chilled air and has a tendency to expand. The positive pressure of the ventilation system also contributes to the higher indoor pressure. During the cooling period, the positive pressure of the ventilation system is counteracted by the higher outdoor pressure difference due to temperature variation across the building envelope. Thus, the overall pressure differential which would drive infiltration or exfiltration is lower during the cooling season, leading to less loss of chilled indoor air compared to the loss of heat through exfiltration during the winter months.

Identical buildings simulated in different cities experienced similar effects; due to reduced heating demand in the warmer climate of Vancouver, savings were slightly reduced than those for Edmonton and Ottawa.

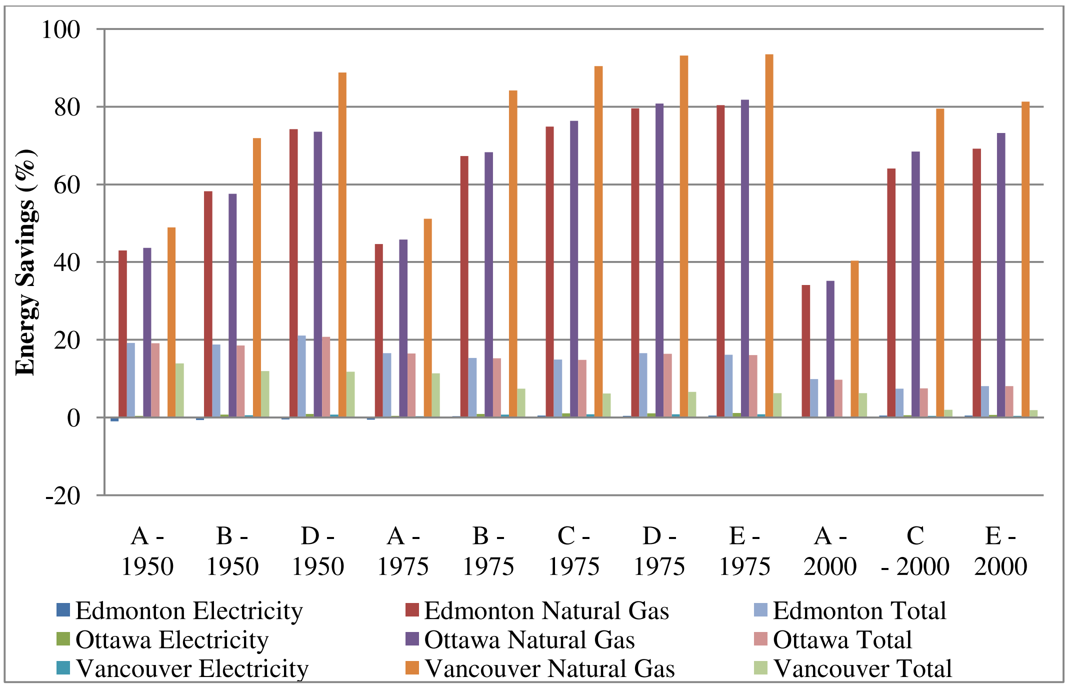

Figure 5.2: Effect of Building Envelope Air Tightness ECM

5.3.2 Building Envelope Thermal Resistance

The influence of ECMs pertaining to improvements in the thermal resistance of the building envelope exhibit similar trends. For increases in the roof, wall, and fenestration thermal resistances, the effect on electrical energy consumption was minimal. Savings were greater in cities with colder climates, and the ECMs resulted in greater impact for buildings where thermal resistance was lower originally (i.e. older buildings). The percentage of natural gas energy savings were greater for Vancouver, however, the ratio of heating to electrical energy consumption is lower, leading to lower overall percentage energy savings.

5.3.2.1 Roof Insulation

As shown in Figure 5.3, upgrading of roof insulation resulted in 2-18% natural gas savings, and up to 6.5% reduction in overall energy use. These values match those found in the literature discussed previously. This ECM had the largest effect in low-rise buildings where the roof accounts for a larger proportion of the overall building envelope surface area, and in older buildings where improvements in the U-value were greater. Results show minimal savings in electrical energy consumption, which is due to reduced heat transfer through the roof during summer months. During the winter season, the positive benefit of solar heat gain is diminished, however this is overshadowed by reduced heat loss through the roof construction.

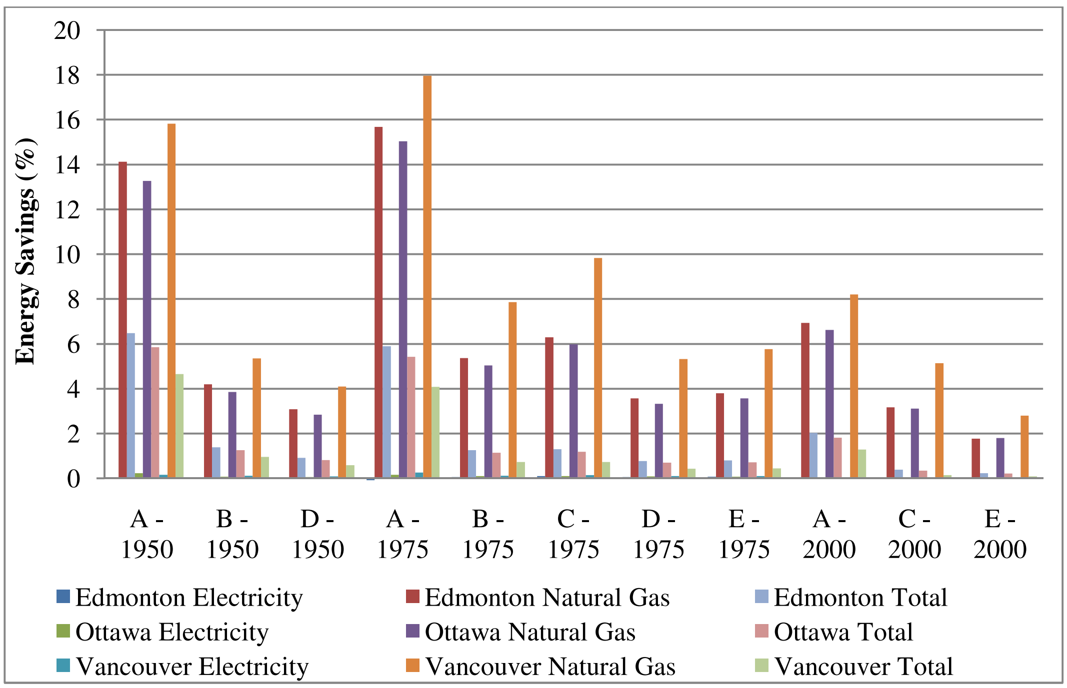

Figure 5.3: Effect of Roof Insulation ECM

5.3.2.2 Wall Insulation – EIFS

The addition of EIFS to the exterior of brick clad buildings lead to 4-15% natural gas savings, which amount up to 2.3% savings in overall energy consumption, as shown in Figure 5.4. Case studies found in current literature vary widely from showing minimal improvement, up to 28% natural gas consumption savings. The results found in this study are within range of the reported results.

Reduction in the conductivity of walls serves to reduce heat loss and gain through this portion of the building envelope. Reduced heat loss during the heating season serves to reduce heating demand on the boiler system. For this reason, natural gas savings are experienced, the percentage of which varies between buildings based on the ratio of perimeter wall to overall floor area. The highest savings were found in the mid-size building, Building B. Compared to Building D, the perimeter zone in Building B comprises a higher percentage of the total per floor area, therefore increasing the influence of the wall thermal resistance on overall heating demand. The foot print of Buildings A and D are identical, however the roof has a greater influence in the low-rise Building A, which reduces the effect of additional wall insulation.

The influence of this ECM on electrical consumption was minimal, as heating demand due to heat gains through the building envelope are small compared to that due to internal heat gains. Electrical savings resulting from reduced envelope heat gains may also be offset by increased radiant heat due to the increased thermal mass of the wall system.

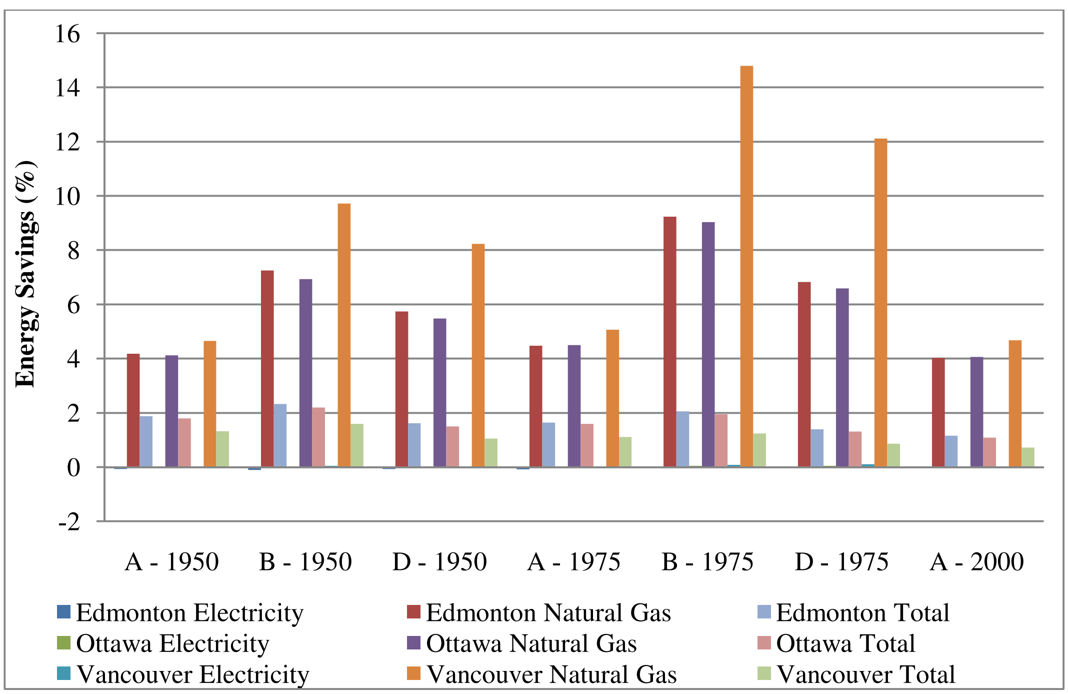

Figure 5.4: Effect of Wall Insulation (EIFS) ECM

5.3.2.3 High Performance Windows – Double and Triple Glazed, Low-E, Argon-Filled

Replacement of existing fenestration with high performance windows garnered positive overall energy savings for all buildings for both types of windows considered. Savings resulting from the installation of double glazed, low-E, argon-filled units reduced natural gas savings between 14-60%, and overall energy savings by 2-15%. Slightly greater savings were experienced when triple glazed, low-E, argon-filled windows were installed, showing savings of 11-65% in natural gas consumption, and 2-17% less overall energy consumption. These results are shown in Figure 5.5 and Figure 5.6 respectively, and compare favourably with results found in the literature.

Similarly to the addition of wall insulation, replacement of existing fenestration with higher thermal resistant windows serves to reduce conductive heat gains and losses through these surfaces. Additionally, the use of low-E glazing coatings limits heat gains due to solar radiation. The trend in energy savings between buildings within the same archetype are the same as described for the above ECM. Overall savings were greater, the larger the difference in U-value and SHGC between the existing and replacement windows.

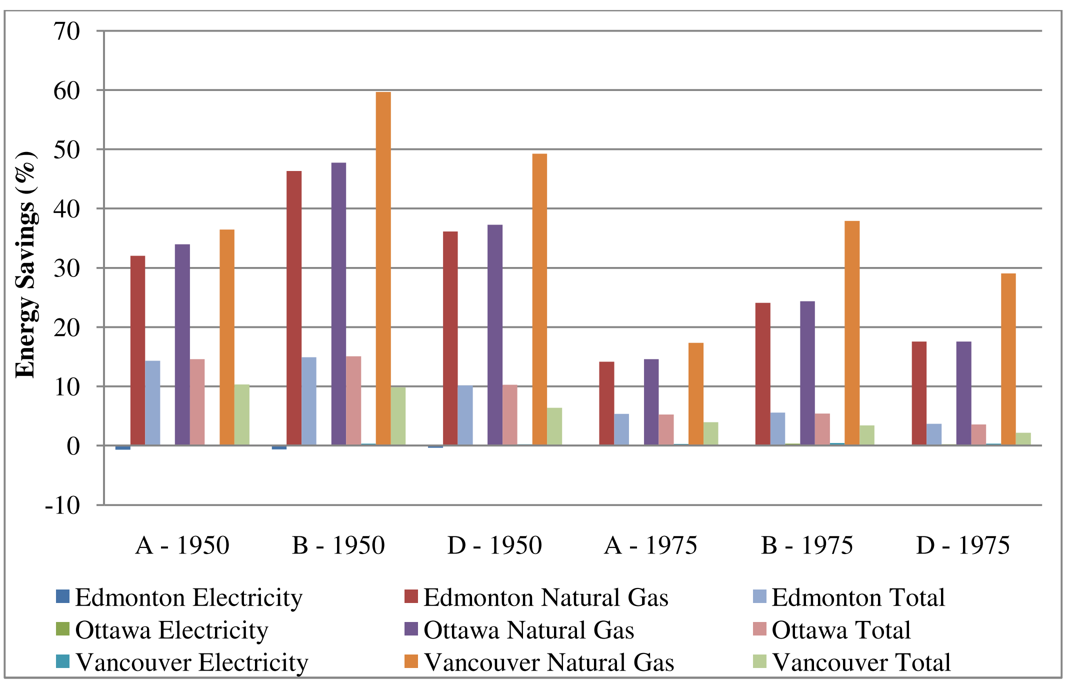

Figure 5.5: Effect of Double Glazed, Low-E, Argon-Filled Windows ECM

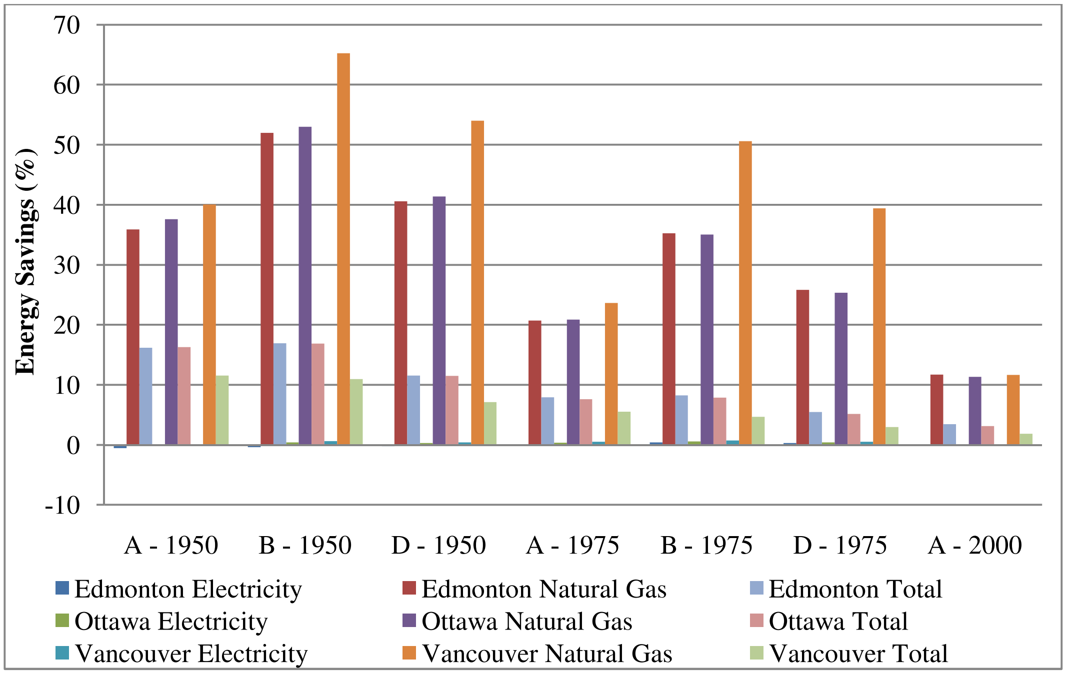

Figure 5.6: Effect of Triple Glazed, Low-E, Argon-Filled Windows ECM

5.3.3 Ventilation System

5.3.3.1 Economizer Control

Implementing ventilation economizer controls was the only ECM of those studied that showed negative overall results. The effect on electricity consumption ranged from 4% increase to 1% savings. Natural gas consumption increased across a wide range from 2-130%. Overall energy consumption increased between 1-8%. These results, shown in Figure 5.7, are counter to the positive results found in the literature that showed significant electrical savings that overshadowed increases in natural gas usage in moderate and warmer climates where temperatures fluctuate between day and night. The results are similar to those found by Chidiac et al. (2011a) for buildings using economizer controls in Vancouver, Edmonton, and Ottawa.

Fixed dry bulb temperature economizer controls with setpoints at 11°C and 24°C were used in the building simulations. In moderate climate of Vancouver, the number of hours where the outdoor temperature falls within this range is greater than for the other two cities, thus the effect on energy consumption is increased. Operation of the economizer controls when the outdoor temperature is above the lower setpoint, but below the indoor temperature set point allows excess cool air to enter the buildings, leading to increased heating demand. True economizers do not allow for additional air intake when it is not beneficial, however limitations in the software program allow for excessive outdoor air to be introduced in the simulation. To allow for direct comparison of results between all buildings, the ECMs were implemented identically in all cities. Should the economizer controls be cut out during the winter in Vancouver, or the setpoints modified to allow increased air intake within a narrower temperature range, positive effects are expected.

In regard to the effect of increased cooling energy use, using fixed dry bulb temperature controls, the suitability of outdoor air was evaluated based solely on temperature without consideration of the air moisture content. If outdoor air brought into the building is of high relative humidity, additional energy is required to cool the air to remove the excess moisture. The use of enthalpy economizer controls may have yielded more favourable results, especially in the humid climates of Ottawa and Vancouver.

Newer buildings showed the highest increases in energy consumption, which may be attributed to the reduced influence of the outdoor climate on indoor conditions due to improvements in the building envelope thermal properties and air tightness. Higher solar heat gains through the building envelope in older buildings would help to offset the additional heating requirements resulting from use of economizer controls.

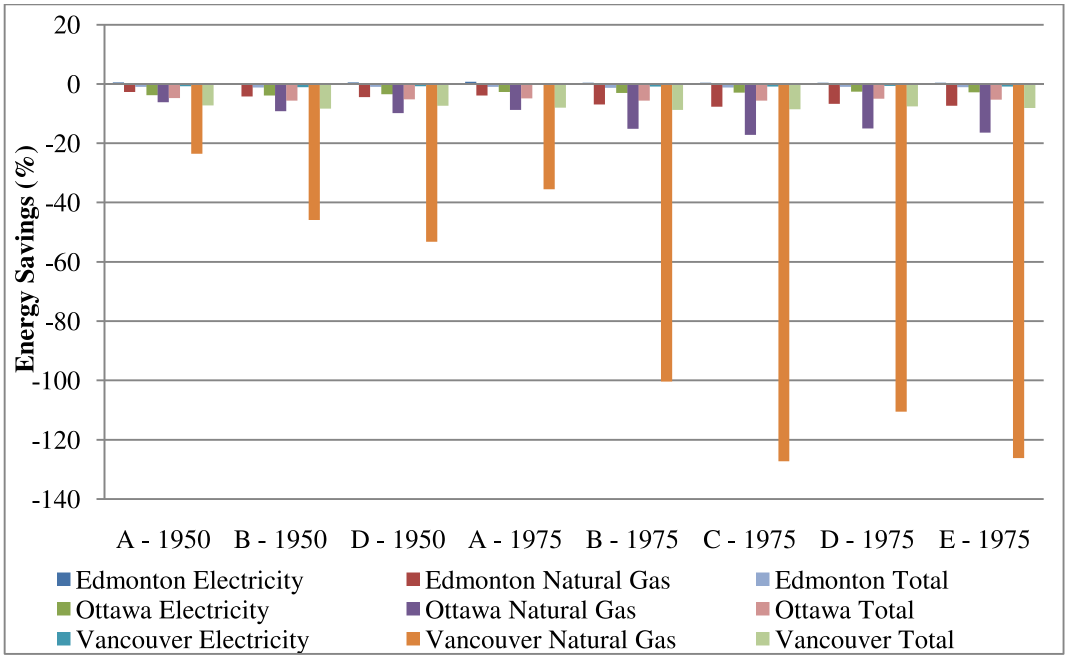

Figure 5.7: Effect of Economizer Controls ECM

5.3.3.2 Variable Air Volume

Conversion from a constant volume ventilation system to variable air volume, or reduction in the VAV ratio, resulted in 2-10% electrical savings, or 1-5% overall energy savings. Natural gas consumption increased between 4-37%. The results are shown in Figure 5.8. Due to the redistribution of chilled air based on zone level demands, reductions in overall chiller and fan electrical consumption were found. However the difference in cooling demand between interior and perimeter zones is minimal due to the larger magnitude of internal heat gains compared to heat gains through the building envelope. Improvements in the building envelope across archetypes reduced the difference in zone cooling demands, leading to reduced electricity savings due to VAV in newer buildings. Electricity savings in the post-1975 archetype were lowest as a VAV system was already in place and the difference in air flow redistribution was minimal. Electricity savings were slightly higher in smaller buildings where the perimeter to interior zone area ratio is greater.

Sizable increases appeared in natural gas consumption due to the implementation of VAV, particularly in the 1950 – 1975 archetype. Heating demand in interior zones is minimal due to high internal loads and requires little, if any, heating. With the implementation of VAV, the volume of hot air required is reduced by the volume that would otherwise be delivered to interior zones unnecessarily. The magnitude of heating saved in interior zones in buildings in all eras between CV and VAV systems is similar. Although heating energy savings are expected due to reduction of heat delivered to interior zones, ventilation systems do not operate as efficiently at lower air flow rates as heat loss within the ducts are greater at reduced air flows. This reduces the amount of heat delivered to the zone per volume of air, requiring the heating system to operate for longer periods of time to meet heating demands. Energy savings due to decreases in the floor area requiring heating are overshadowed by the amount of energy required to operate the heating system for longer time periods. As this ECM in pre-1950 and 1950 – 1975 buildings is identical, the magnitude of savings is similar. However, as the initial natural gas energy consumption in 1950 – 1975 era buildings is less as a result of better building envelopes, the percentage of heating energy use appears larger.

Overall energy savings were greater in the moderate climates of Vancouver where increases in the magnitude of heating energy use were less.

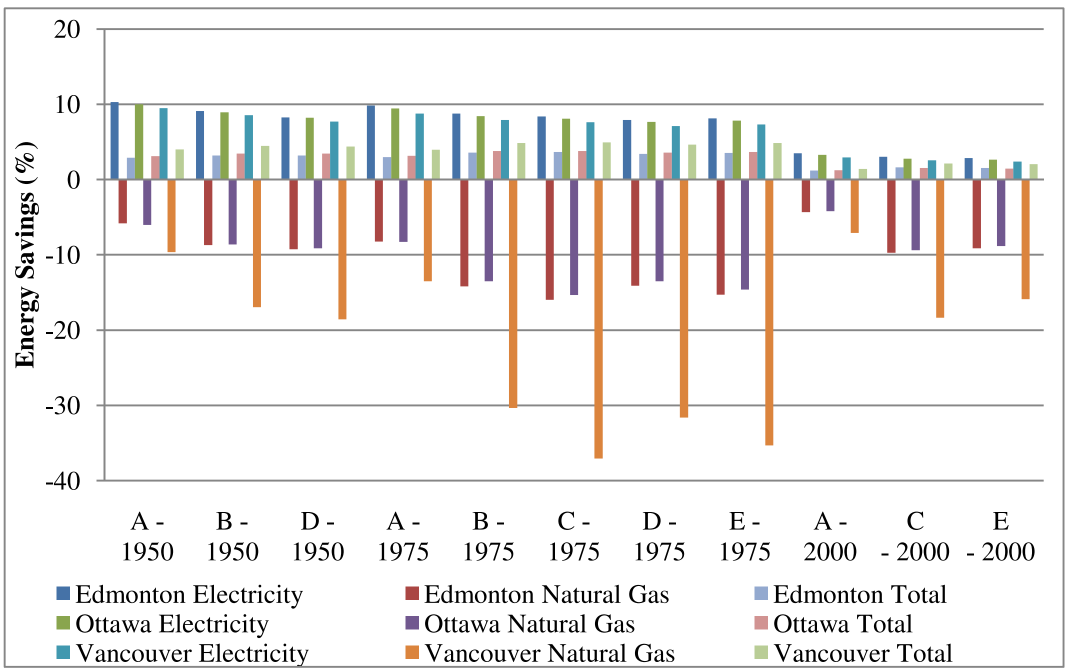

Figure 5.8: Effect of Variable Air Volume ECM

5.3.3.3 Exhaust Air Heat Recovery

Implementation of exhaust air heat recovery showed positive savings up to 2% of total energy consumption, as shown in Figure 5.9. Pre-heating of incoming outdoor air with heat recovered from the exhaust air stream provided natural gas energy savings of 3.4-9%. Results obtained are lower than those found in the literature. This is likely due to the colder climate of the buildings simulated compared to the locations of buildings for which results were reported.

Electrical energy increased marginally due to the additional demand of the enthalpy wheel fan. The percentage of heating energy offset by heat recovery was greater in newer buildings that have higher thermal resistance to heat loss through the building envelope and higher air tightness. These factors allow for more heat to be returned to the heat exchanger through the ventilation system. Overall, the percent savings was consistent across all building types and archetypes. Higher results were found in colder cities where the temperature difference between incoming outdoor air and exiting exhaust air was larger, allowing for increased heat exchange efficiency.

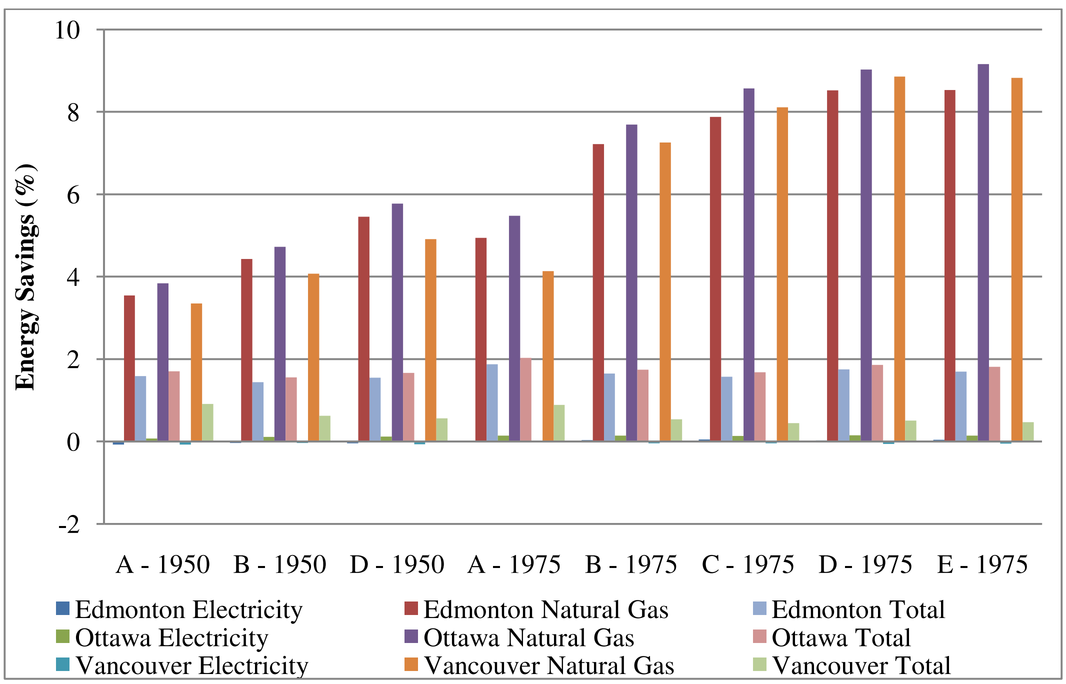

Figure 5.9: Effect of Exhaust Air Heat Exchanger ECM

5.3.4 Lighting

5.3.4.1 Energy Efficient Luminaires

Improvements in lighting energy intensity resulted in electrical savings of 6-22%, and overall energy savings of 3-13%. Natural gas consumption increased between 5-50%. These savings, shown in Figure 5.10, are consistent with those found in the literature.

Upgrading to higher efficiency lighting fixtures allows for the illuminance of the space to be maintained using less energy. The majority of the savings were obtained directly from savings in lighting energy use. Chiller, chilled water loop supply pump (CWLSP), and condenser water loop supply pump (CNWLSP) energy consumption were also reduced post-ECM. These savings are attributable to reduced heat gains due to lighting during the cooling season, as higher efficiency lamps emit less heat compared to lower efficiency lamps. Boiler energy use was also affected for the same reason; heating demand increased to compensate for the reduced lighting heat gains. As boiler systems are much more efficient heat sources than lighting, the increase in boiler use is overshadowed by the benefit in lighting energy improvements.

The greater the improvement in lighting energy use intensity, the greater the savings. The magnitude of the effects on energy use are constant between cities, however the percentage increase or decrease varies due to the difference in electricity to natural gas usage within each building.

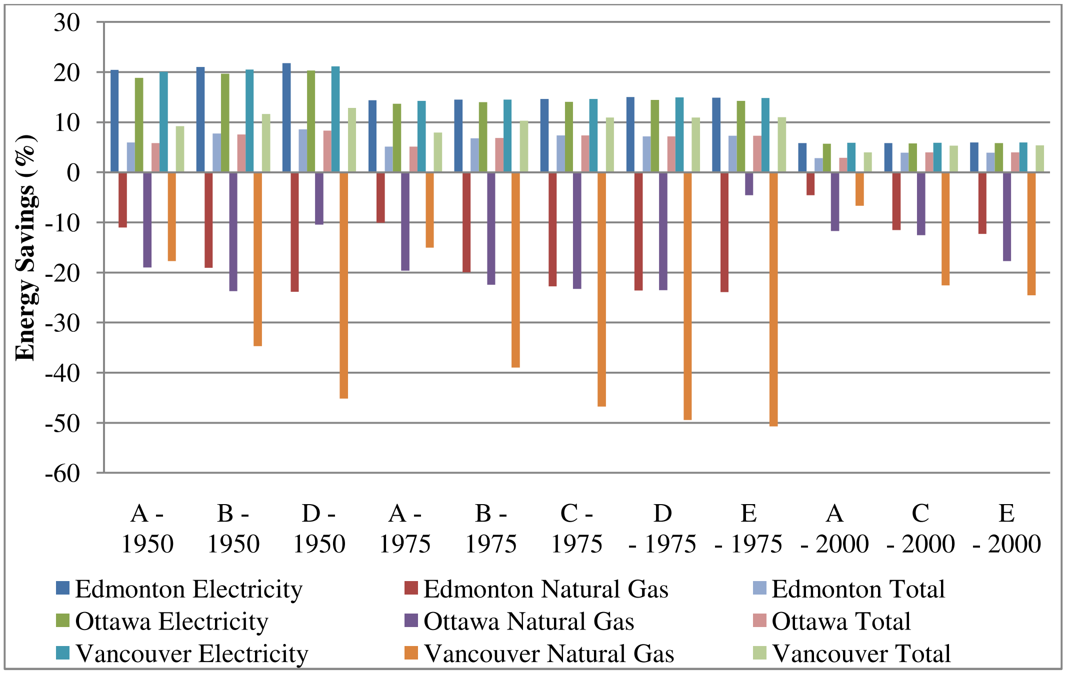

Figure 5.10: Effect of Energy Efficient Luminaries ECM

5.3.4.2 Daylight Sensor Lighting Controls

Installation of daylight sensor lighting controls resulted in both electrical and natural gas savings for all buildings. Results range from 2-8% electricity savings, 3-13% natural gas savings, and 2-9% overall energy savings. These results, shown in Figure 5.11, are slightly lower than those found in the literature.

Electrical savings arose mainly due to reduced use of artificial lighting when sufficient natural light is available. Window shading control was set to be to be off, except when high glare is transmitted through the windows. This control differs from the base case where window blinds were always drawn. Owing to this difference, solar heat gains through the fenestration were higher when daylighting controls were used, contributing to natural gas savings. Increases in chiller consumption for the same reason were not observed, as periods of high glare are likely to coincide with the cooling season and the window shading control will be effective in limiting solar heat gains during these periods.

Higher energy savings were experienced in older buildings where the difference in pre- and post-ECM lighting intensity was greatest. Maximum percent savings were found in smaller buildings where lighting and heating account for a larger percentage of the overall energy use of the building, and the perimeter zones comprise a larger percentage of the overall floor area. Savings were relatively consistent between the three locations studied.

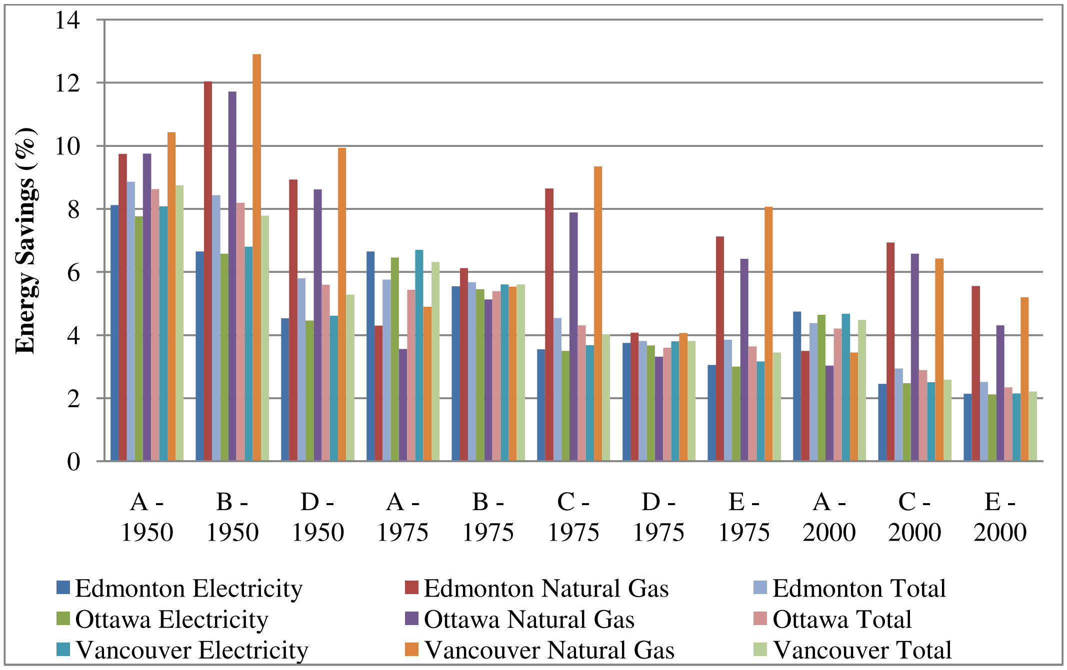

Figure 5.11: Effect of Daylight Sensor Lighting Controls ECM

5.3.5 Cooling and Heating System Efficiency

5.3.5.1 Chiller COP

Positive energy savings were experienced in all buildings following improvements in chiller COP. Electricity savings range between 2-22%, while overall energy consumption fell between 2-17%. As expected, natural gas consumption was unaffected. The results are shown in Figure 5.12.

Higher savings were found in older buildings where the improvement in COP between the existing and replacement equipment is the highest. The percentage of savings gained was also higher in larger buildings and in warmer climates where cooling loads are greater. Changes in the chiller COP affect the electrical energy consumption of the chiller and condenser water loop supply pump, and also the condenser water flow rate. The condenser pump and water flow rates are affected to a lesser extent than the chiller, however the trend in energy use reductions are similar.

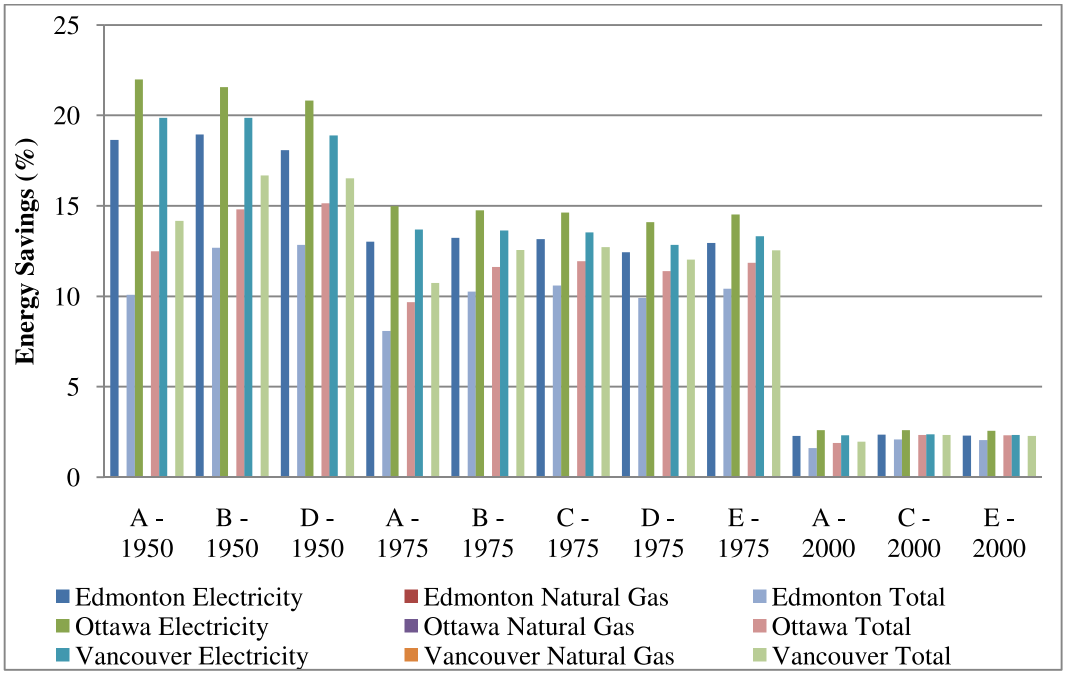

Figure 5.12: Effect of Chiller COP ECM

5.3.5.2 Boiler Efficiency

Increases in boiler energy efficiency resulted in consistent percent savings of natural gas energy between buildings with similar initial boiler efficiency. Buildings in the pre-1950 and 1950-1975 archetypes saved 22%, while those post-1975 saved 12% natural gas. Electricity consumption remained unaffected. Overall energy savings range up to 10%. These results, shown in Figure 5.13, fall within the range of those presented in published case studies.

Differences in the overall energy savings appeared as the ratio of natural gas to total energy use varies between buildings, archetypes, and locations. Older buildings experienced increased savings as improvement in boiler efficiency was higher than newer buildings. The ratio of natural gas to electrical energy use in smaller buildings is higher due to the higher ratio of building envelope surface area to gross floor area. Buildings located in older climates also require increased use of the heating system. The higher the percentage of natural gas consumption, the greater the influence of boiler system efficiency improvements. Conversely, larger, newer buildings located in a moderate climate showed minimal improvement in natural gas consumption due to this ECM.

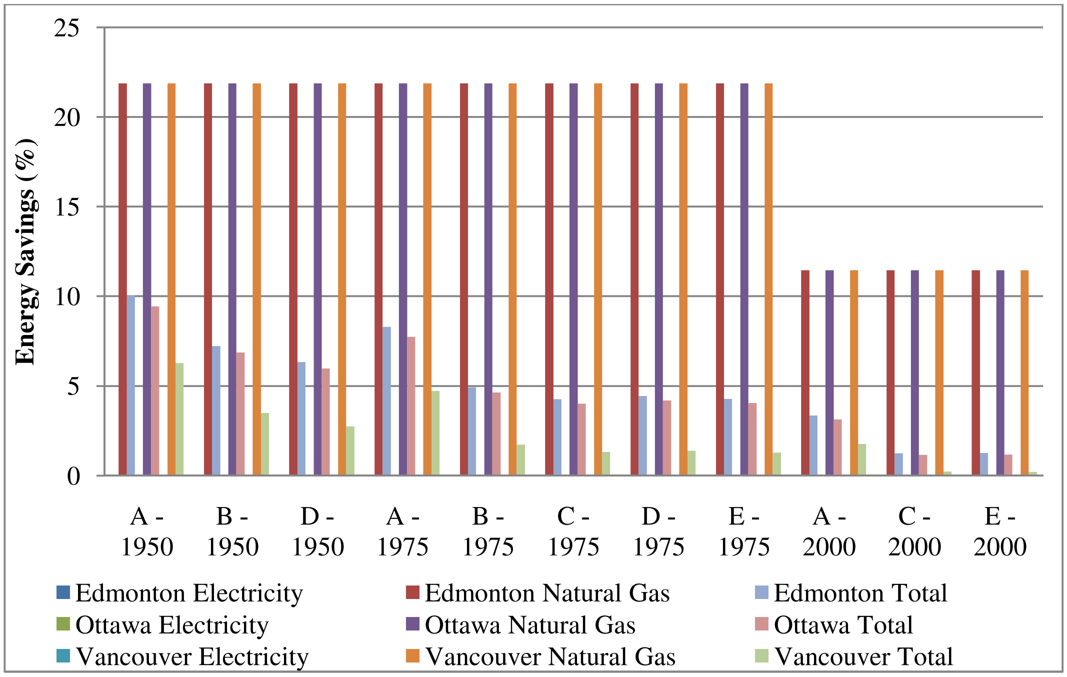

Figure 5.13: Effect of Boiler Efficiency ECM

5.4 Energy Consumption Comparison – EnergyPlus vs. Mathematical Model

Considering change in energy consumption is central to the analysis of ECMs, accuracy of the mathematical model predictions is of high importance. EnergyPlus simulation results have been used as a basis for comparison to validate the use of the mathematical model in predicting energy consumption for the separate building components.

For all pre- and post-ECM energy consumption predictions using the sample buildings, the percent difference between the EnergyPlus simulation and mathematical model results is calculated for each of the nine energy end use components. The mean and standard deviations of the errors have been found and are presented as a general measure of the fit of the results, as shown in Figure 5.14.

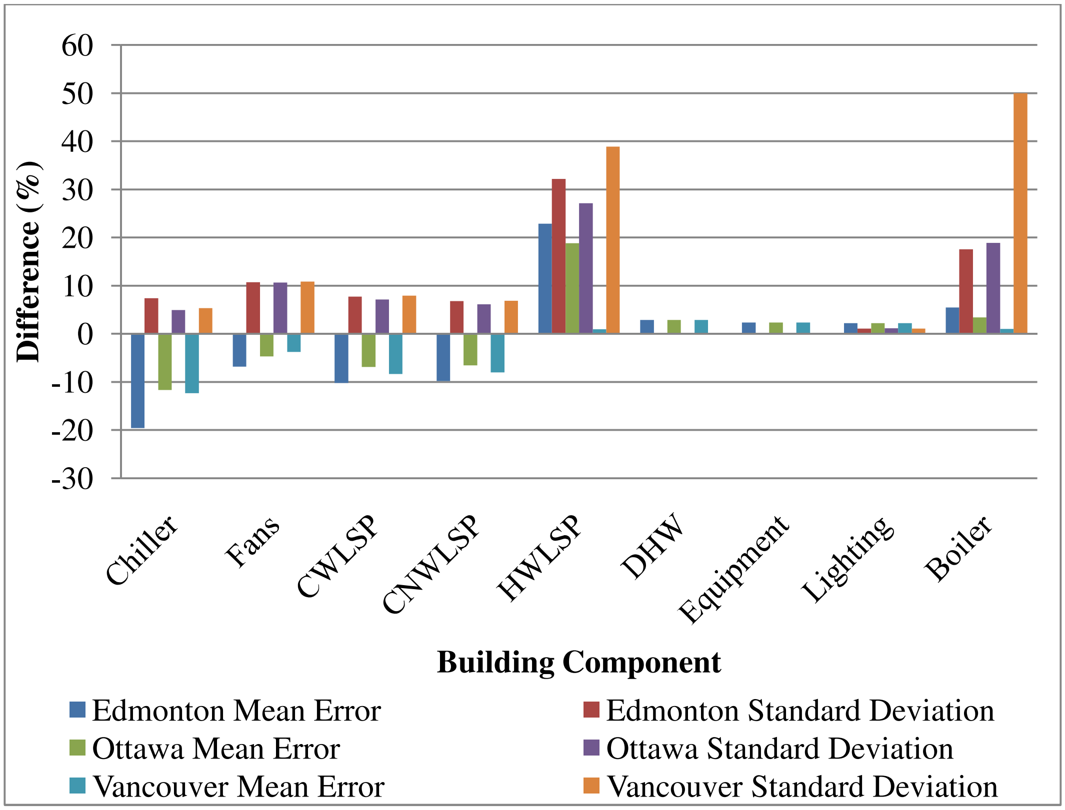

Figure 5.14: Energy Prediction Comparison - EnergyPlus vs. Mathematical Model

Overall, the acceptability of the model predictions is good considering the intent of the tool as a preliminary evaluation of building energy use. The mean of all the errors for the separate components fall within the range of -15% to 14%. However, sizable average errors are observed for predictions of the chiller, and hot water loop supply pump (HWLSP), and there is large variability in the accuracy of predictions of boiler energy consumption.

To allow for more in depth comparison, the mathematical model predicted energy consumption for each of the nine components is plotted against the EnergyPlus simulation results. Sets of plots are presented in Appendix C for each sample building size, for each of the three cities studied.

The most variance between the results is found in the energy consumption estimates for interdependent system components, such as the chiller, fans, and chilled, condenser, and hot water loop supply pumps. The equations of the mathematical model for these components are complex and are dependent on a large number of variables, which increases the difficulty of fitting the model to the simulation results used in the model development.

The largest variations between the predicted (mathematical model) and actual (EnergyPlus) results are found to occur in older buildings. In particular, hot water loop supply pump (HWLSP) energy use is over predicted for Pre-1950 era buildings in Edmonton and Ottawa. In Vancouver the model predictions appear to be less varied, however fluctuate between over and under predicted without showing a clear trend in the errors. The variability in the predictions is of little relevance to the selection of ECMs, due to the relatively low energy use of this component.

The mathematical model provides good estimations of boiler energy use for buildings in the colder climates of Edmonton and Ottawa. However, predictions of boiler consumption in Vancouver show a wider spread in the accuracy of the results, particularly for buildings with high percentage of windows. This variance in the energy predictions is of relevance to consideration of the boiler efficiency improvement ECM. Severe under prediction of the energy consumption would devalue the influence of this ECM in comparison to the other ECMs considered.

EnergyPlus results show constant energy consumption for fans, however the mathematical model predicts variation in the energy consumption of this component for same sized buildings with different characteristics. This error arises due to the fact that the fan flow rate in the EnergyPlus simulations is set to be constant, while the mathematical model incorporates prediction of the maximum fan flow rate based on the building characteristics. When an ECM is implemented in the model, the maximum fan flow rate may be affected, whereas this is not the case in the simulations.

Energy predictions for independent component energy consumptions, such as domestic hot water (DHW), equipment, and lighting, match the simulation results with high precision. The mathematical model consistently over predicts energy consumption of these components by three percent (3%). The accuracy of the predictions for these components is expected, as they are dependant upon a small set of variables that are unaffected by changes in other building systems or climatic conditions.

In using the results of the screening methodology, it is important that the accuracy of the energy predictions be kept in mind, particularly for ECMs that result in energy savings largely due to conservation in the energy consumption of one component where there is little opportunity for errors to be averaged out across multiple components.

5.5 ECM Comparison Based on Energy Consumption

As the acceptability of the mathematical model in predicting energy consumption has been shown, the model can be used with confidence to make comparisons between ECMs based on energy consumption savings for buildings of various sizes, archetypes, and in various locations. For each of the sample buildings, the energy savings resulting form the implementation of the twelve ECMs considered are presented in Figure 5.15 through Figure 5.25. The ECM descriptions are listed in Table 5.8 for reference.

Table 5.8: ECM Descriptions

ECM Description	
Building Envelope	
01-AT	Reduce Air Infiltration
02-RI	Insulate Roof (W/m^2·°C)
03-WI	Install EIFS (W/m^2·°C)
04-WD	Install Double Glazed, Argon, Low-E Windows (W/m^2·°C)
05-WT	Install Triple Glazed, Argon, Low-E Windows (W/m^2·°C)
Electrical Systems	
06-EC	Include an Economizer
07-VA	Introduce/ Reduce VAV Ratio
08-HR	Include Heat Recovery Unit
09-LI	Upgrade Lighting to T8 (W/m^2)
10-DL	Include Daylighting
11-CH	Improve Chiller COP
Natural Gas System	
12-BO	Improve Heating Efficiency

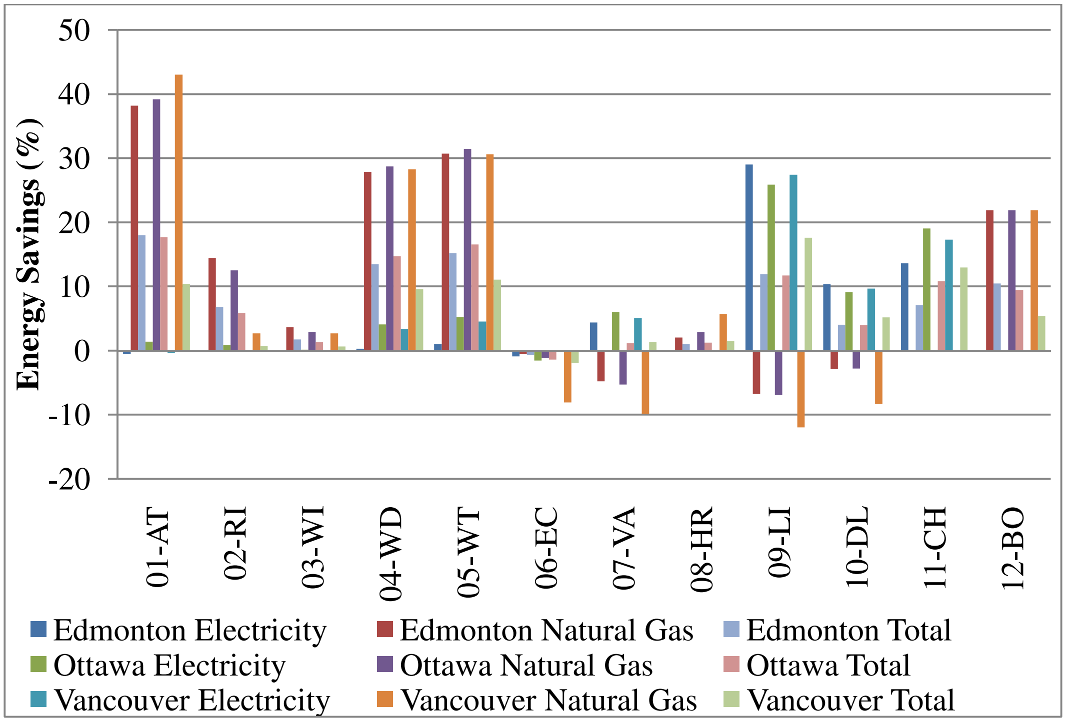

Figure 5.15: ECM Comparison - Building A, Pre-1950

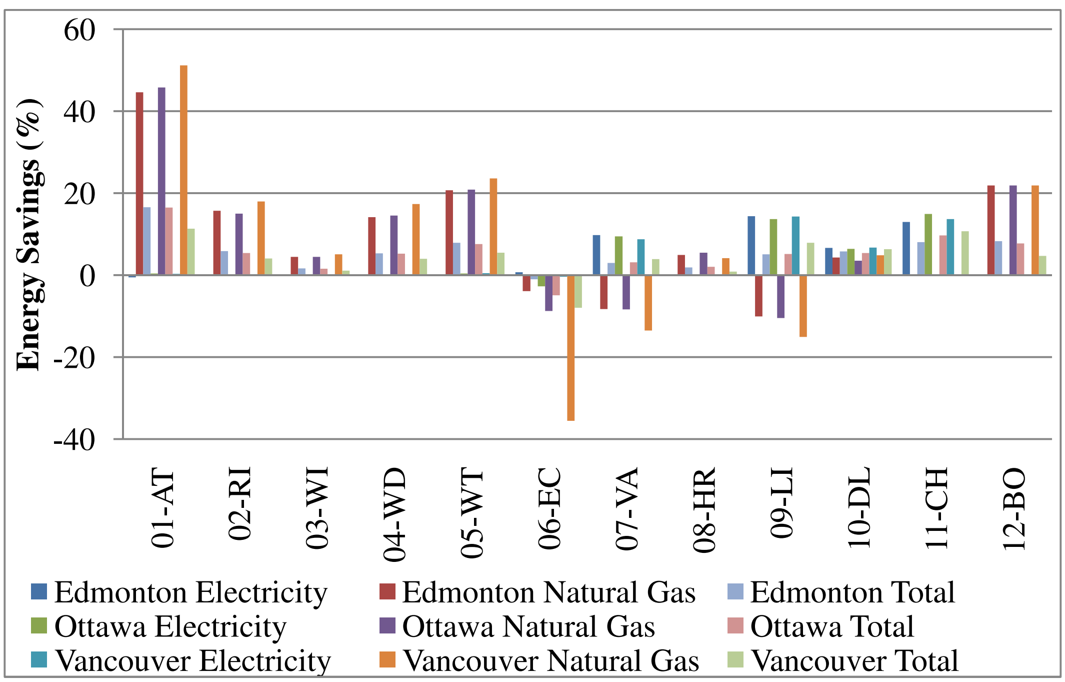

Figure 5.16: ECM Comparison - Building A, 1950 - 1975

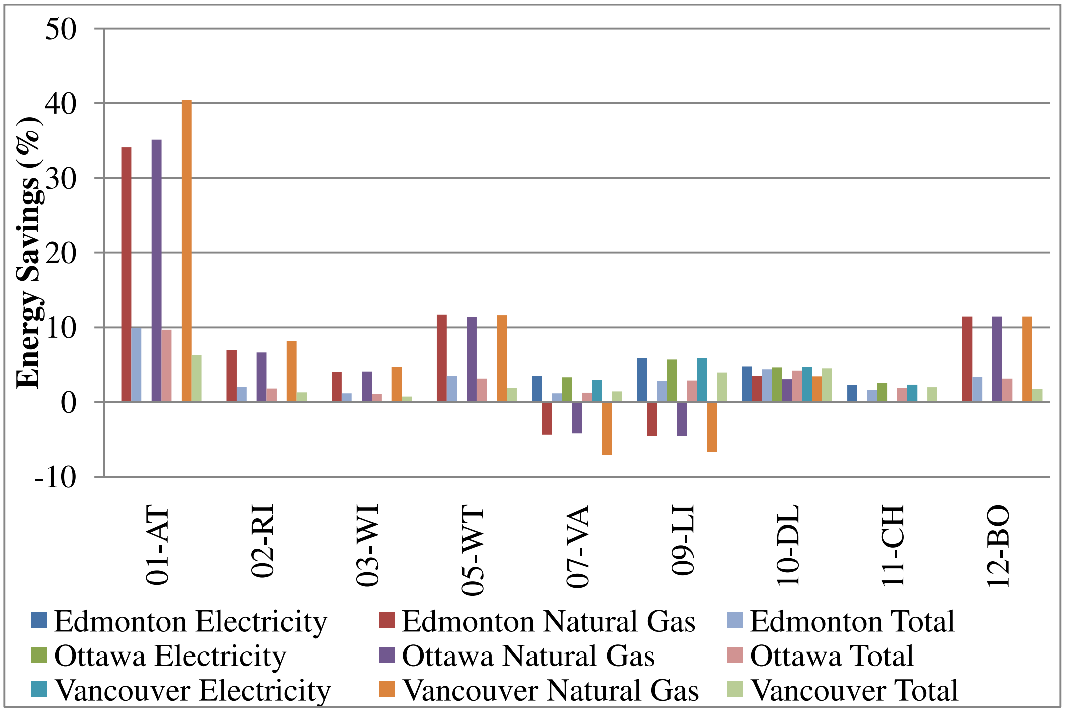

Figure 5.17: ECM Comparison - Building A, Post-1975

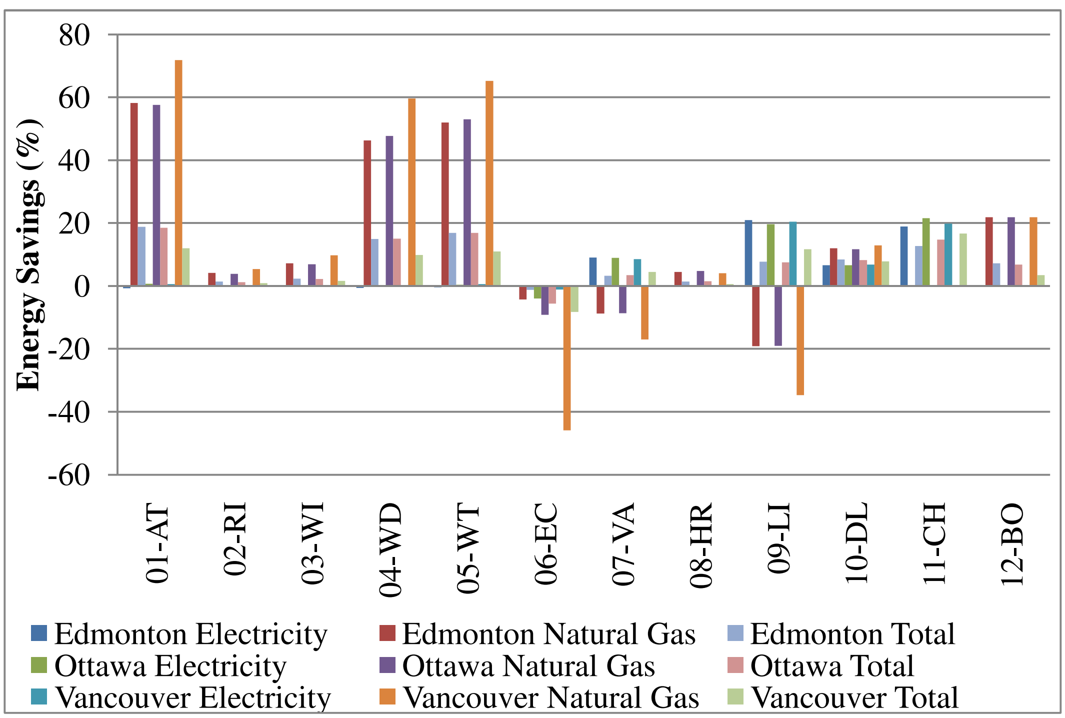

Figure 5.18: ECM Comparison - Building B, Pre-1950

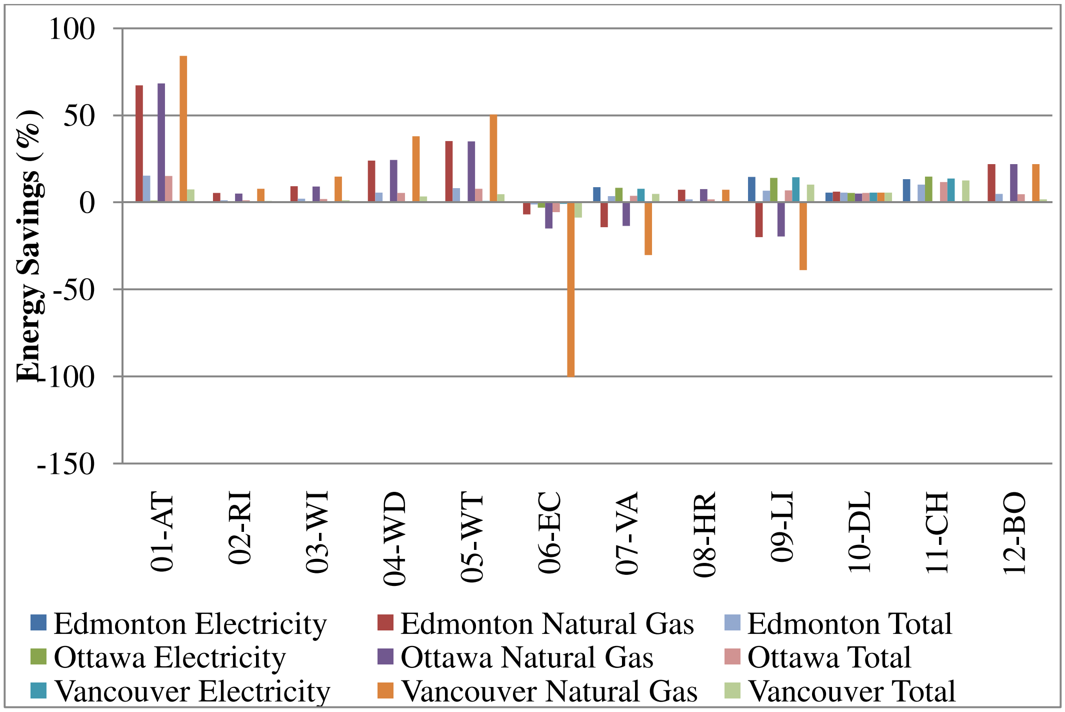

Figure 5.19: ECM Comparison - Building B, 1950 - 1975

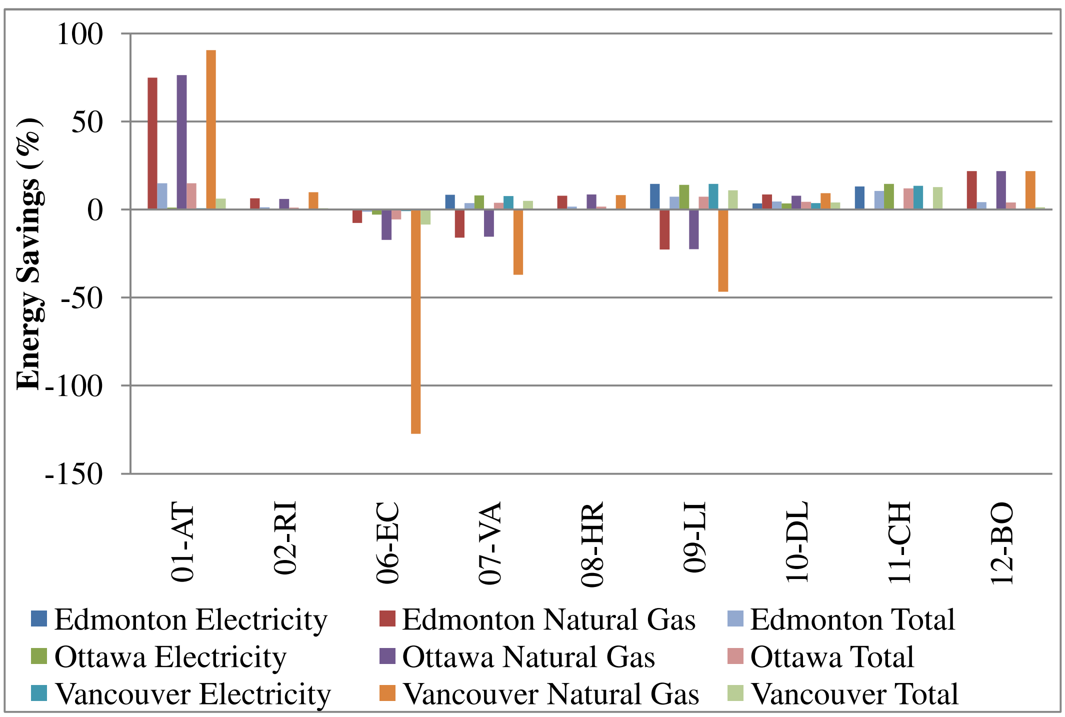

Figure 5.20: ECM Comparison - Building C, 1950 - 1975

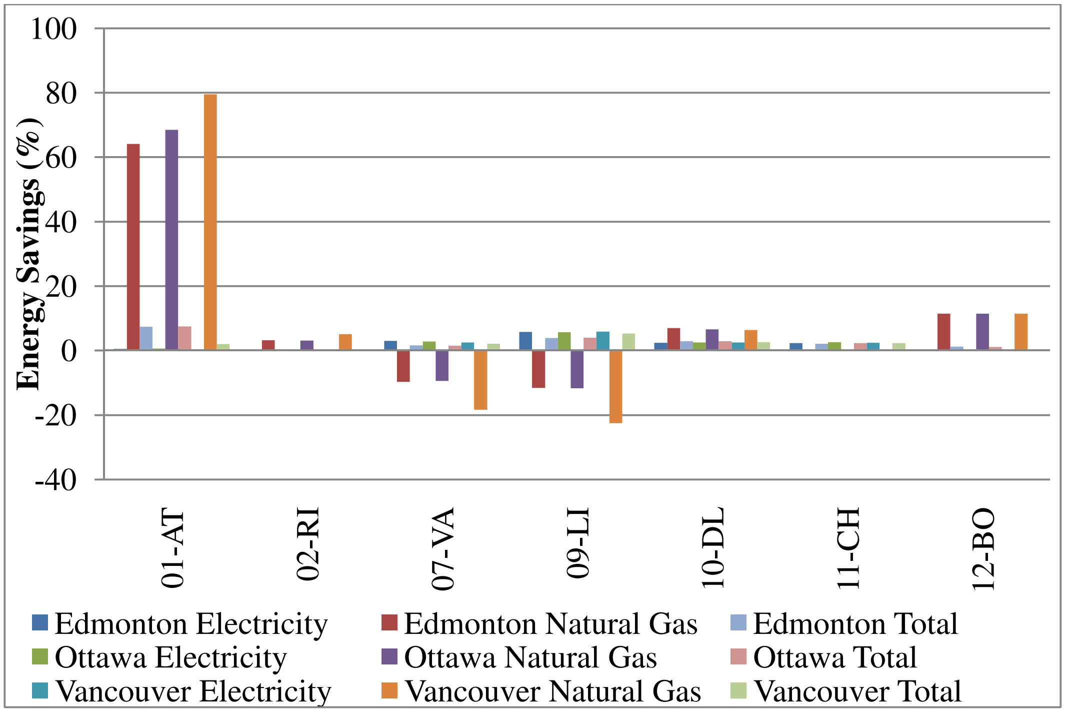

Figure 5.21: ECM Comparison - Building C, Post-1975

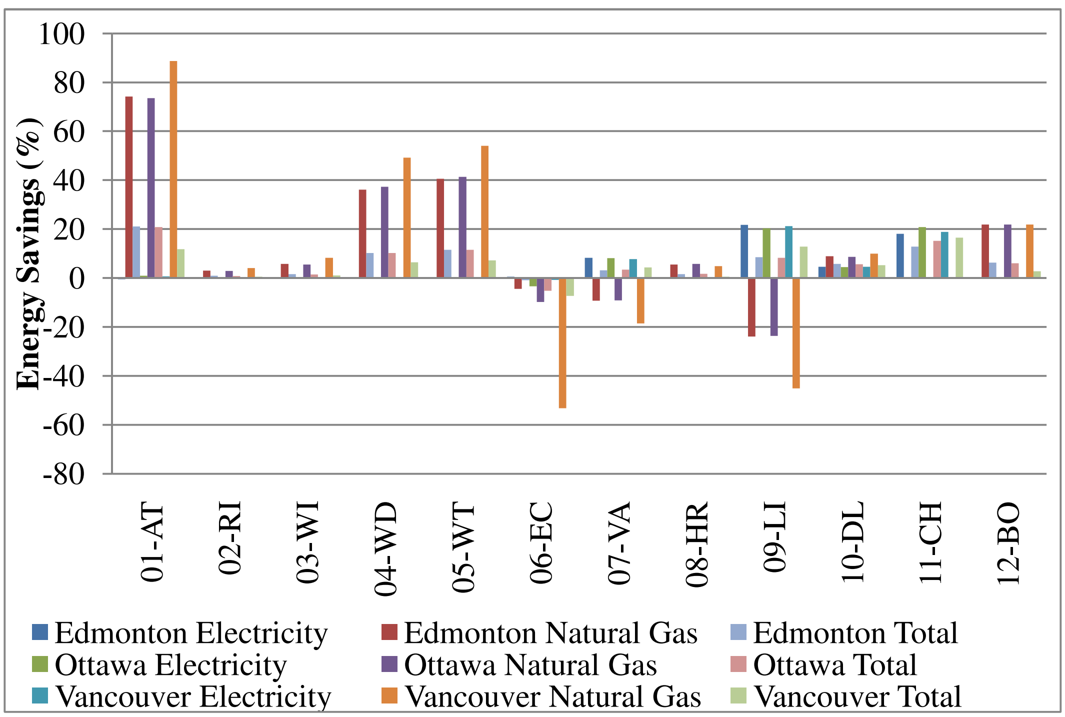

Figure 5.22: ECM Comparison - Building D, Pre-1950

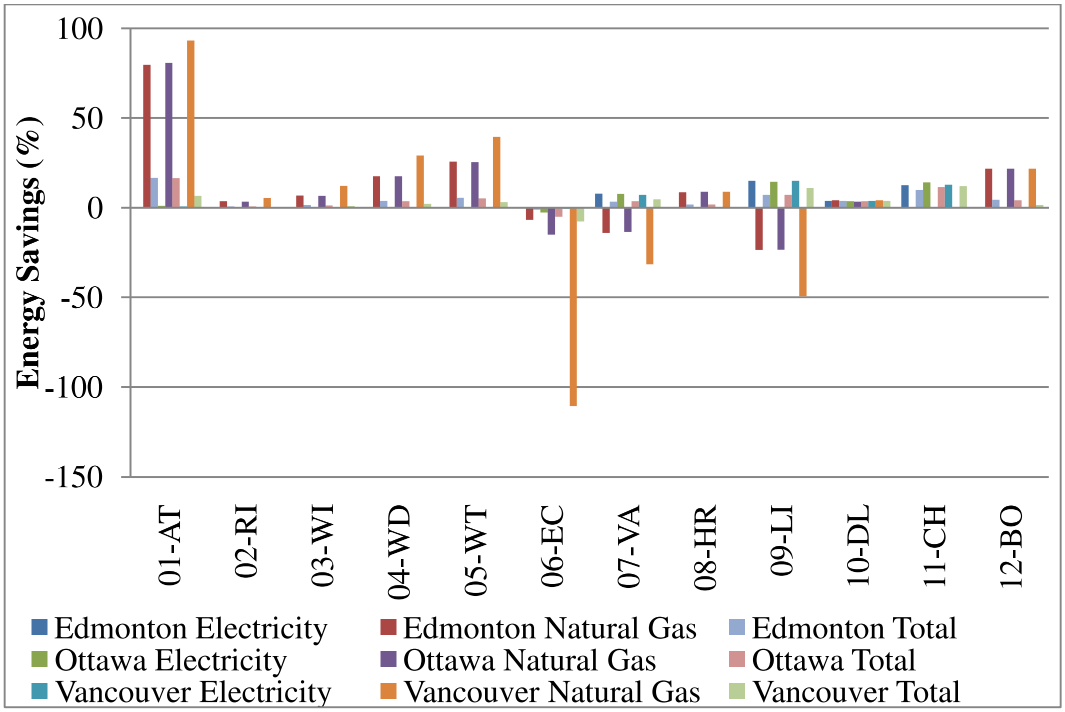

Figure 5.23: ECM Comparison - Building D, 1950 - 1975

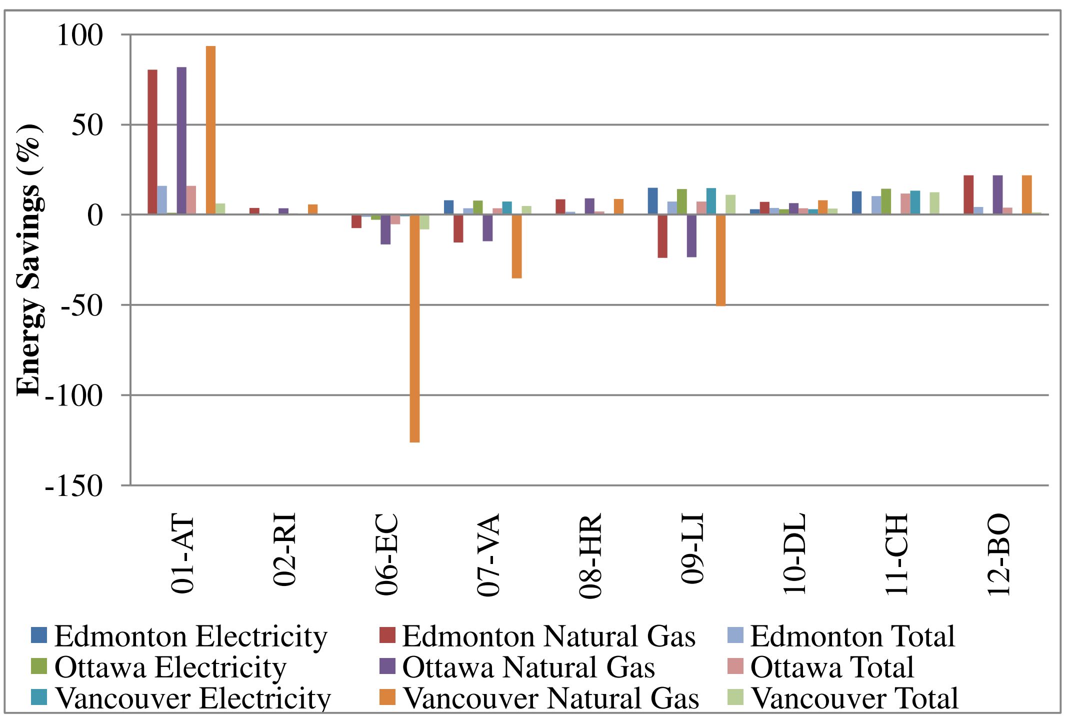

Figure 5.24: ECM Comparison - Building E, 1950 - 1975

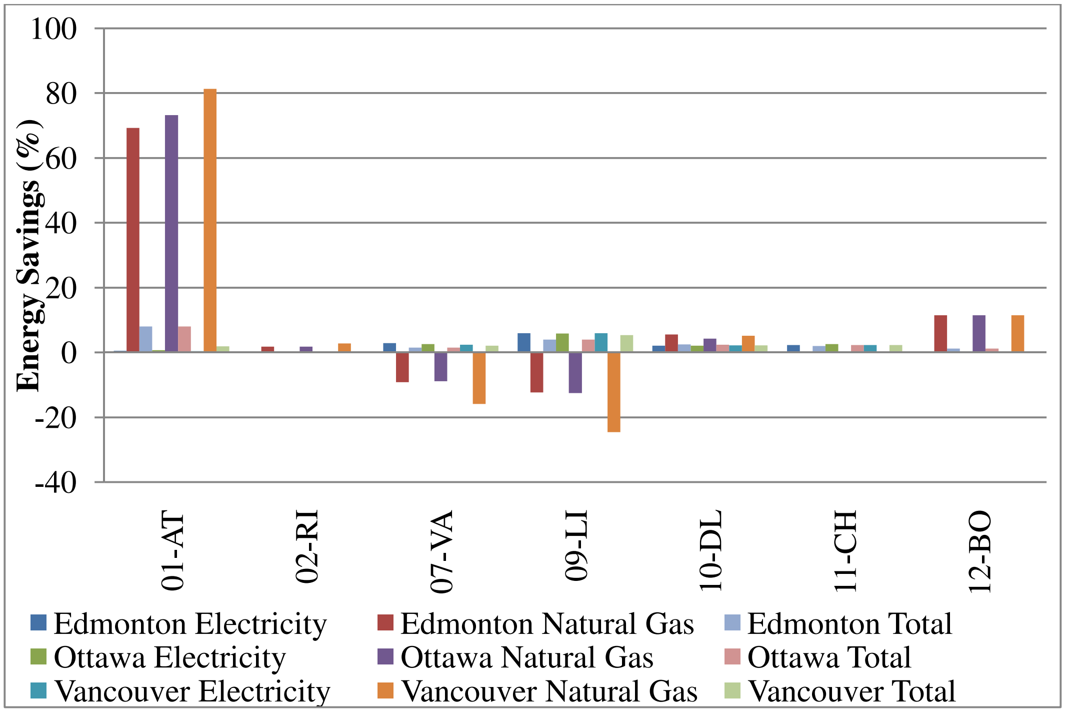

Figure 5.25: ECM Comparison - Building E, Post-1975

Although the magnitude of the savings differs, the comparison of ECMs is similar between buildings. Reducing air infiltration is consistently the most effective ECM with regard to energy savings. Other effective ECMs include upgrade to energy efficient lighting, replacement of windows with either triple glazed or double glazed, improvement in the chiller and boiler efficiency. The effectiveness of these ECMs appears to be consistent between buildings, however the order of their effectiveness based on percent energy savings varies.

5.6 Financial Data

The energy saving potential of ECMs is of importance, however for the implementation of an ECM to be feasible, it must also be financially viable. Several parameters are required as input to evaluate ECMs using financial analysis methods. For this study, the rate of inflation is taken as the national average inflation rate based on the core consumer price index, as reported by the Bank of Canada for May 2011 of 1.8% (Bank of Canada, 2011). Similarly, the interest rate is taken to be equal to the prime business rate of 3.0% reported for June 30, 2011 (Bank of Canada, 2011). Implementation costs are assumed to be paid with a capital loan, borrowed for a period of four years. The minimum acceptable rate of return (MARR) on investment is assumed to be set at ten percent (10%).

Current utility costs are taken as $0.07/kWh and $0.04/kWh for electricity and natural gas respectively. Growth rates for utility costs, based on historical commercial prices over the past twenty years are 2.72% for electricity and 4.8% for natural gas (Statistics Canada, 2011a; Statistics Canada, 2011b).

Due to high variability and uncertainty, maintenance costs, training costs, and loss of production costs are neglected in the analyses. For the same reason, the salvage value of ECMs is also assumed to be zero at the end of the study period where the life expectancy exceeds the study period.

5.6.1 ECM Costs

RS Means Costworks (Reed Construction Data, 2011) maintains a current database of construction costs with adjustment factors for locations throughout North America. The Costworks database has been used to obtain estimates of the cost of implementation of ECMs in all sample buildings in each of the three locations studied. Estimated implementation costs include the cost of required materials, labour, and equipment. Where the equipment required for an ECM was not available in the Costworks database, such as for large chillers and boilers, manufacturers were contacted to obtain current cost estimates. Applicable sales taxes have been added to the cost estimates based on the current federal and provincial rates in Alberta, Ontario, and British Columbia of 5%, 13% and 12% respectively (Canada Revenue Agency, 2011).

The methods used to obtain costs for each ECM are outlined in the following sub-sections. Costs associated with the implementation of the ECMs are listed in Appendix D, Table D.1 through Table D.5.

5.6.1.1 Building Envelope Air Tightness

Reduction of air infiltration through the building envelope is readily achieved by replacing caulking around all windows, doors and other openings. Costs associated with this work include removal and replacement of existing sealant. Cost estimates for this work are based on the linear length of caulking to be replaced. As an estimate of the caulking length on the sample buildings, a standard window size of 2.74 m wide by 1.524 m high (9 ft by 5 ft) has been assumed. The total window area of the building is divided by the area of the standard window to determine the number of windows. The length of caulking on each of the sample buildings is estimated by multiplying the perimeter of the standard window by the estimated number of standard windows on each building.

5.6.1.2 Roof Insulation

The addition of roof insulation requires the removal of the existing roofing layers above existing insulation, removal and replacement of existing insulation, and replacement of the layers removed. The ECM considered herein includes replacement of existing insulation with three inches (3") of extruded polystyrene (XPS) insulation. Costs for retrofit of all sample buildings have been obtained from the RS Means Costworks database based on the roof area of each building. It has been assumed that it is not possible to salvage existing insulation as it is likely to be damaged during removal of overlaying materials.

5.6.1.3 Wall Insulation

Improvement in the insulating value of walls is achieved through application of EIFS on the building exterior. The retrofit considered in this study includes application of two inches (2") of insulating material applied directly to brick veneer. This ECM is applied only to brick buildings considering the prohibitive cost of changing a curtain wall glazing system. Costs for installation of EIFS are obtained from the RS Means Costworks database based on the wall surface area of each of the sample buildings. The cost estimates include provision for scaffolding and consideration for additional effort required to work above the height of one storey.

5.6.1.4 Windows – Double Glazed, Low-E, Argon

Cost estimates for the removal and replacement of existing fenestration units with double glazed, low emissivity, argon filled windows have been obtained through the RS Means Costworks database. A standard window size of 2.74 m wide by 1.52 m high (9 ft x 5 ft) has been assumed. The total implementation cost was found by multiplication of the cost per standard unit by the number of standard units required to make up the glazing area of the building.

5.6.1.5 Windows – Triple Glazed, Low-E, Argon

Cost of implementation of triple glazed, low emissivity, argon filled windows for each of the sample buildings were obtained using the RS Means

Costworks database in a similar manner as described above for window improvements using double glazed units.

5.6.1.6 Economizer

Introduction of economizer controls to an existing building involves installation of an electronic control panel. Typically one unit is required per building. Installation of a control damper may also be required if not already present in the outdoor air intake ductwork. Estimates of installation cost of these components have been obtained from the RS Means Costworks database.

5.6.1.7 VAV Ratio

The work required to convert a constant air volume ventilation system to variable air volume includes replacement of constant speed fans with variable speed fans, and installation of variable air flow terminal boxes at the zone level. Cost estimates for the conversion of the sample buildings to variable air volume ventilation have been obtained using the RS Means Costworks database. The number of terminal boxes required in each building was found through division of the peak air flow rate by the capacity of one unit. In buildings with existing VAV ventilation systems, setting adjustments to the VAV ratio is assumed to be feasible using existing equipment, therefore costs associated with this ECM involve only adjustment of the VAV boxes.

5.6.1.8 Heat Recovery

Several types of ventilation heat recovery units are available for use in recovering ventilation exhaust heat. An enthalpy wheel is considered for the ECM in the decision making tool. The cost of this retrofit installation is obtained from the RS Means Costworks database. One unit is required per building.

5.6.1.9 Lighting

The measure for reducing lighting energy use involves replacement of existing lighting fixtures with those including T8 lamps and electronic ballasts. The cost per fixture with these components has been found from the RS Means Costworks database. The total replacement cost for each of the sample buildings has been found by determining the number of fixtures required to maintain an illumination level of 500 lux. Existing fixtures are assumed to use T12 lamps, as these are most commonly found in Canadian office buildings. As T12 and T8 lamps emit similar light output, the number of fixtures is assumed to remain constant.

5.6.1.10 Daylighting

To account for the benefit of natural lighting, daylight sensors are needed to detect the level of illuminance in the work space, and photoelectric controls are required to adjust artificial lighting to maintain an overall pre-set level of illuminance. Cost estimates for these components are available through the RS Means Costworks database. The cost estimates assume installation of one photoelectric control and two daylight sensors per zone.

5.6.1.11 Chiller COP

Replacement of inefficient chiller equipment with higher efficiency equipment is considered in this study. Centrifugal chillers with variable speed controls under optimized operation are the most beneficial. As the type of chiller equipment present in existing buildings is unknown, for purposes of this study, installation of a centrifugal chiller with variable speed controls is assumed necessary to achieve high COP, as opposed to retrofit of existing equipment. Costs of equipment replacement for the size chillers required for the sample buildings have been obtained from a local Ontario supplier and adjusted to the locations studied using the RS Means Costworks locations factors.

5.6.1.12 Boiler Efficiency

The use of condensing boilers is required to achieve the highest efficiency. As discussed previously, conversion from non-condensing to condensing is possible for existing boilers is possible, however is costly and therefore resorted to only when circumstances dictate. Therefore, complete replacement of existing boilers is considered in this study. The number of boilers needed per building was determined based on the overall required heating capacity. Cost estimates for boilers of various sizes were obtained from a local Ontario supplier. The costs were adjusted for Edmonton and Vancouver using location factors from the RS Means Costworks database.

5.7 Life Expectancy of ECMs

To be able to assess the value of an ECM, the life expectancy of the components must be known. That is the useful length of time before replacement is required. Should the life expectancy of an ECM be shorter than the study period used in the financial analysis, the ECM must be repeated. It is at the end of the life expectancy that the replacement cost will be incurred again. Estimates of the life expectancies for each of the ECMs considered in the decision tool have been made, making reference to published reports and are shown in Table 5.9.

Table 5.9: Life Expectancy of ECMs

ECM Description		***Life Exp. (years)***
Building Envelope		
01-AT	Reduce Air Infiltration	10
02-RI	Insulate Roof ($W/m^2·°C$)	20
03-WI	Install EIFS ($W/m^2·°C$)	20
04-WD	Install Double Glazed, Argon, Low-E Windows ($W/m^2·°C$)	20
05-WT	Install Triple Glazed, Argon, Low-E Windows ($W/m^2·°C$)	20
Electrical Systems		
06-EC	Include an Economizer	10
07-VA	Introduce/ Reduce VAV Ratio	10
08-HR	Include Heat Recovery Unit	10
09-LI	Upgrade Lighting to T8 (W/m^2)	10
10-DL	Include Daylighting	10
11-CH	Improve Chiller COP	20
Natural Gas System		
12-BO	Improve Heating Efficiency	20

5.8 Prioritization of ECM Implementation

The twelve ECMs considered in the screening methodology have been prioritized for the sample buildings based on energy savings and present value (PV) at one, five, and ten years after implementation. The rankings are shown in numerical order with the most favourable ECM ranked as 1, second most favourable ranked as 2, and so on.

Prioritization of the ECMs within the building stock overall based on energy savings is shown in Table 5.10. Only ECMs for which energy savings were predicted to be greater than or equal to five percent (5%) are ranked. As is to be expected, a greater number of ECMs show positive benefit in older buildings compared to those in later archetypes, as there is greater room for improvement of older constructions and building systems.

Strong similarities are apparent in the ranking of ECMs for the sample buildings at each location, however the order of priority varies between building sizes and archetypes. Improving roof thermal resistance only appears in the ranking for low-rise Building A in Edmonton and Ottawa. This is due to the increased relative influence of the roof in lower buildings where the roof accounts for a larger portion of the overall building surface area compared to mid- or high-rise buildings. It is reasonable that this ECM does not rank in Vancouver, where building envelope improvements are less beneficial where heating and cooling demands are lower due to the moderate climate. Likewise, within the results for Vancouver, improving boiler efficiency is only shown to save greater than 5% energy in the low-rise building. This result is attributable to the greater relative ratio of overall energy consumed for heating in this city, and in particular in the smaller building.

For mid- to high-rise buildings of the same archetype, ECMs are ranked identically in each city. The one exception is for Building B 1950-1975, where energy savings due to installation of triple gazed windows are marginally greater than that for infiltration improvements. Observations such as this are useful for building owners and managers as selection of ECMs can be carried out by archetypes.

Many similarities are found between the ranking of ECMs for buildings in Edmonton and Ottawa, with minor variations. This is an anticipated result as the climates in these two locations are similar. The main difference is in the relative ranking of improvements in chiller COP. This ECM is more beneficial than others for buildings in Ottawa compared to Edmonton, as the cooling load is greater in Ottawa. The ECM that ranks most favourably in both locations is improvement in air tightness of the building envelope save for the exception noted above.

The ranking of ECMs for buildings in Vancouver differ from that in the other two cities due to climatic variations. Improvements to the building envelope and HVAC systems are less of a priority as a greater portion of energy is consumed due to internal loads. Installation of energy efficient light fixtures ranks as the most beneficial ECM with regard to energy savings in all Vancouver buildings, with the exception of Building A Pre-1950. It is predictable that building envelope improvements and heating/cooling related ECMs do not dominate the rankings as seen in Edmonton and Ottawa, as internal loads account for a greater portion of energy consumption due to the reduced loads resulting from the moderate climate.

The overall ranking of ECMs based on energy consumption between all buildings in all locations is useful to prioritize the implementation of ECMs within the building stock as a whole. For the stock of sample buildings, the most beneficial ECMs for the group are found to be for Building D Pre-1950 and Building E 1950 – 1975. As is expected based on the magnitude of energy use at each location, the greatest savings are to be had in buildings located in Edmonton and Ottawa. Only two of the top ten ECMs overall are found to be for buildings in Vancouver.

Table 5.10: ECM Ranking Based on Energy Savings

Building	*ECM*	*Edmonton*	*Ottawa*	*Vancouver*
Building A Pre-1950	Infiltration	83	81	102
	Roof Insulation	106	111	
	Double Glazing	91	89	105
	Triple Glazing	88	85	101
	Lighting	94	93	92
	Daylighting			122
	Chiller COP	103	97	100
	Boiler Efficiency	98	99	121
Building A 1950-1975	Infiltration	95	96	116
	Roof Insulation	120	123	
	Triple Glazing	115	114	
	Lighting	108	107	104
	Chiller COP	117	110	113
	Boiler Efficiency	109	112	
Building A Post-1975	Infiltration	118	119	124
Building B Pre-1950	Infiltration	50	49	76
	Double Glazing	53	52	66
	Triple Glazing	51	46	64
	Lighting	59	57	55
	Daylighting			79
	Chiller COP	65	56	61
	Boiler Efficiency	69	74	

Building	***ECM***	***Edmonton***	***Ottawa***	***Vancouver***
Building B 1950-1975	Infiltration	63	62	80
	Double Glazing	84	82	
	Triple Glazing	78	77	87
	VAV			86
	Lighting	73	71	67
	Daylighting			90
	Chiller COP	75	68	70
Building C 1950-1975	Infiltration	34	33	
	Lighting	42	41	39
	Chiller COP	47	40	43
Building C Post-1975	Infiltration	60	58	
	Lighting			72
Building D Pre-1950	Infiltration	**2**	**1**	35
	Double Glazing	14	13	31
	Triple Glazing	**9**	**7**	25
	Lighting	12	**10**	**5**
	Chiller COP	22	**8**	15
	Boiler Efficiency	36	38	
Building D 1950-1975	Infiltration	20	19	
	Triple Glazing	48	44	
	VAV			54
	Lighting	27	26	23
	Chiller COP	32	24	29
Building E 1950-1975	Infiltration	**4**	**3**	
	VAV			37
	Lighting	16	18	**6**
	Chiller COP	21	11	17
Building E Post-1975	Infiltration	30	28	
	Lighting			45

Although energy conservation of importance and is achievable through implementation of several ECMs as seen above, projects must be financially beneficial to be of interest to investors. Table 5.11 shows the ranking of the ECMs within the building stock as a whole based on present value using a MARR of 10% over the short, mid, and long term. Many ECMs show energy savings greater than 5%, however when costs are taken into consideration, fewer are found to be beneficial. This observation highlights the importance of prioritizing which selection criteria is to be used to decide which ECMs are to be implemented.

The financial analysis results show several ECMs to be beneficial over the short, mid, and long terms. Ten ECMs give a payback period of 1 year or less, 60 ECMs have payback periods of 5 years or less, and 84 ECMs pay back in ten years or less. All ECMs that are beneficial in the first year are also beneficial in the longer study periods; similarly, ECMs that are ranked in the five year study period are also ranked for the ten year study period, although the order of priority changes in some instances.

Many similarities are seen in the ranking of ECMs based on costs over all buildings, even more so than in the results based on energy savings alone. Although, significantly fewer ECMs are ranked in the financial analysis for the Pre-1950 and 1950 – 1975 archetype buildings, which leaves less opportunity for difference to appear.

The ranking of ECMs is directly related to the cost of implementation. Only the least expensive ECMs are shown to be beneficial within one year, namely reduction of air infiltration and reduction of the VAV ratio in pre-existing VAV ventilation systems. Air infiltration is beneficial in Edmonton and Ottawa for four buildings, and reduction of the VAV ratio is beneficial for Buildings D and E in the 1950 – 1975 era in Vancouver. Due to the significant benefit of energy savings and low initial costs, it is not surprising these inexpensive ECMs rank high when considered over longer time periods as well. It is also notable that improving air tightness of the building envelope is the only ECM that is cost effective in Post-1975 archetype buildings in Edmonton and Ottawa, although greater than one year of energy savings are required to offset the implementation costs. This result is predictable as the energy saving opportunities in newer buildings are limited compared to older buildings.

ECMs with moderate implementation cost are beneficial within five years, which includes the lighting related ECMs of upgrading lighting fixtures and introducing daylighting controls. Lighting fixture improvement is the highest ranked ECM for buildings in Vancouver based on energy savings, however the step in improvement in Post-1975 era buildings does not generate sufficient energy savings to justify the expense. Daylighting retrofit is found to be financially beneficial in Vancouver for buildings with smaller footprints in which the perimeter area comprises a higher percentage of the overall floor area. While also beneficial in the other two locations, due to the relative higher percentage of energy end uses for heating and cooling, the relative benefit of daylighting does not meet the minimum 5% energy saving criteria. Chiller and boiler ECMs also rank within the five year period for Building D Pre-1950 and Buildings C and D 1950 – 1975 for locations in Ottawa where the energy savings due to the boiler and chiller efficiency improvements are sizable.

Boiler and chiller replacement are expensive ECMs. As this is the case, longer time periods are generally required to generate sufficient energy savings to offset implementation costs. Chiller replacement ranks in most Pre-1950 and 1950 – 1975 archetype buildings regardless of location. On the other hand, boiler efficiency upgrades are only cost effective in older buildings in Edmonton and Ottawa. This result is predictable due to the higher heating loads in these two cities and the larger improvement in efficiency in older buildings.

Within the financial analysis, ECMs related to improving the thermal resistance of the building envelope are not financially viable under the given criteria. The magnitude of the energy savings are insufficient to justify the large capital investments required of these projects.

Overall, the most profitable ECMs are found to be in older, larger buildings, particularly in the cold climates of Edmonton and Ottawa. The least cost ECMs are typically the most beneficial regardless of the payback period used.

Table 5.11: ECM Ranking Based on Energy and Present Value

	Edmonton				***Ottawa***				***Vancouver***			
	Energy	***Payback Period (yrs)***			***Energy***	***Payback Period (yrs)***			***Energy***	***Payback Period (yrs)***		
Building / ECM		***1***	***5***	***10***		***1***	***5***	***10***		***1***	***5***	***10***
A Pre-1950												
Infiltration	83	**10**	42	62	81	**9**	41	60	102		52	75
Roof Insulation	106				111							
Double Glazing	91				89				105			
Triple Glazing	88				85				101			
Lighting	94		44	61	93		45	63	92		43	59
Daylighting									122		51	74
Chiller COP	103			81	97			70	100			77
Boiler Eff.	98				99				121			
A 1950-1975												
Infiltration	95		48	68	96		47	67	116		54	78
Roof Insulation	120				123							
Triple Glazing	115				114							
Lighting	108		58	72	107		59	73	104		57	71
Chiller COP	117				110			84	113			
Boiler Eff.	109				112							
A Post-1975												
Infiltration	118		55	79	119		56	80	124			83
B Pre-1950												
Infiltration	50	**7**	20	42	49	**6**	19	40	76		38	56
Double Glazing	53				52				66			
Triple Glazing	51				46				64			
Lighting	59		23	36	57		25	37	55		22	35
Daylighting									79		30	53
Chiller COP	65			55	56			45	61			50
Boiler Eff.	69			66	74			69				
B 1950-1975												
Infiltration	63		28	47	62		27	46	80		50	64
Double Glazing	84				82							
Triple Glazing	78				77				87			
VAV									86		40	57
Lighting	73		53	52	71			54	67		49	51

	Edmonton	Edmonton Payback Period (yrs)			Ottawa	Ottawa Payback Period (yrs)			Vancouver	Vancouver Payback Period (yrs)		
Building / ECM	***Energy***	***1***	***5***	***10***	***Energy***	***1***	***5***	***10***	***Energy***	***1***	***5***	***10***
B 1950-1975									90		39	58
Daylighting	75			82	68			65	70			76
Chiller COP												
C 1950-1975	34		15	26	33		12	24				
Infiltration	42		46	30	41			32	39		37	27
Lighting	47			44	40		60	34	43			43
Chiller COP												
C Post-1975	60		34	49	58		33	48				
Infiltration									72			
Lighting												
D Pre-1950	**2**	**2**	**2**	**5**	**1**	**1**	**1**	**4**	35		**17**	**31**
Infiltration	14				13				31			
Double Glazing	**9**				**7**				25			
Triple Glazing	12		**5**	**2**	**10**		**7**	**3**	**5**		**4**	**1**
Lighting	22		21	14	**8**		11	7	15		14	11
Chiller COP	36		29	39	38		35	41				
Boiler Eff.												
D 1950-1975	20	**5**	**9**	16	19	**4**	**8**	15				
Infiltration	48				44							
Triple Glazing									54	8	13	29
VAV	27		36	21	26			22	23		31	19
Lighting	32			38	24			23	29			33
Chiller COP												
E 1950-1975	**4**		**6**	**9**	**3**		**3**	**6**				
Infiltration									37	3	10	18
VAV	16		32	**10**	18			**13**	**6**		24	**8**
Lighting	21			20	11		26	12	17			17
Chiller COP												
E Post-1975	30		18	28	28		16	25				
Infiltration									45			
Lighting	83	**10**	42	62	81	**9**	41	60	102		52	75

Comparing the priority of the ECMs for the building stock as a whole based on energy savings and present value analysis, it can be seen from Table

5.11 that the order of implementation changes with change in selection criteria. This is most evident in comparison of the order of ECM selection based on energy savings and PV at 10 years, as shown in Table 5.12. The ECMs that are ranked within the top ten most beneficial ECMs are very similar between the two selection criteria used, although the order of optimum implementation varies significantly.

Table 5.12: Comparison of Top Ten ECMs Based on Energy Savings and Present Value at 10 years

Building	***ECM***	***City***	***Energy Savings***	***PV 10 Years***
D Pre-1950	Infiltration	Ottawa	**1**	**4**
D Pre-1950	Infiltration	Edmonton	**2**	**5**
E 1950-1975	Infiltration	Ottawa	**3**	**6**
E 1950-1975	Infiltration	Edmonton	**4**	**9**
D Pre-1950	Lighting	Vancouver	**5**	**1**
E 1950-1975	Lighting	Vancouver	**6**	**8**
D Pre-1950	Triple Glazing	Ottawa	**7**	-
D Pre-1950	Chiller COP	Ottawa	**8**	**7**
D Pre-1950	Triple Glazing	Edmonton	**9**	-
D Pre-1950	Lighting	Ottawa	**10**	**3**
D Pre-1950	Lighting	Edmonton	12	**2**
E 1950-1975	Lighting	Edmonton	16	**10**

5.9 Discussion

Using five different building sizes, applied to three different archetypes in three Canadian cities, the screening methodology has been shown to be a useful tool to prioritize ECM implementation within a large stock of office buildings of varying characteristics and locations.

The mathematical model, shown to be capable of predicting energy consumption within a reasonable error range for preliminary decision making needs for the various energy end use components, allows for evaluation of multiple ECMs for all buildings within a significantly shorter time period compared to utilizing energy simulation software.

Results from the screening methodology are clearly presented and easily understood by those involved in the selection of ECMs. Variation in the recommended order of implementation based on energy savings and present value at one, five, and ten years demonstrates the importance considering costs in the decision processes. ECMs that show high potential for energy savings are not necessarily financially beneficial.

Chapter 6: Conclusions & Future Work

6.1 Conclusions

Reducing energy consumption in commercial buildings has significant potential to improve energy consumption on a large scale and mitigate associated environmental impacts. The purpose of this work is to provide a method by which to prioritize the implementation of ECMs in a large stock of office buildings for the purpose of achieving energy and cost savings. The following conclusions can be made from the work presented herein:

1. A multitude of ECMs applicable to office buildings are available and have been shown to be effective in practice. Nonetheless, rates of implementation remain low due to a lack of knowledge of available options on the part of building owners and managers.

2. Several tools are available to aid in selection of ECMs. However, none are applicable to the evaluation of multiple ECMs for a large number of buildings simultaneously, based on building specific energy consumption.

3. Mathematical models are an effective method of obtaining building specific energy consumption based on a compact set of input variables in a timely manner.

4. The mathematical model utilized in this work has been shown to be capable of predicting pre- and post-ECM energy consumption for a variety of buildings of different sizes, constructions, and archetypes in several Canadian cities.

5. The screening methodology clearly shows which ECMs are effective based on energy savings and which are financial viable within a large stock of office buildings.

6. From the analysis of energy consumption, it is found that the effect of ECMs differs between buildings of varying types and geographical locations. In colder climates, building envelope improvements were found to be most beneficial, whereas efficiency upgrades of internal energy end uses, such as lighting, were found to be favoured in moderate climates.

7. The recommended order of implementation is found to be similar for buildings with common archetype and location based on either energy savings or present value.

8. The overall order of priority of the ECMs within the building stock differs based on the selection criteria considered.

9. The most beneficial ECMs based on energy savings and cost analysis are found in larger, older buildings where the magnitude of energy consumption, and therefore energy savings, are large and the potential for improvements is greater.

10. Most ECMs that show a minimum of five percent energy savings are found to have a payback period of ten years or less. However, building envelope retrofits that have potential for large reductions in energy use require large capital investments, which make them financially unviable within a ten year timeframe.

6.2 Future Work

To this point, the screening methodology has been shown to be effective in ranking individually applied ECMs for large stocks of office buildings. As is evident from the interaction of various terms within the mathematical model, the effect of ECMs applied in combination is non-linear. This has been shown to be true in previous work, however has not been explored using the current mathematical model. Thus, it is suggested for future work that verification of the model in predicting the impact of combinations of ECMs be explored to ensure the model is sufficiently robust for this purpose.

The screening methodology is currently set to rank ECMs based on a cost/benefit analysis of energy and cost savings. As discussed in Chapter 4, the use of other criteria, such as GHG emissions, is possible. Further development to include the ranking of ECMs based on the reduction of GHG emissions would lend the tool to application in the selection of ECMs for projects pursuing green building ratings in which this factor is of importance.

The twelve ECMs currently considered in the decision tool are a sample of potential retrofits that can be implemented in buildings to reduce energy consumption. Inclusion of additional ECMs would make the tool more comprehensive and add to its appeal to building managers looking for a wide variety of options. Particularly, expansion to include ECMs pertaining to "green" technologies is of interest as the LEED building certification program is more widely used. At the start of the current work, the mathematical model had not been developed to include appropriate variables to reflect the change in the building due to these retrofits. Some of the ECMs to consider include advanced building envelope materials and constructions (e.g. green and white roofs, solar walls, advanced glazings), and complementary or alternate HVAC systems (e.g. geothermal heating, thermal mass walls). Progress in this direction has been made with the inclusion of roof solar absorptance and fenestration solar heat gain coefficient (SHGC) as variables. Further improvement in this direction is suggested.

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Appendix A: Mathematical Model Equations

A.1 Energy Consumption

Boiler = f[Above Grade Wall Area, Area Per Floor, Daylight Area, Daylighting, Days Per Week, Economizer, Equipment Load, Equivalent Fenestration U, Equivalent SHGC, Fan Pressure Rise, Heat Recovery, Heating Setback, Infiltration Rate, Lighting Load, Number of Storeys, Number of Basements, Occupancy Density, Occupied Hours Per Day, Roof Solar Absorptance, Roof U, Temperature Difference, VAV, Wall U, Window Area]

Chiller = f[Chilled Water Pump Flow (m^3/s), Economizer, Fan Pressure Rise, Sum of Gains and Losses, VAV Ratio]

Chilled Water Loop Supply Pump = f[Chilled Water Pump Flow (m^3/s), Sum of Gains and Losses]

Condenser Water Loop Supply Pump = f[Condenser Water Pump Flow (m^3/s), Sum of Gains and Losses]

DHW = f[Days Per Week, Number of Storeys, Number of Basements, Occupancy Density, Occupied Hours Per Day]

Equipment = f[Area Per Floor, Days Per Week, Equipment Load, Number of Storeys, Number of Basements, Occupied Hours per Day]

Fans = f[Fan Pressure Rise, Max Fan Flow (m^3/s), Sum of Gains and Losses, VAV]

Hot Water Loop Supply Pump = f[Above Grade Wall Area, Area Per Floor, Economizer, Fan Pressure Rise, Heat Recovery, Heating Setback, Hot Water Pump Flow (m^3/s), Number of Basements, Roof Solar Absorptance, Roof U, Sum of Gains and Losses, Temperature Difference, VAV, Wall U]

Lighting = f[Daylight Area, Days Per Week, Lighting Load, Number of Storeys, Number of Basements, Occupied Hours per Day]

A.2 Heat Gains and Losses

Equipment Gain = f[Area Per Floor, Days Per Week, Equipment Load, Number of Storeys, Number of Basements, Occupied Hours Per Day]

Infiltration Gain = f[Fan Pressure Rise, Infiltration Rate, Occupancy Schedule Per Day, VAV, Weekends]

Infiltration Loss = f[Fan Pressure Rise, Infiltration Rate, Occupancy Schedule Per Day, VAV, Weekends]

Light Gain = f[Area Per Floor, Daylight Area, Daylighting, Days Per Week, Lighting Load, Number of Storeys, Number of Basements, Occupied Hours Per Day]

People Gain = f[Days Per Week, Number of Basements, Occupancy Density, Occupied Hours Per Day]

Window Gain = f[Equivalent Fenestration U, Equivalent SHGC, Fenestration Area]

Window Loss = f[Equivalent Fenestration U, Equivalent SHGC, Fenestration Area, Temperature Difference]

A.3 Pump and Ventilation Flow Rates

Hot water flow rate = f[Above Grade Wall Area, Area Per Floor, Below Grade Wall Area, Equipment Load, Equivalent Fenestration U, Fenestration Area, Ground Temperature Difference, Humidity Ratio, Infiltration Rate, Lighting Load, Number of Storeys, Number of Basements, Occupancy Density, Roof U, Temperature Difference, Volume, Wall U]

Chilled water flow rate = f[Above Grade Wall Area, Area Per Floor, Below Grade Wall Area, Equipment Load, Equivalent Fenestration U, Fenestration Area, Ground Temperature Difference, Humidity Ratio, Infiltration Rate, Lighting Load, Number of Storeys, Number of Basements, Occupancy Density, Roof U, Temperature Difference, Volume, Wall U]

Condenser water flow rate = f Above Grade Wall Area, Area Per Floor, Below Grade Wall Area, Equipment Load, Equivalent Fenestration U, Fenestration Area, Ground Temperature Difference, Humidity Ratio, Infiltration Rate, Lighting Load, Number of Storeys, Number of Basements, Occupancy Density, Roof U, Temperature Difference, Volume, Wall U]

Max air flow rate = f[Above Grade Wall Area, Area Per Floor, Below Grade Wall Area, Equipment Load, Equivalent Fenestration U, Fenestration Area, Ground Temperature Difference, Humidity Ratio, Infiltration Rate, Lighting Load, Number of Storeys, Number of Basements, Occupancy Density, Roof U, Temperature Difference, Volume, Wall U]

Appendix B: Sample Building Definitions

Table B.1: Sample Building Definitions (Pre-1950: Building A & B)

Characteristic	***Building A***	***Building B***
Number of Floors	2 above grade	10 above + 2 below
Gross Area (m^2)	3,000	18,000
Gross Volume (m^3)	11,250	63,750
Building Envelope		
Walls	Brick/ Concrete Block	Brick/ Concrete Block
Roof	Built-up Metal	Built-up Metal
Windows	Single Glazed	Single Glazed
Windows to Wall (%)	0.5	0.2
Infiltration Rate (ach)	1.0	1.0
Roof U-Value ($W/m^2 \cdot K$)	1.18	1.18
Wall U-Value ($W/m^2 \cdot K$)	0.76	0.76
Wind. U-Value ($W/m^2 \cdot K$)	6.0 (SHGC 0.)	6.0
HVAC & Electrical System		
Description	Combined AHU and Pumps	Combined AHU and Pumps
Fan Pressure Rise (Pa)	300	300
Economizer	No	No
VAV Turndown Ratio	1.0	1.0
Heat Recovery	No	No
Lighting (W/m^2)	26	26
Equipment Load (W/m^2)	40	40
Chiller Type	Centrifugal	Centrifugal
COP	1.8	1.8
Natural Gas System		
Boiler Fuel	Natural Gas	Natural Gas
Type	Hot Water	Hot Water
Efficiency	0.75	0.75
Service Hot Water Fuel	Electricity	Electricity
Occupancy Characteristic		
Occupancy Schedule	18 hrs, 5 days/week	18 hrs, 5 days/week
Density (m^2/person)	25	25
System Schedule	No Setback, Off Eve.	No Setback, Off Eve.

Table B.2: Sample Building Definitions (Pre-1950: Building D)

Characteristic	***Building D***
Number of Floors	18 above + 2 below
Gross Area (m^2)	90,000
Gross Volume (m^3)	317,250
Building Envelope	
Walls	Brick/ Concrete Block
Roof	Built-up Concrete
Windows	Single Glazed
Windows to Wall (%)	0.5
Infiltration Rate (ach)	1.0
Roof U-Value ($W/m^2{\cdot}K$)	1.18
Wall U-Value ($W/m^2{\cdot}K$)	0.76
Wind. U-Value ($W/m^2{\cdot}K$)	6.0
HVAC & Electrical System	
Description	Combined AHU and Pumps
Fan Pressure Rise (Pa)	300
Economizer	No
VAV Turndown Ratio	1.0
Heat Recovery	No
Lighting (W/m^2)	26
Equipment Load (W/m^2)	40
Chiller Type	Centrifugal Chiller
COP	1.8
Natural Gas System	
Boiler Fuel	Natural Gas
Type	Hot Water
Efficiency	0.75
Service Hot Water Fuel	Electricity
Occupancy Characteristic	
Occupancy Schedule	18 hrs, 5 days/week
Density (m^2/person)	25
System Schedule	No Setback, Off Eve.

Table B.3: Sample Building Definitions (1950 – 1975: Building A & B)

Characteristic	*Building A*	*Building B*
Number of Floors	2 above grade	10 above + 2 below
Gross Area (m^2)	3,000	18,000
Gross Volume (m^3)	11,250	63,750
Building Envelope		
Walls	Brick/ Concrete Block	Brick/ Concrete Block
Roof	Built-up Metal	Built-up Metal
Windows	Double Glazed	Double Glazed
Windows to Wall (%)	0.5	0.2
Infiltration Rate (ach)	0.75	0.75
Roof U-Value ($W/m^2{\cdot}K$)	0.54	0.54
Wall U-Value ($W/m^2{\cdot}K$)	0.67	0.67
Wind. U-Value ($W/m^2{\cdot}K$)	2.7	2.7
HVAC & Electrical System		
Description	Combined AHU and Pumps	Combined AHU and Pumps
Fan Pressure Rise (Pa)	300	300
Economizer	No	No
VAV Turndown Ratio	1.0	1.0
Heat Recovery	No	No
Lighting (W/m^2)	17.8	17.8
Equipment Load (W/m^2)	40	40
Chiller Type	Centrifugal Chiller	Centrifugal Chiller
COP	2.5	2.5
Natural Gas System		
Boiler Fuel	Natural Gas	Natural Gas
Type	Hot Water	Hot Water
Efficiency	0.75	0.75
Service Hot Water Fuel	Electricity	Electricity
Occupancy Characteristic		
Occupancy Schedule	18 hrs, 5 days/week	18 hrs, 5 days/week
Density (m^2/person)	25	25
System Schedule	No Setback, Off Eve.	No Setback, Off Eve.

Table B.4: Sample Building Definitions (1950 – 1975: Building C & D)

Characteristic	***Building C***	***Building D***
Number of Floors	10 above + 2 below	18 above + 2 below
Gross Area (m^2)	54,000	90,000
Gross Volume (m^3)	191,250	317,250
Building Envelope		
Walls	Metal Curtain Wall	Brick/ Concrete Block
Roof	Built-up Metal	Built-up Concrete
Windows	Double Glazed	Double Glazed
Windows to Wall (%)	0.8	0.5
Infiltration Rate (ach)	0.75	0.75
Roof U-Value ($W/m^2 \cdot K$)	0.54	0.54
Wall U-Value ($W/m^2 \cdot K$)	0.49	0.67
Wind. U-Value ($W/m^2 \cdot K$)	2.7	2.7
HVAC & Electrical System		
Description	Combined AHU and Pumps	Combined AHU and Pumps
Fan Pressure Rise (Pa)	300	300
Economizer	No	No
VAV Turndown Ratio	1.0	1.0
Heat Recovery	No	No
Lighting (W/m^2)	17.8	17.8
Equipment Load (W/m^2)	40	40
Chiller Type	Centrifugal Chiller	Centrifugal Chiller
COP	2.5	2.5
Natural Gas System		
Boiler Fuel	Natural Gas	Natural Gas
Type	Hot Water	Hot Water
Efficiency	0.75	0.75
Service Hot Water Fuel	Electricity	Electricity
Occupancy Characteristic		
Occupancy Schedule	18 hrs, 5 days/week	18 hrs, 5 days/week
Density (m^2/person)	25	25
System Schedule	No Setback, Off Eve.	No Setback, Off Eve.

Table B.5: Sample Building Definitions (1950 – 1975: Building E)

Characteristic	***Building E***
Number of Floors	18 above + 2 below
Gross Area (m^2)	150,000
Gross Volume (m^3)	528,750
Building Envelope	
Walls	Metal Curtain Wall
Roof	Built-up Metal
Windows	Double Glazed
Windows to Wall (%)	0.8
Infiltration Rate (ach)	0.75
Roof U-Value ($W/m^2{\cdot}K$)	0.54
Wall U-Value ($W/m^2{\cdot}K$)	0.49
Wind. U-Value ($W/m^2{\cdot}K$)	2.7
HVAC & Electrical System	
Description	Combined AHU and Pumps
Fan Pressure Rise (Pa)	300
Economizer	No
VAV Turndown Ratio	1.0
Heat Recovery	No
Lighting (W/m^2)	17.8
Equipment Load (W/m^2)	40
Chiller Type	Centrifugal Chiller
COP	2.5
Natural Gas System	
Boiler Fuel	Natural Gas
Type	Hot Water
Efficiency	0.75
Service Hot Water Fuel	Electricity
Occupancy Characteristic	
Occupancy Schedule	18 hrs, 5 days/week
Density (m^2/person)	25
System Schedule	No Setback, Off Eve.

Table B.6: Sample Building Definitions (Post-1975: Building A & C)

Characteristic	***Building A***	***Building C***
Number of Floors	2 above grade	10 above + 2 below
Gross Area (m^2)	3,000	54,000
Gross Volume (m^3)	11,250	191,250
Building Envelope		
Walls	Brick/ Concrete Block	Metal Curtain Wall
Roof	Built-up Metal	Built-up Metal
Windows	Double Glazed, Argon, Low-E	Double Glazed, Argon, Low-E
Windows to Wall (%)	0.5	0.8
Infiltration Rate (ach)	0.5	0.5
Roof U-Value ($W/m^2{\cdot}K$)	0.32	0.32
Wall U-Value ($W/m^2{\cdot}K$)	0.39	0.49
Wind. U-Value ($W/m^2{\cdot}K$)	1.5	1.5
HVAC & Electrical System		
Description	Combined AHU and Pumps	Combined AHU and Pumps
Fan Pressure Rise (Pa)	300	300
Economizer	Yes	Yes
VAV Turndown Ratio	0.65	0.65
Heat Recovery	Yes	Yes
Lighting (W/m^2)	9.3	9.3
Equipment Load (W/m^2)	40	40
Chiller Type	Centrifugal Chiller	Centrifugal Chiller
COP	5.2	5.2
Natural Gas System		
Boiler Fuel	Natural Gas	Natural Gas
Type	Hot Water	Hot Water
Efficiency	0.85	0.85
Service Hot Water Fuel	Electricity	Electricity
Occupancy Characteristic		
Occupancy Schedule	18 hrs, 5 days/week	18 hrs, 5 days/week
Density (m^2/person)	25	25
System Schedule	No Setback, Off Eve.	No Setback, Off Eve.

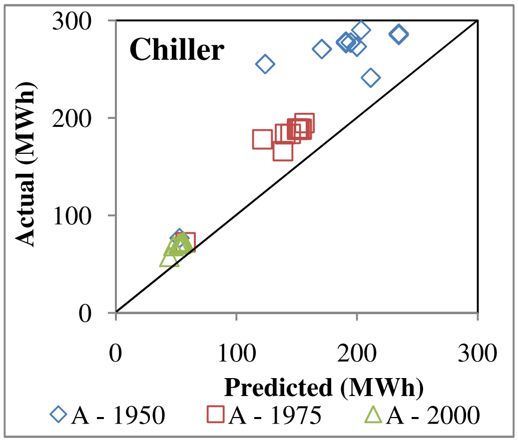
Table B.7: Sample Building Definitions (Post-1975: Building E)

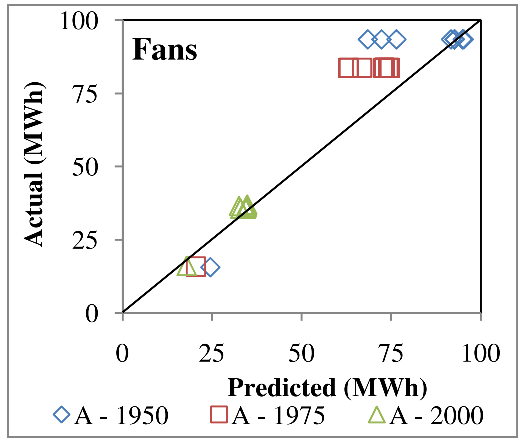
Characteristic	*Building E*
Number of Floors	18 above + 2 below
Gross Area (m^2)	150,000
Gross Volume (m^3)	528,750
Building Envelope	
Walls	Metal Curtain Wall
Roof	Built-up Metal
Windows	Double Glazed, Argon, Low-E
Windows to Wall (%)	0.8
Infiltration Rate (ach)	0.5
Roof U-Value ($W/m^2{\cdot}K$)	0.32
Wall U-Value ($W/m^2{\cdot}K$)	0.49
Wind. U-Value ($W/m^2{\cdot}K$)	1.5
HVAC & Electrical System	
Description	Combined AHU and Pumps
Fan Pressure Rise (Pa)	300
Economizer	Yes
VAV Turndown Ratio	0.65
Heat Recovery	Yes
Lighting (W/m^2)	9.3
Equipment Load (W/m^2)	40
Chiller Type	Centrifugal Chiller
COP	5.2
Natural Gas System	
Boiler Fuel	Natural Gas
Type	Hot Water
Efficiency	0.85
Service Hot Water Fuel	Electricity
Occupancy Characteristic	
Occupancy Schedule	18 hrs, 5 days/week
Density (m^2/person)	25
System Schedule	No Setback, Off Eve.

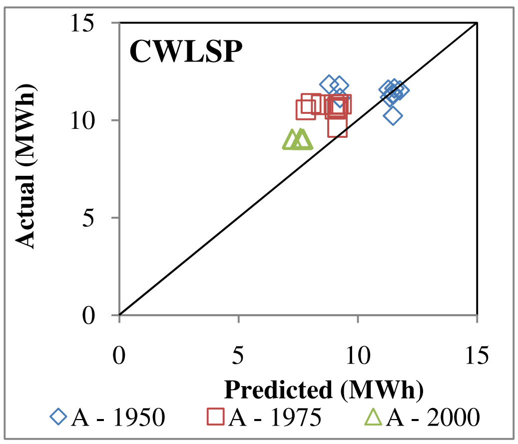
Appendix C: Building Component Energy Prediction Comparison

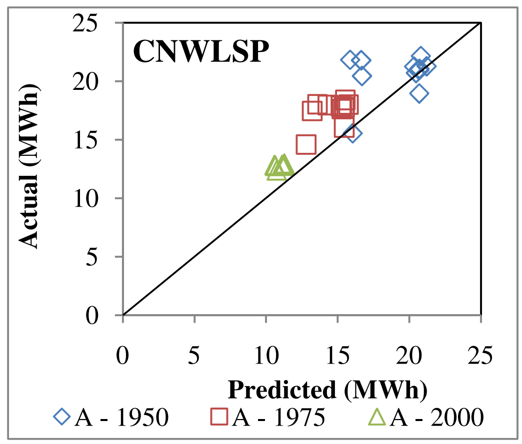
C.4 Building A

C.4.1 Edmonton









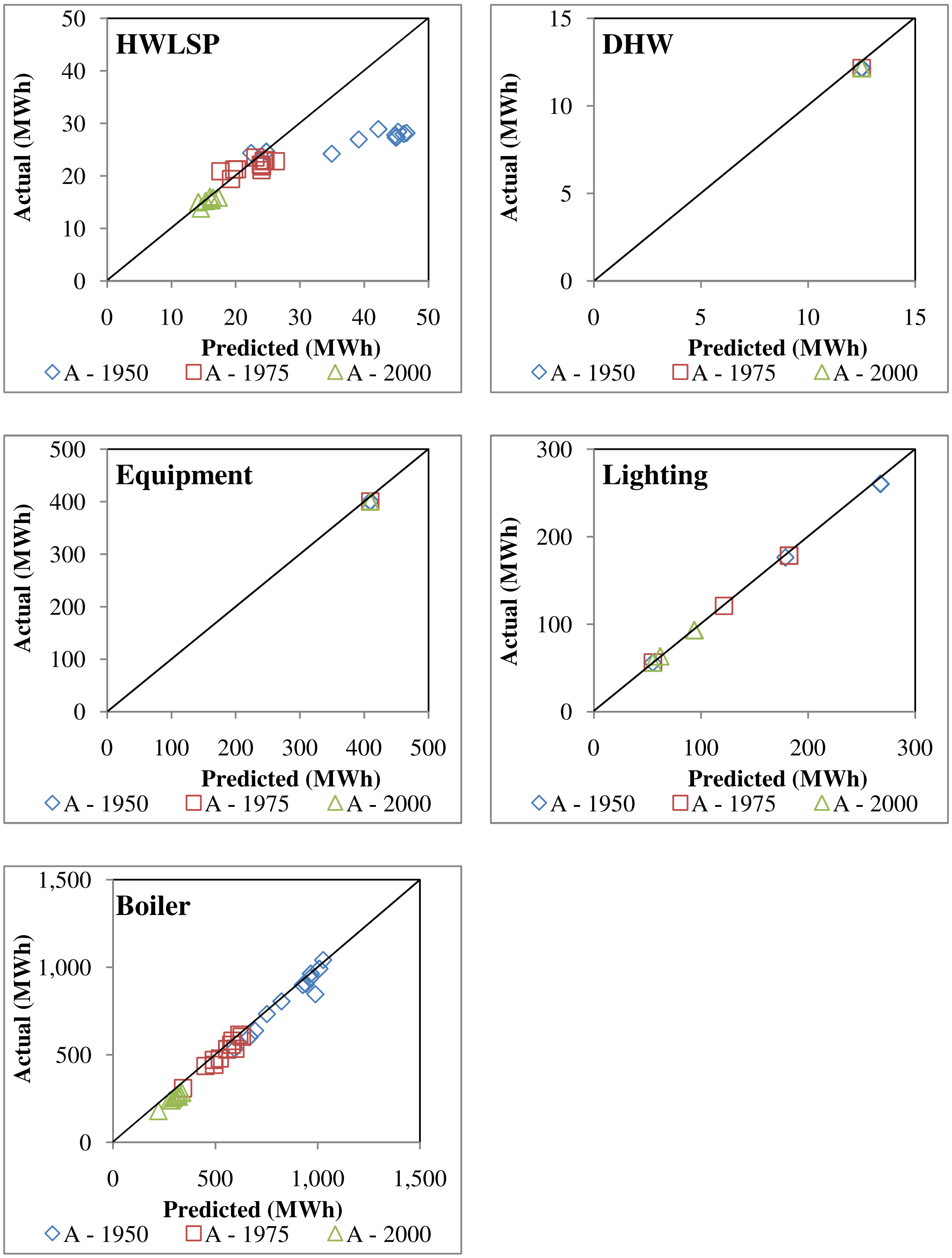
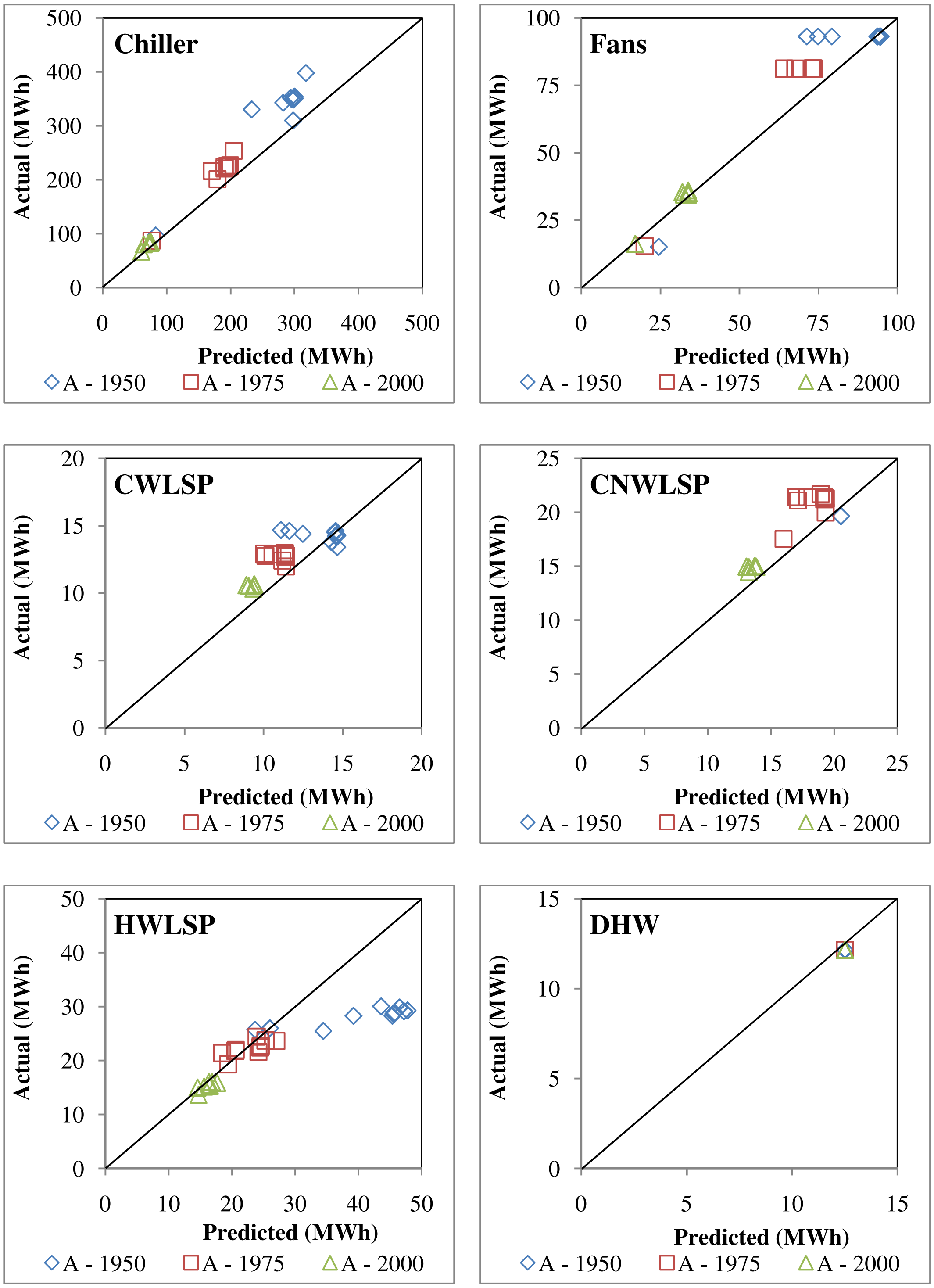


Figure C.1: Building A Energy Prediction Comparison (Edmonton)

C.4.2 Ottawa


Chiller
Actual (MWh)
Predicted (MWh)
0 100 200 300 400 500
A - 1950
A - 1975
A - 2000
Fans
Actual (MWh)
Predicted (MWh)
0 25 50 75 100
A - 1950
A - 1975
A - 2000
CWLSP
Actual (MWh)
Predicted (MWh)
0 5 10 15 20
A - 1950
A - 1975
A - 2000
CNWLSP
Actual (MWh)
Predicted (MWh)
0 5 10 15 20 25
A - 1950
A - 1975
A - 2000
HWLSP
Actual (MWh)
Predicted (MWh)
0 10 20 30 40 50
A - 1950
A - 1975
A - 2000
DHW
Actual (MWh)
Predicted (MWh)
0 5 10 15
A - 1950
A - 1975
A - 2000

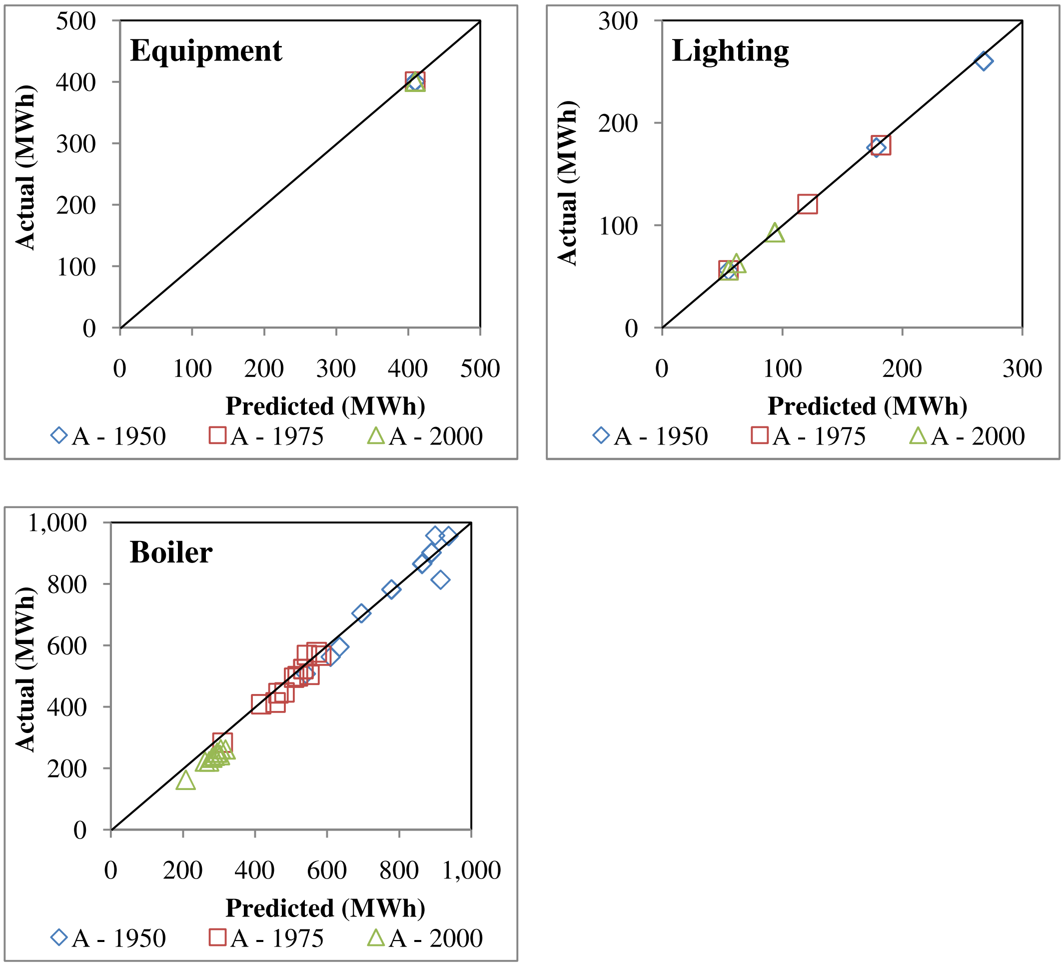
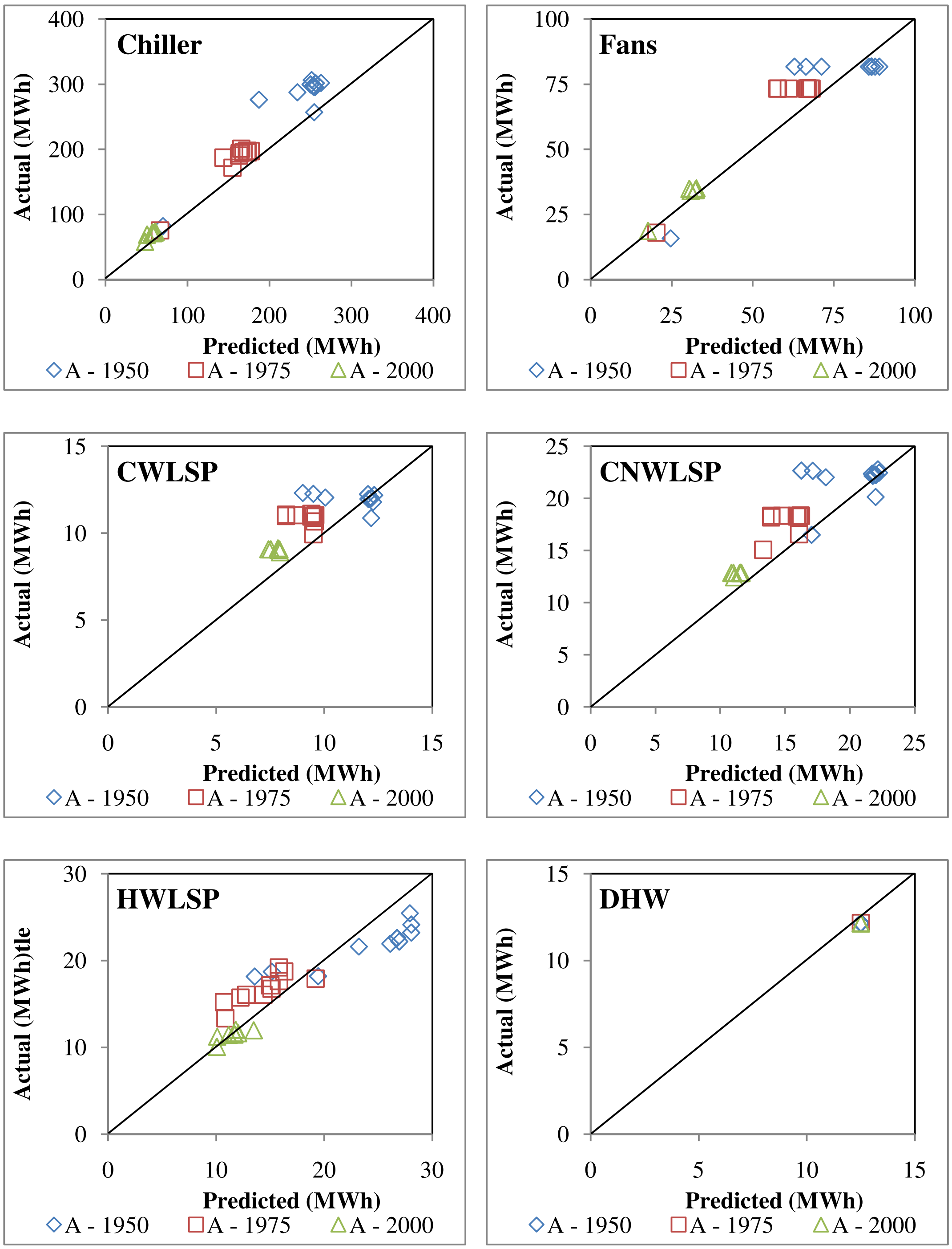


Figure C.2: Building A Energy Prediction Comparison (Ottawa)

C.4.3 Vancouver



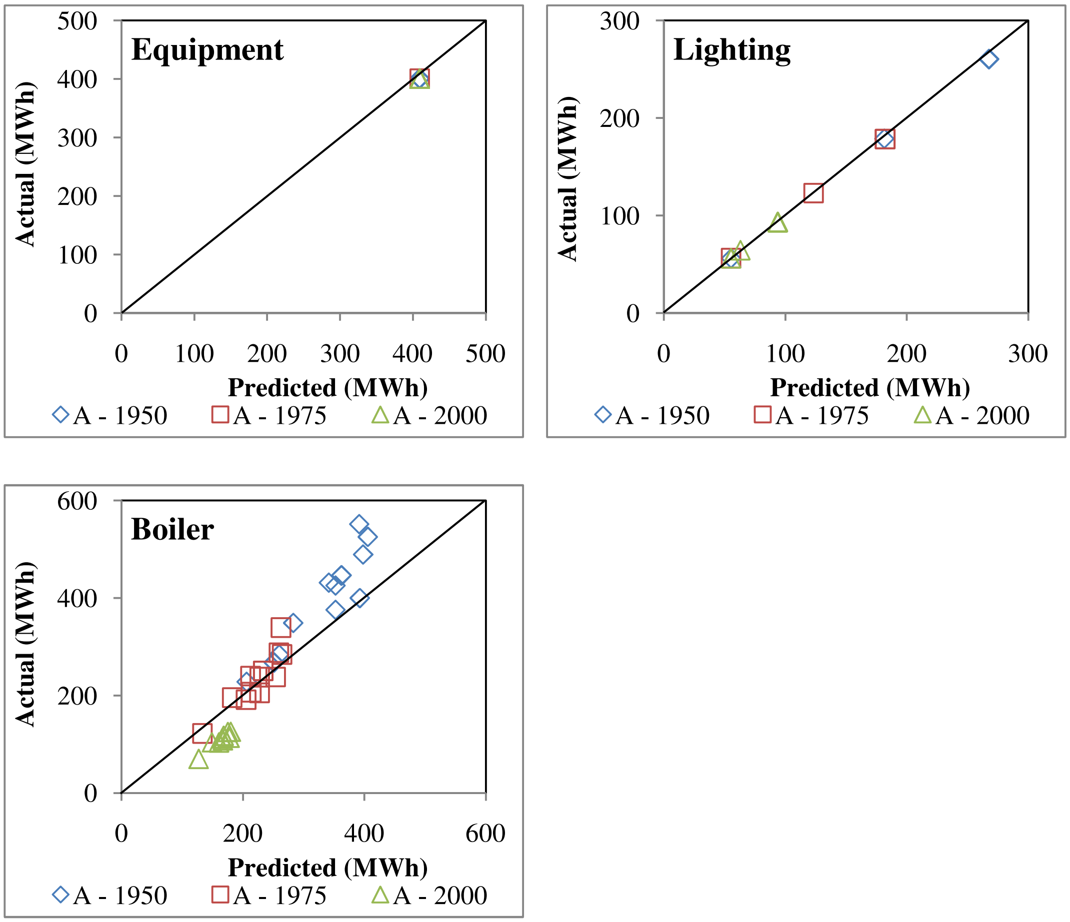
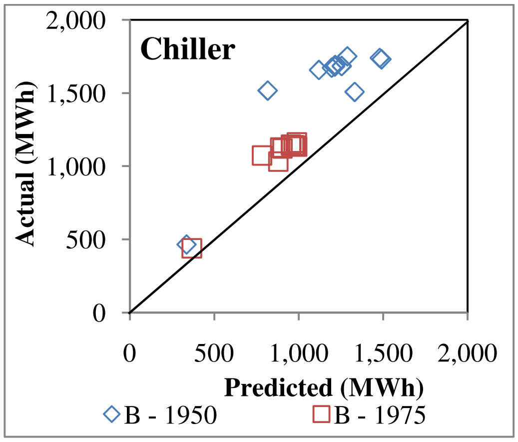
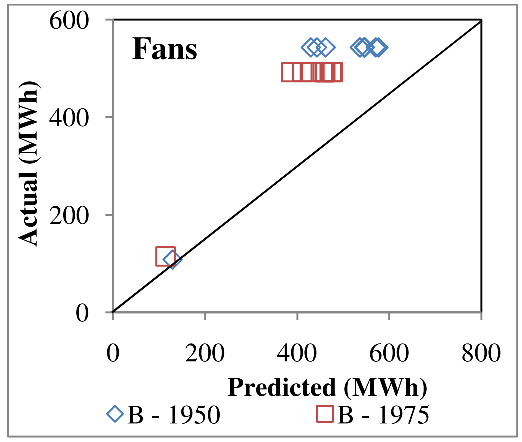


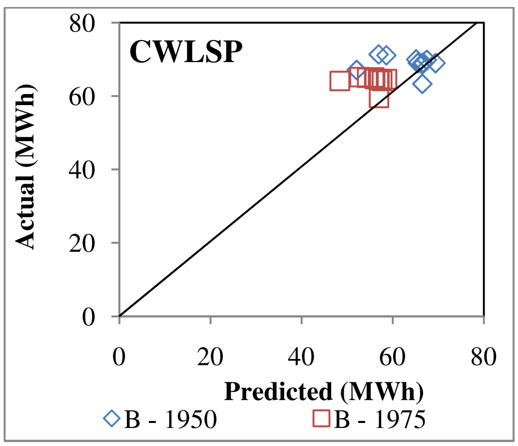
Figure C.3: Building A Energy Prediction Comparison (Vancouver)

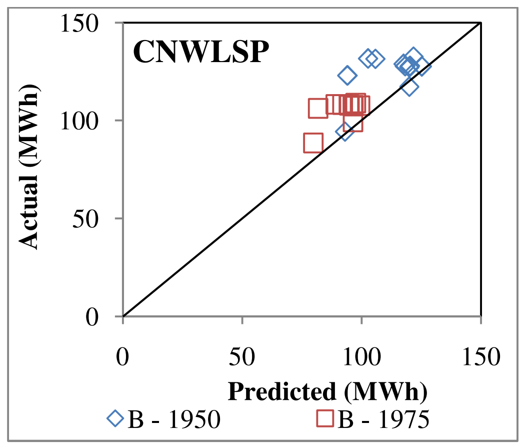
C.5 Building B

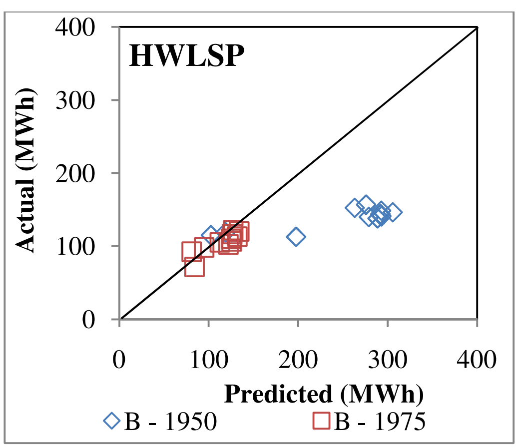
C.5.4 Edmonton

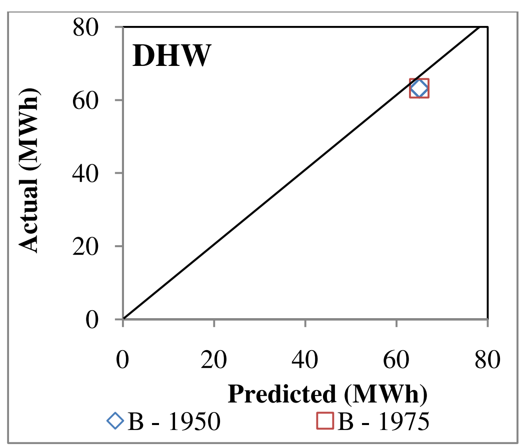












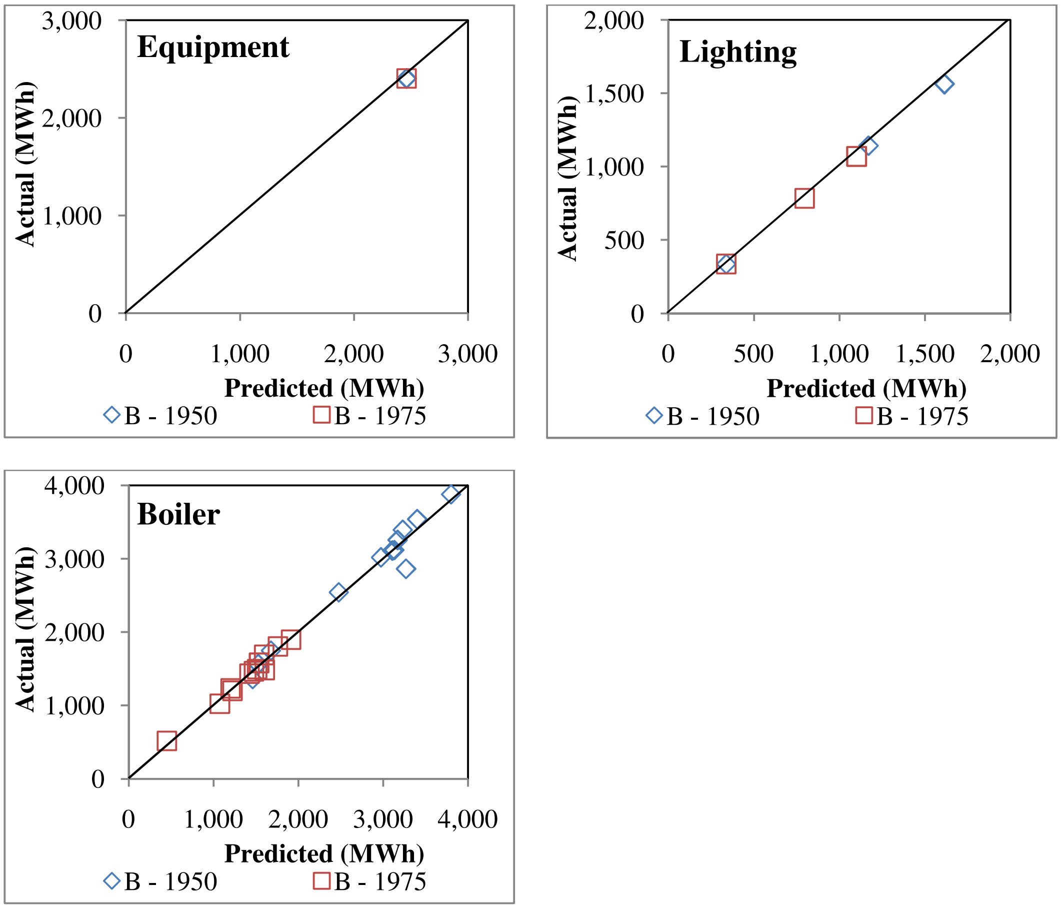
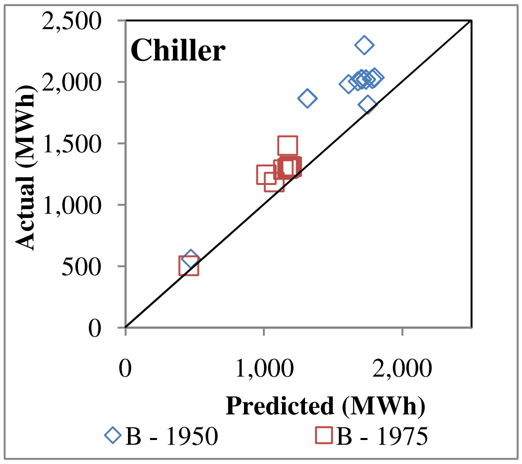
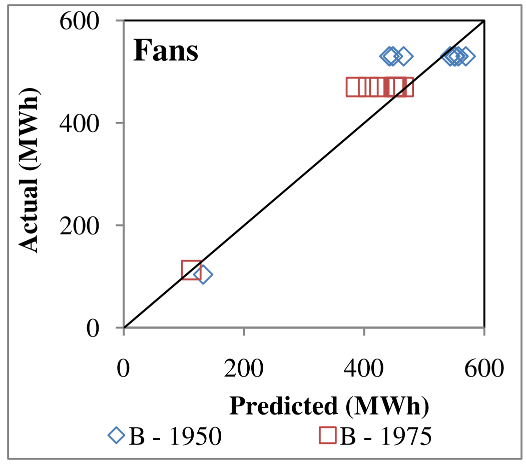
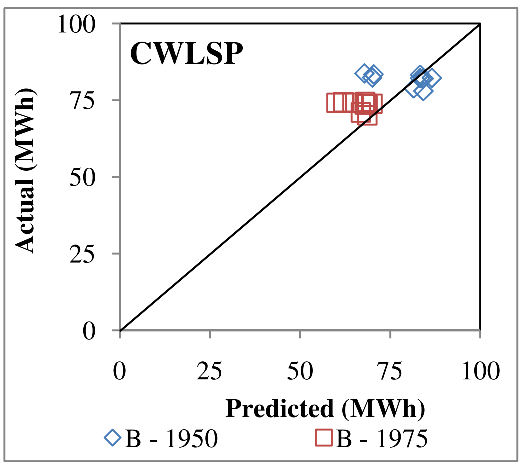


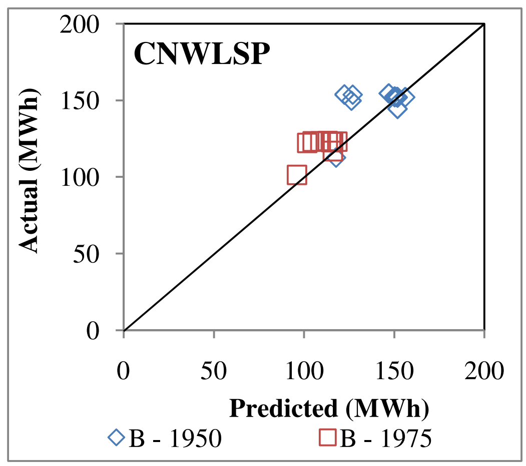
Figure C.4: Building B Energy Prediction Comparison (Edmonton)

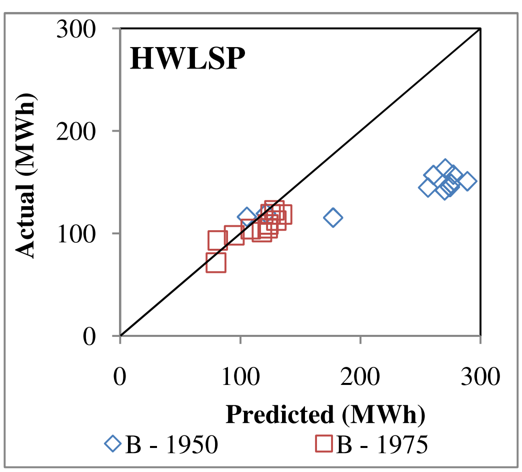
C.5.5 Ottawa

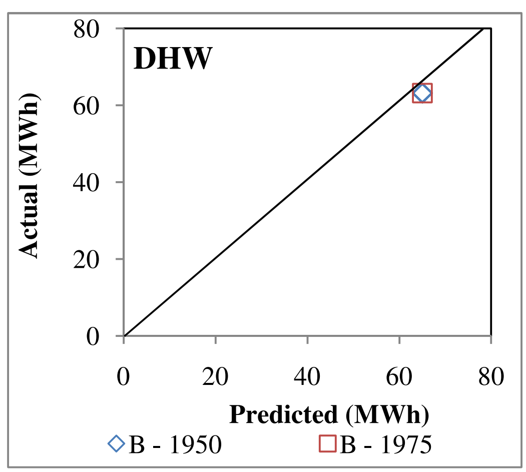

Chiller
Actual (MWh)
0
500
1,000
1,500
2,000
2,500
0
1,000
2,000
Predicted (MWh)
B - 1950
B - 1975


Fans
Actual (MWh)
0
200
400
600
0
200
400
600
Predicted (MWh)
B - 1950
B - 1975


CWLSP
Actual (MWh)
0
25
50
75
100
0
25
50
75
100
Predicted (MWh)
B - 1950
B - 1975


CNWLSP
Actual (MWh)
0
50
100
150
200
0
50
100
150
200
Predicted (MWh)
B - 1950
B - 1975


HWLSP
Actual (MWh)
0
100
200
300
0
100
200
300
Predicted (MWh)
B - 1950
B - 1975


DHW
Actual (MWh)
0
20
40
60
80
0
20
40
60
80
Predicted (MWh)
B - 1950
B - 1975

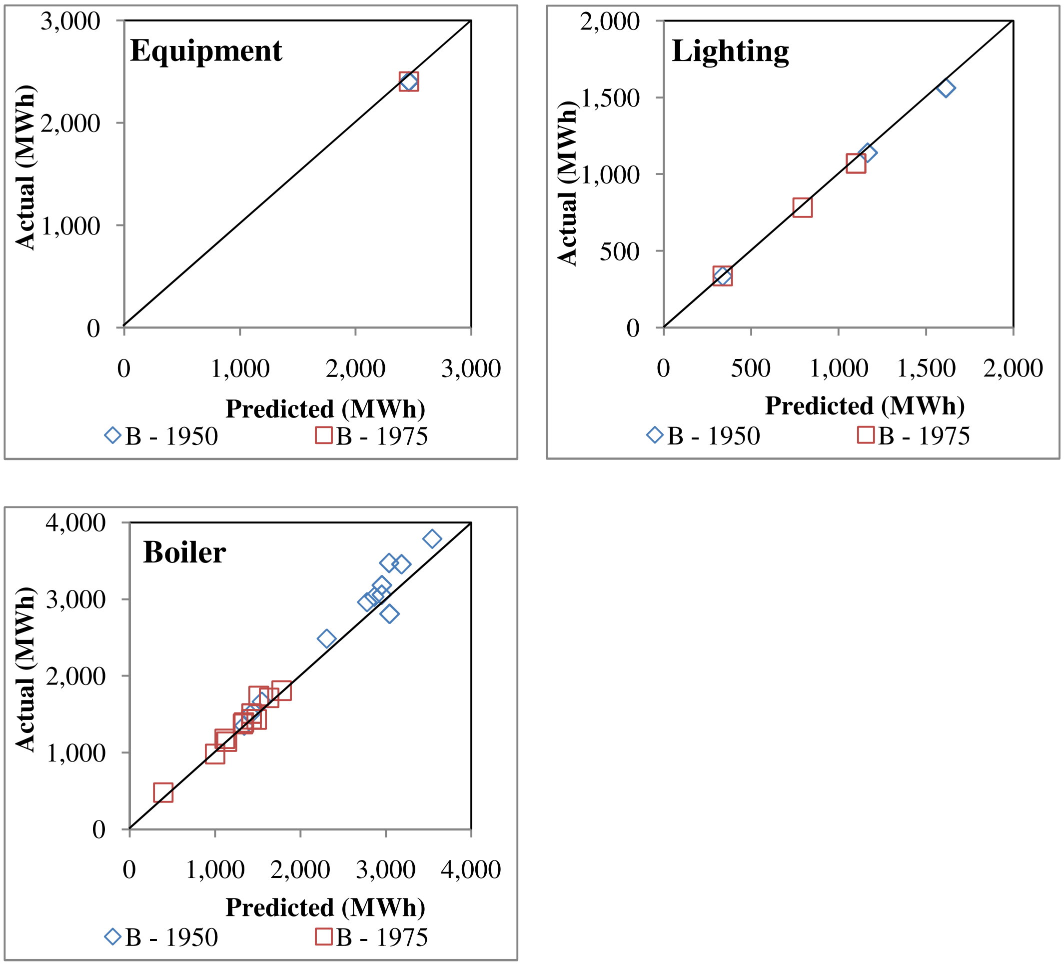
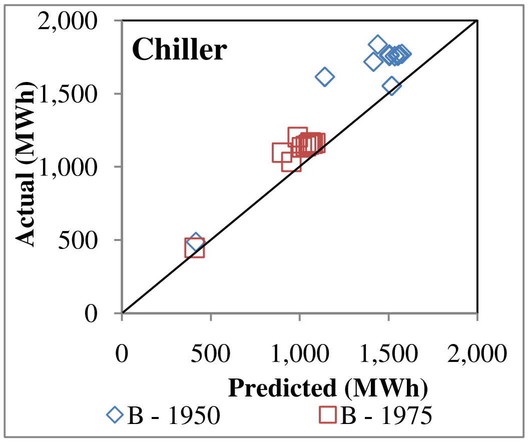
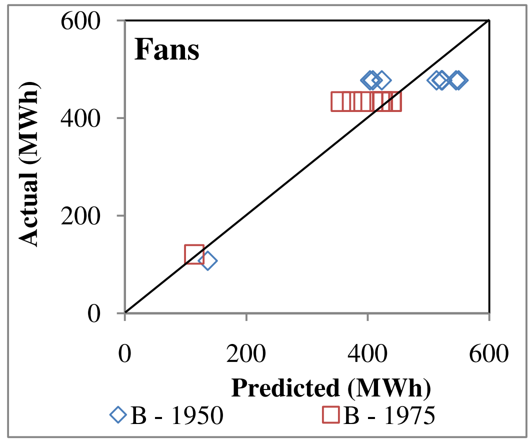
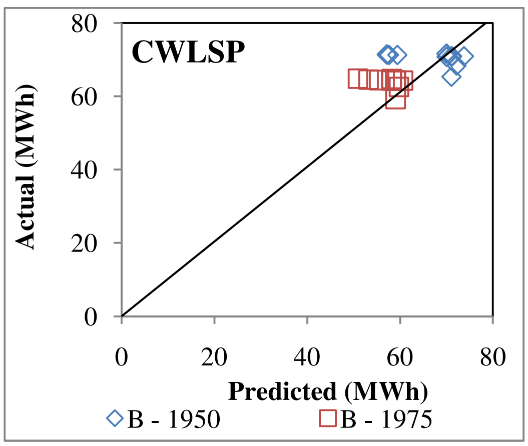


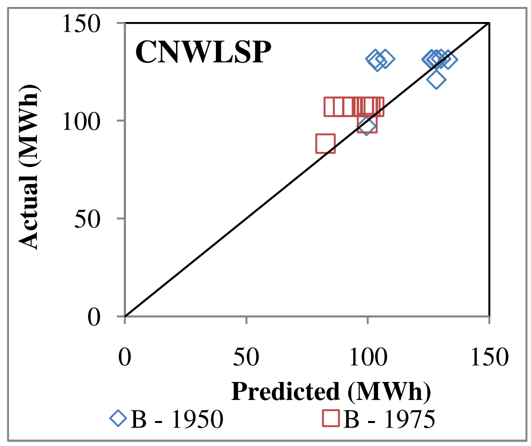
Figure C.5: Building B Energy Prediction Comparison (Ottawa)

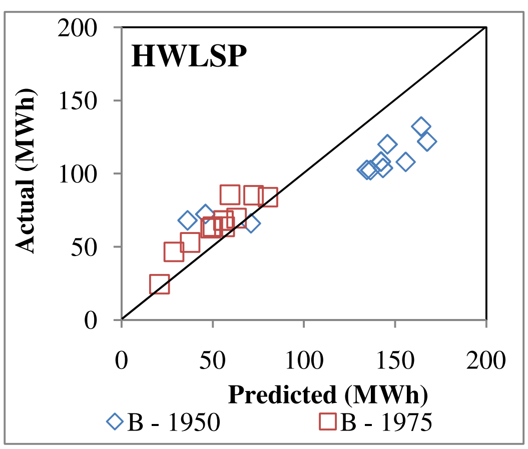
C.5.6 Vancouver

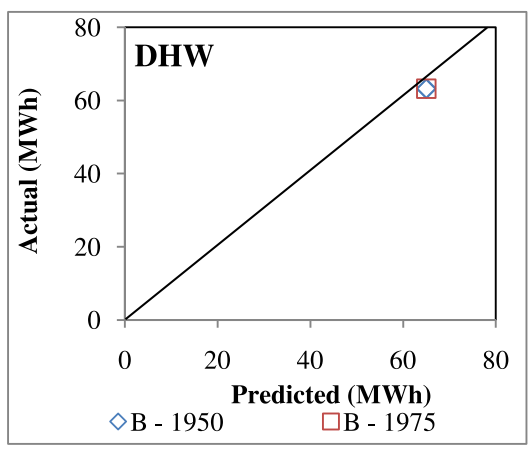












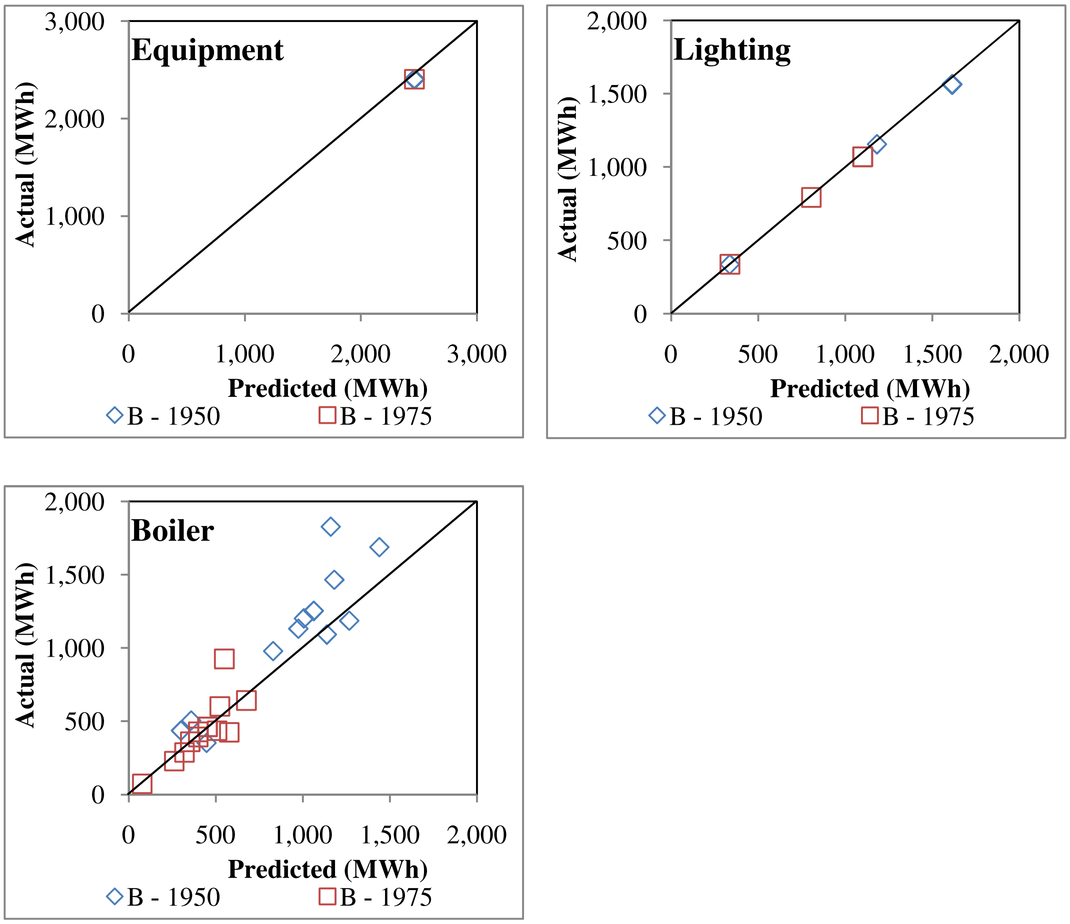
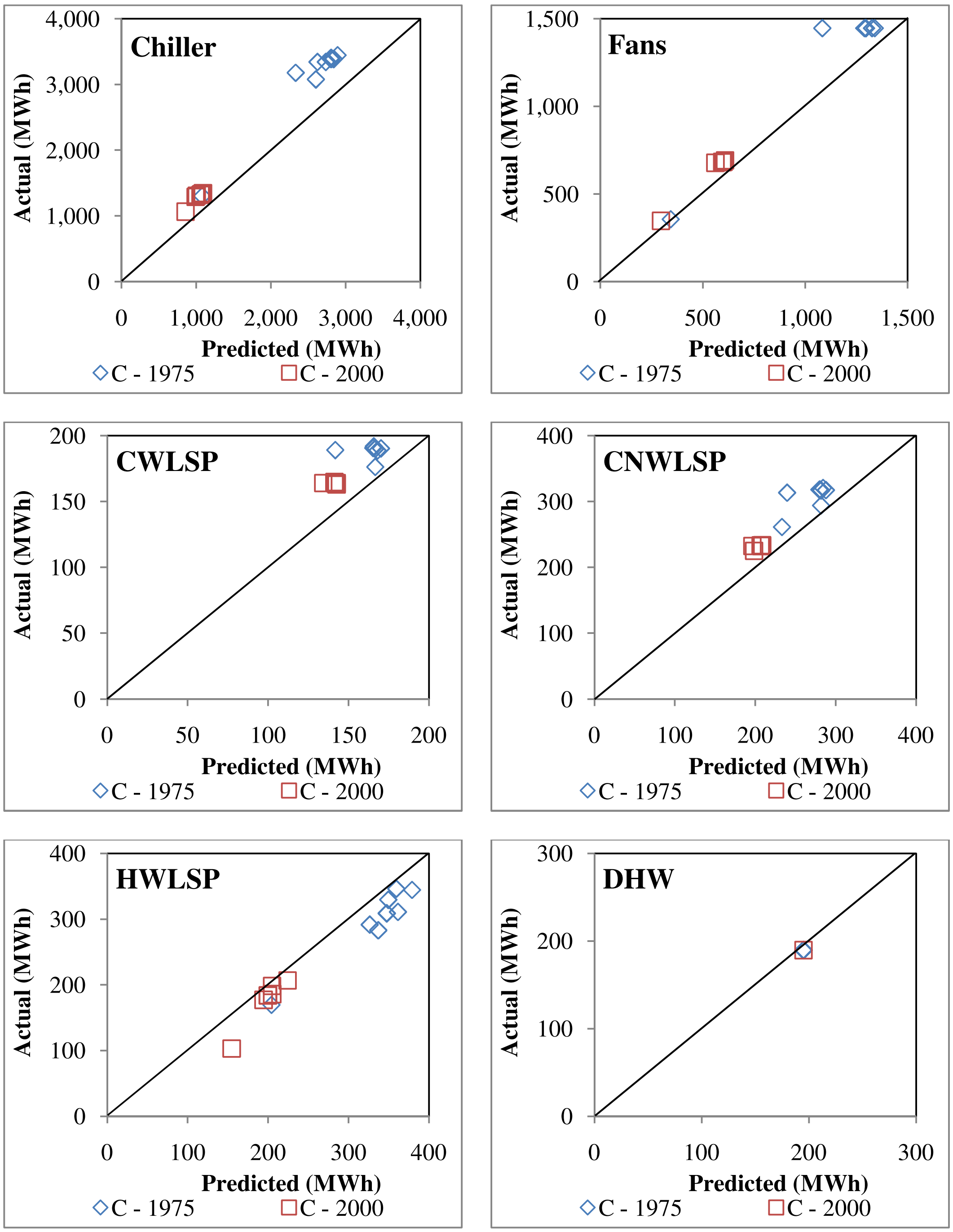


Figure C.6: Building B Energy Prediction Comparison (Vancouver)

C.6 Building C

C.6.7 Edmonton



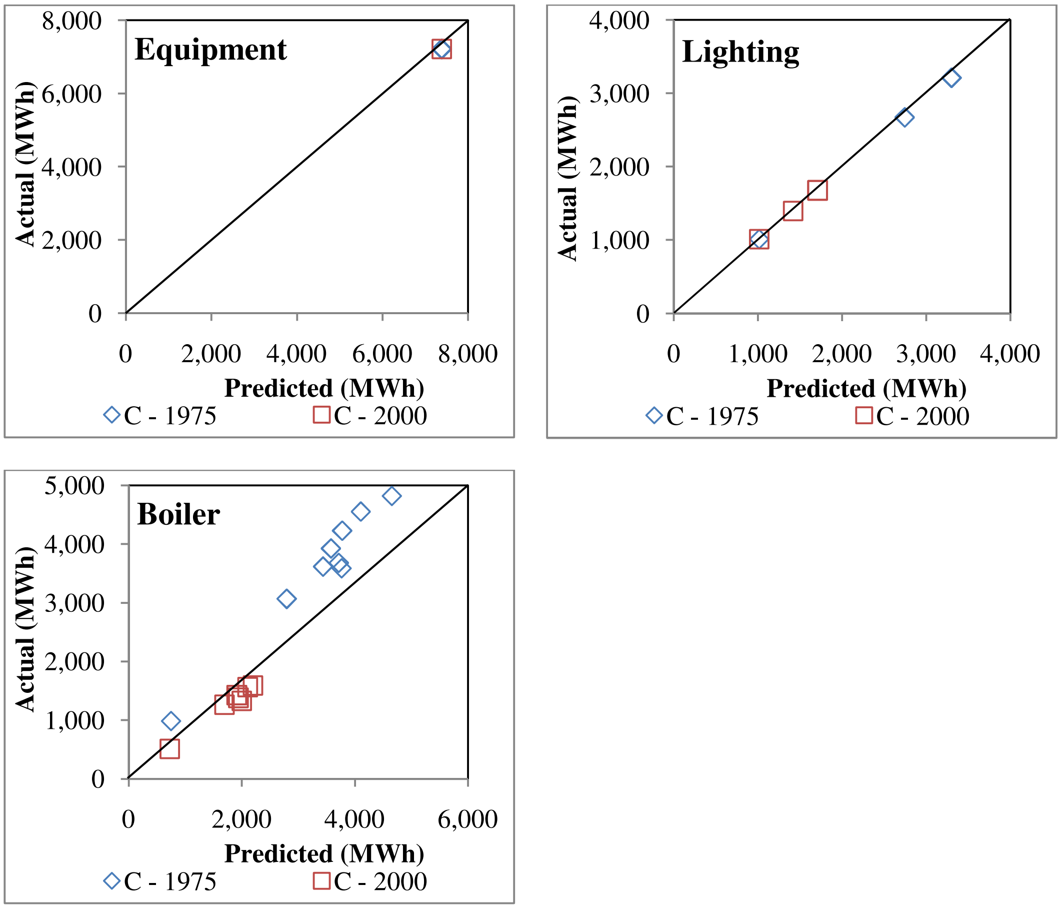
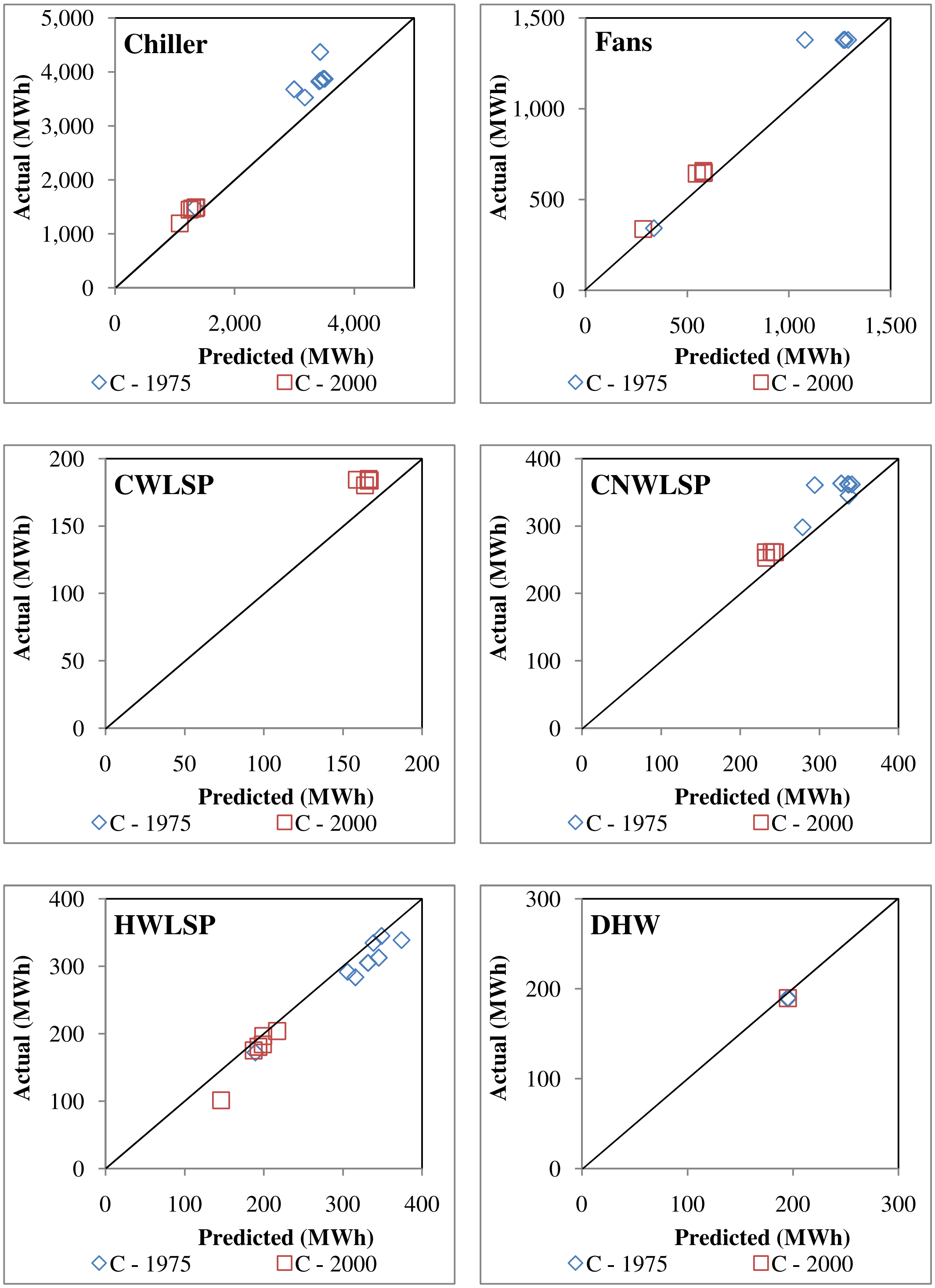


Figure C.7: Building C Energy Prediction Comparison (Edmonton)

C.6.8 Ottawa


Chiller
Actual (MWh)
5,000
4,000
3,000
2,000
1,000
0
0
2,000
4,000
Predicted (MWh)
C - 1975
C - 2000
Fans
Actual (MWh)
1,500
1,000
500
0
0
500
1,000
1,500
Predicted (MWh)
C - 1975
C - 2000
CWLSP
Actual (MWh)
200
150
100
50
0
0
50
100
150
200
Predicted (MWh)
C - 1975
C - 2000
CNWLSP
Actual (MWh)
400
300
200
100
0
0
100
200
300
400
Predicted (MWh)
C - 1975
C - 2000
HWLSP
Actual (MWh)
400
300
200
100
0
0
100
200
300
400
Predicted (MWh)
C - 1975
C - 2000
DHW
Actual (MWh)
300
200
100
0
0
100
200
300
Predicted (MWh)
C - 1975
C - 2000

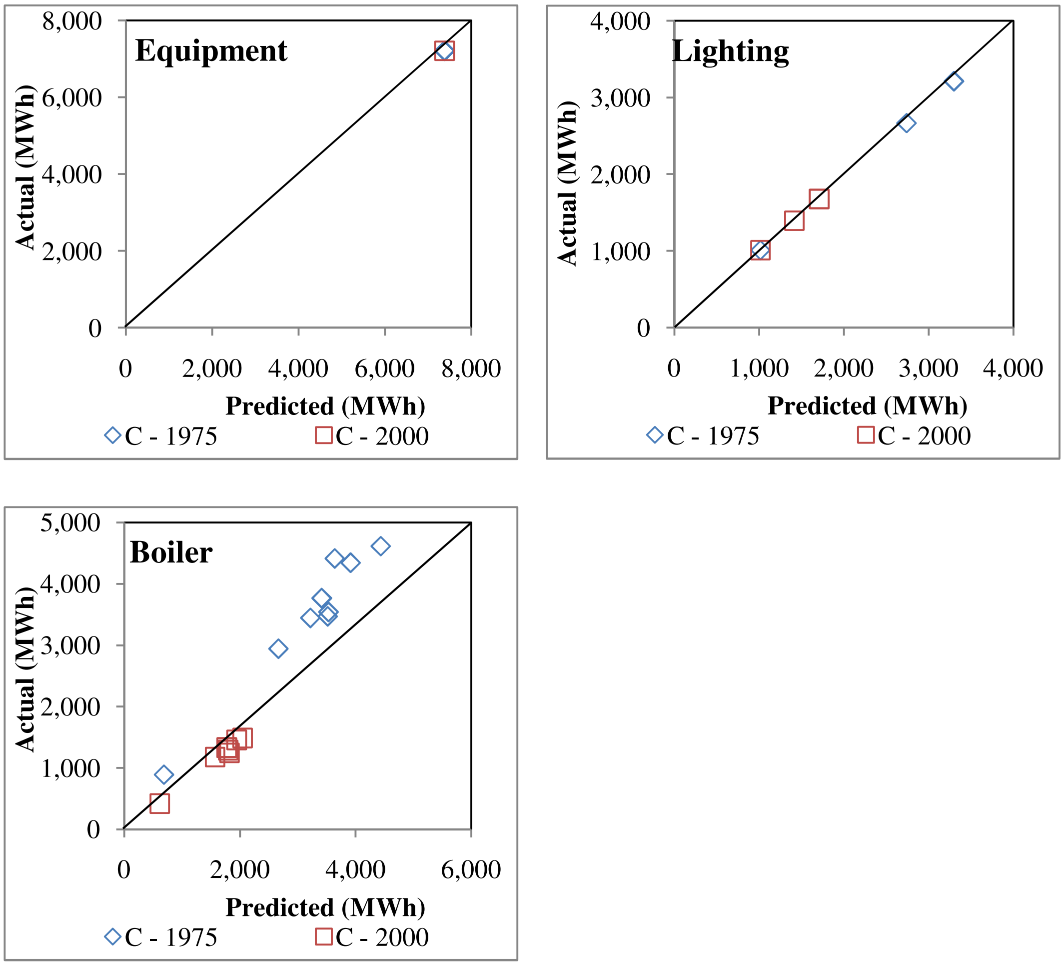
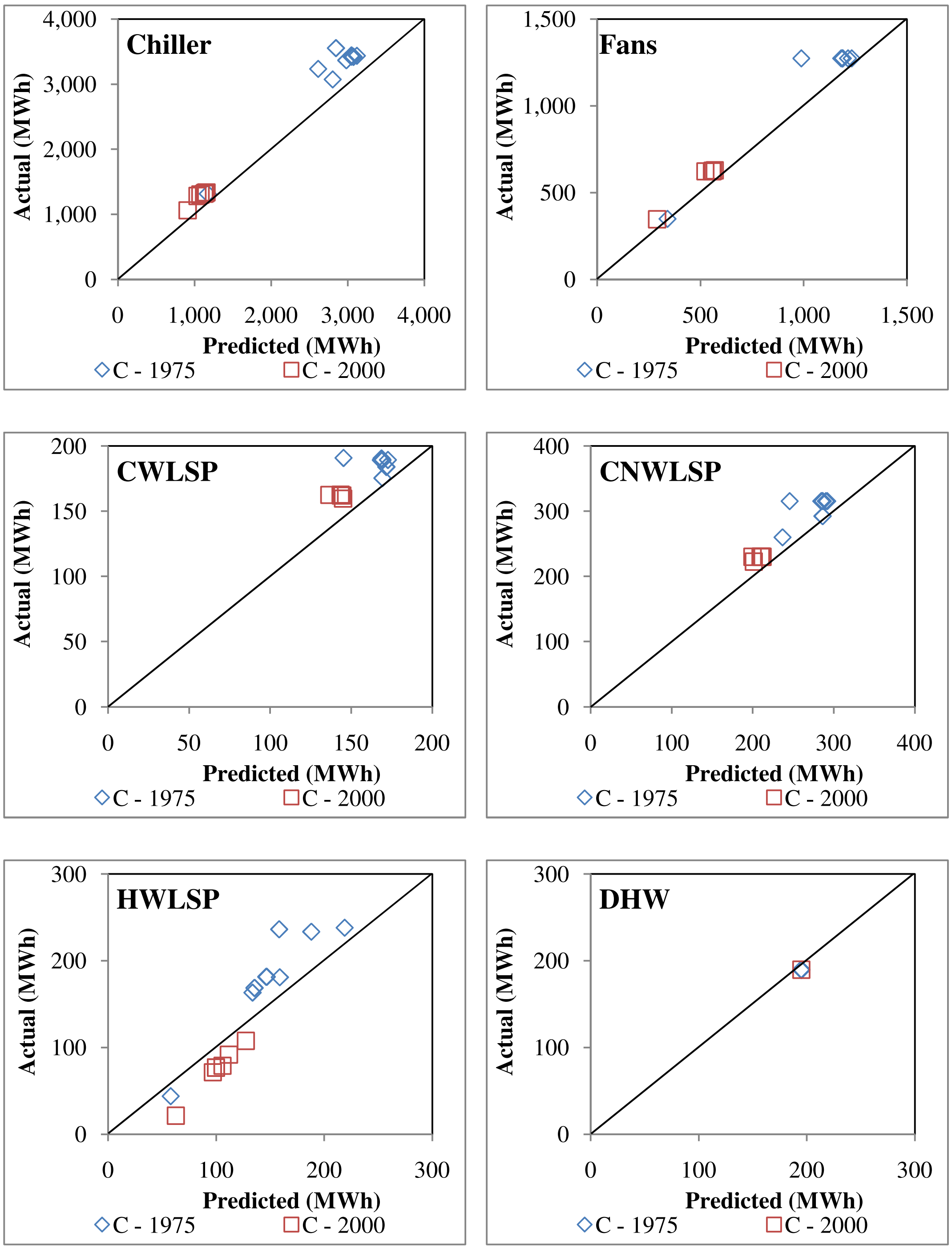


Figure C.8: Building C Energy Prediction Comparison (Ottawa)

C.6.9 Vancouver



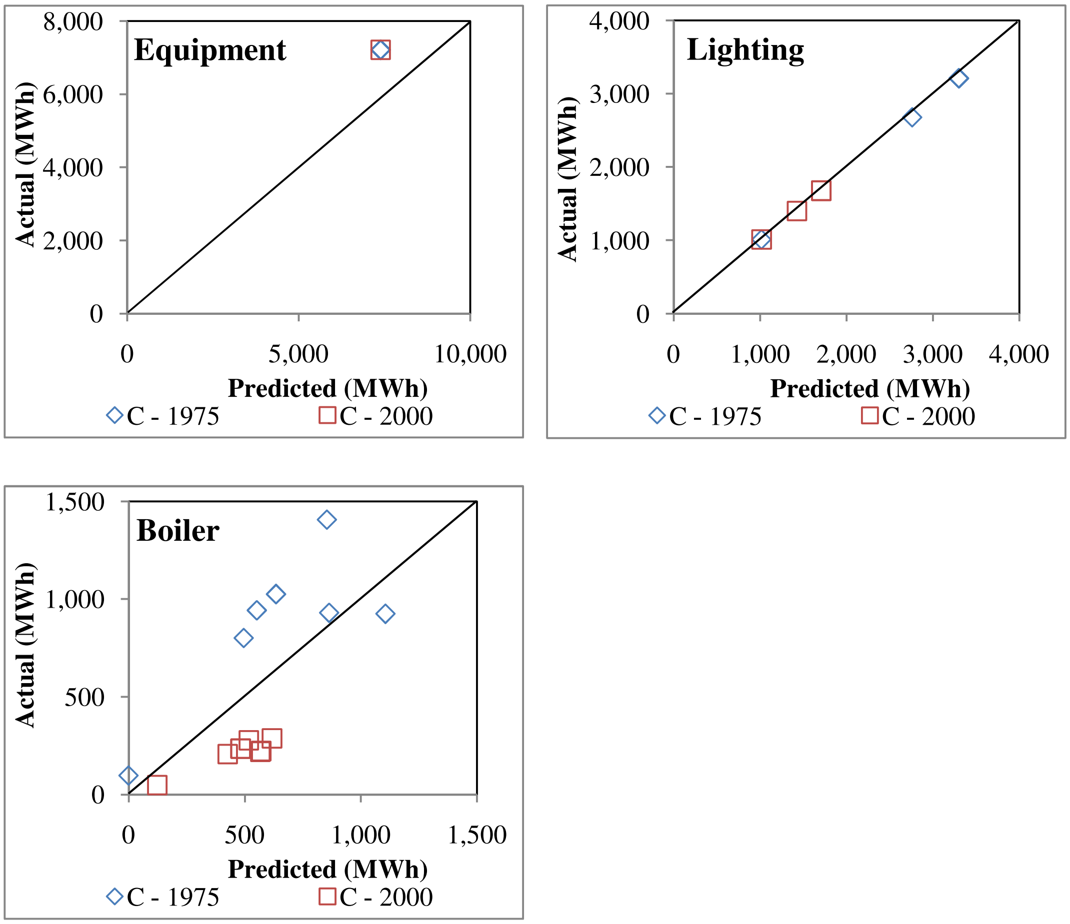
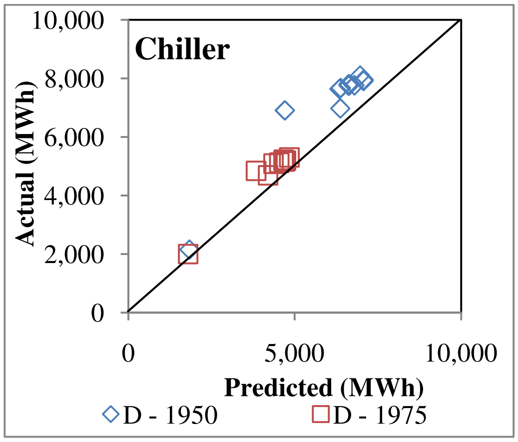
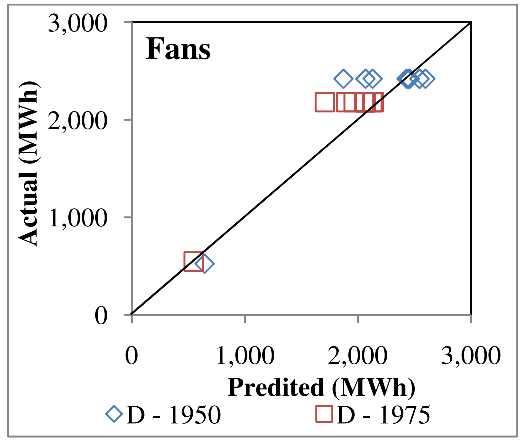


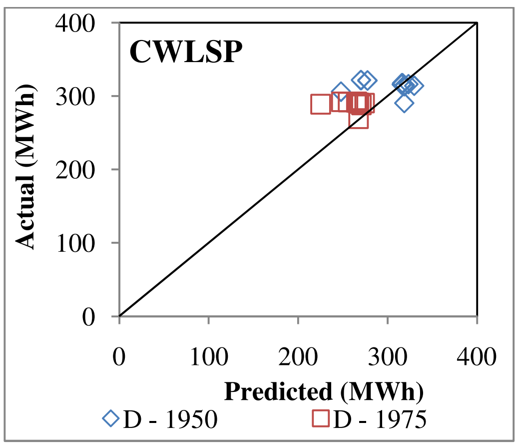
Figure C.9: Building C Energy Prediction Comparison (Vancouver)

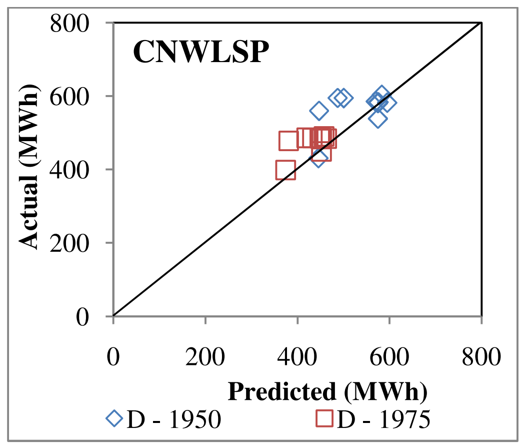
C.7 Building D

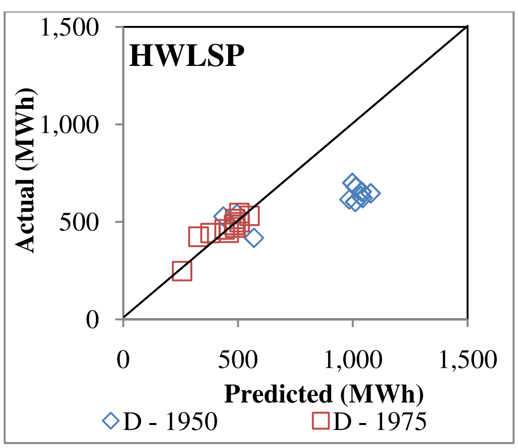
C.7.10 Edmonton

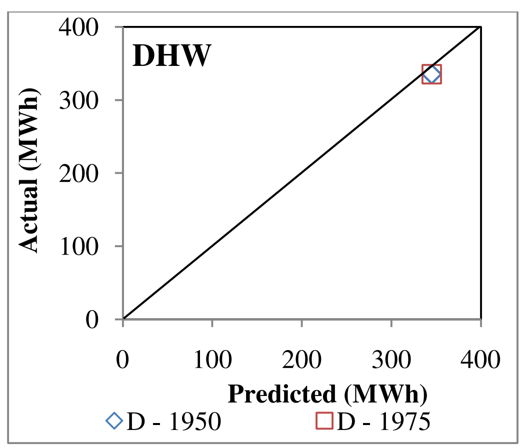












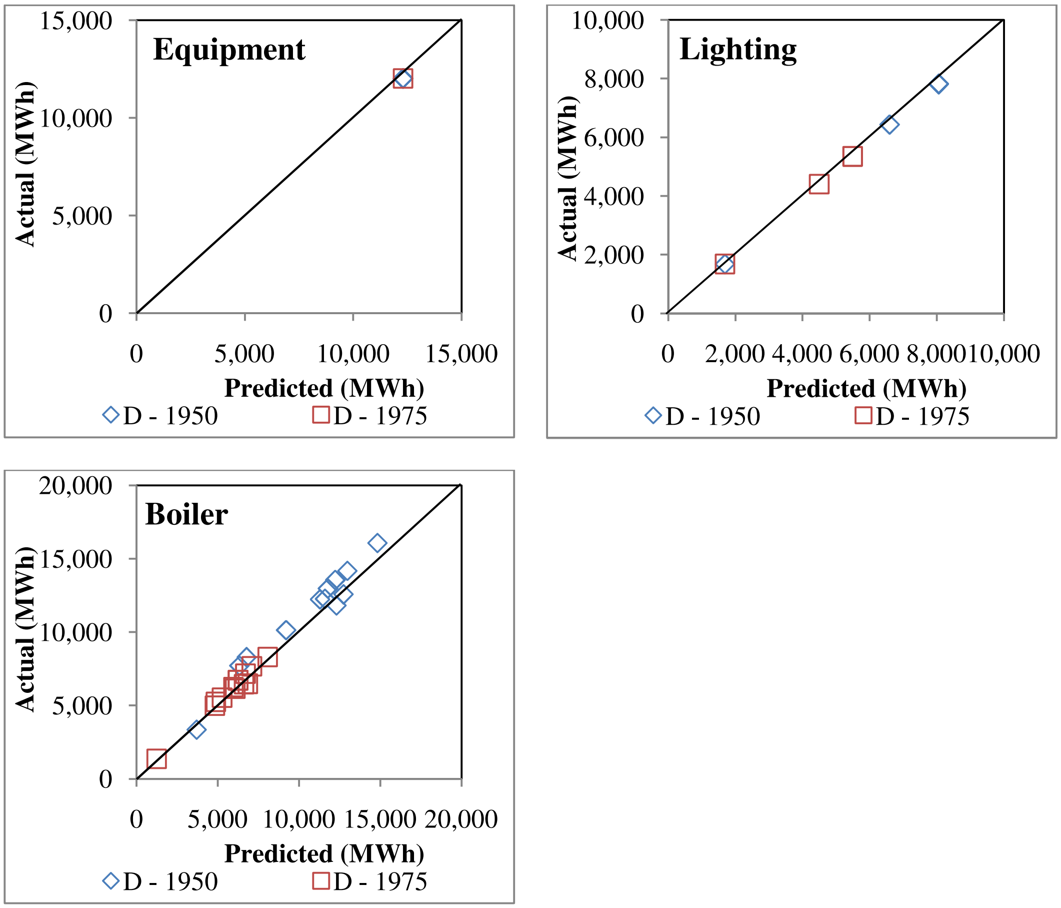
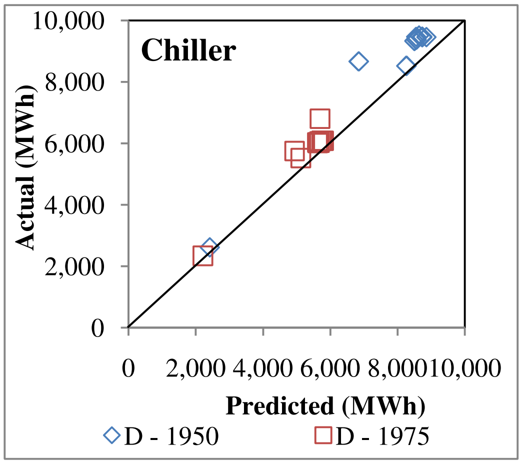
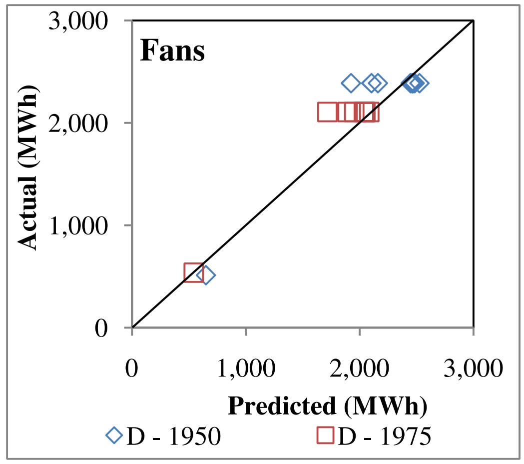
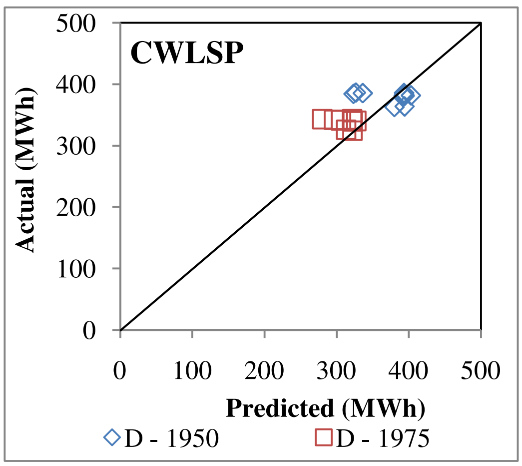


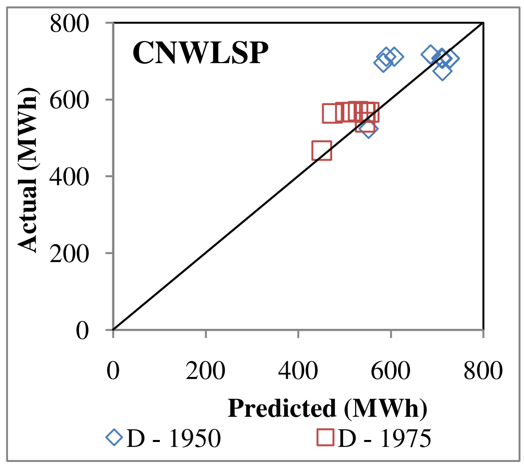
Figure C.10: Building D Energy Prediction Comparison (Edmonton)

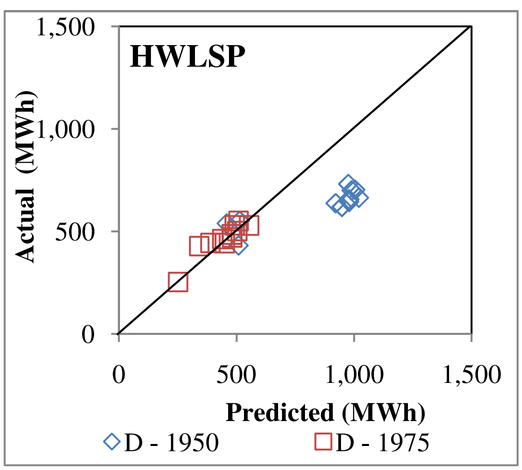
C.7.11 Ottawa

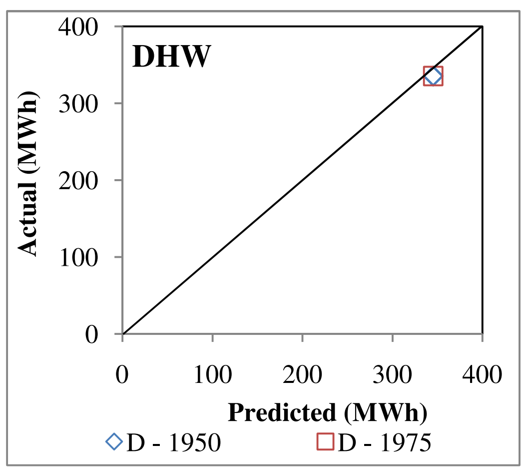

Chiller
Actual (MWh)
10,000
8,000
6,000
4,000
2,000
0
0
2,000 4,000 6,000 8,000 10,000
Predicted (MWh)
D - 1950
D - 1975


Fans
Actual (MWh)
3,000
2,000
1,000
0
0
1,000
2,000
3,000
Predicted (MWh)
D - 1950
D - 1975


CWLSP
Actual (MWh)
500
400
300
200
100
0
0
100
200
300
400
500
Predicted (MWh)
D - 1950
D - 1975


CNWLSP
Actual (MWh)
800
600
400
200
0
0
200
400
600
800
Predicted (MWh)
D - 1950
D - 1975


HWLSP
Actual (MWh)
1,500
1,000
500
0
0
500
1,000
1,500
Predicted (MWh)
D - 1950
D - 1975


DHW
Actual (MWh)
400
300
200
100
0
0
100
200
300
400
Predicted (MWh)
D - 1950
D - 1975

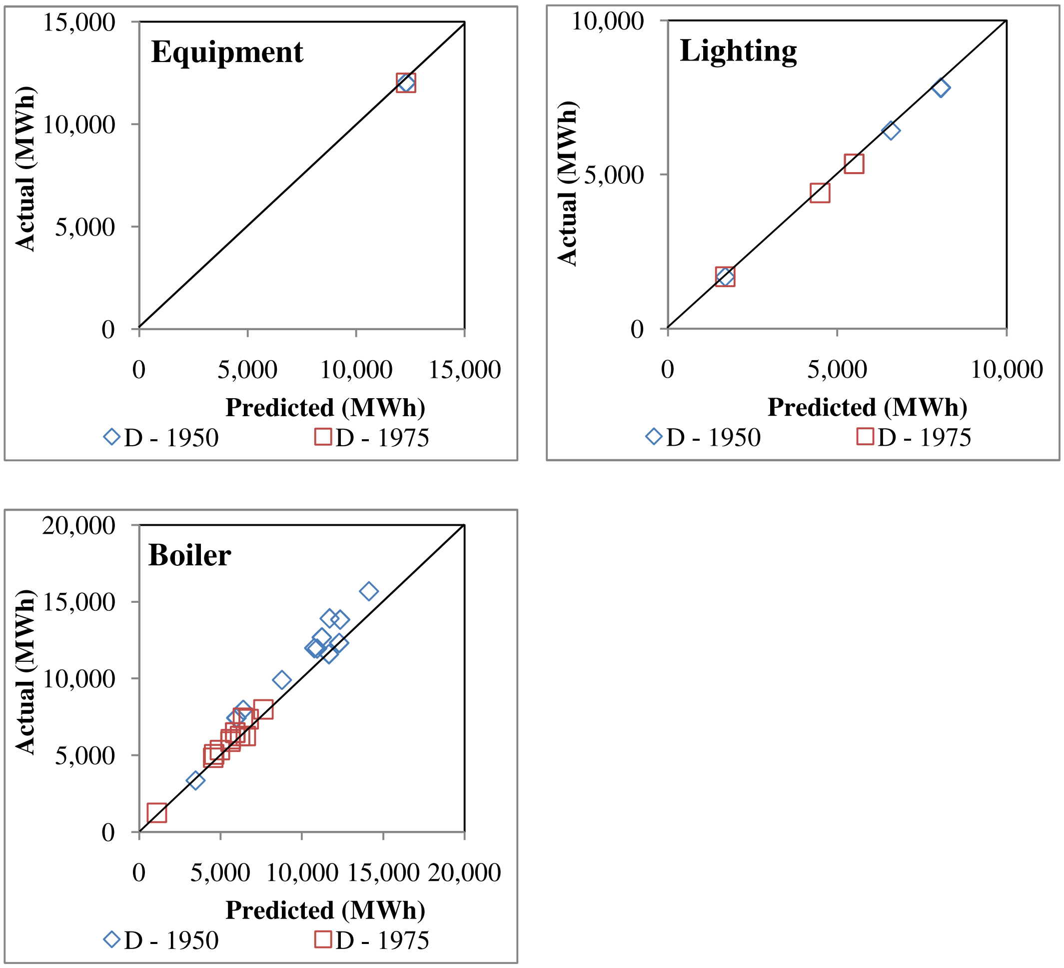
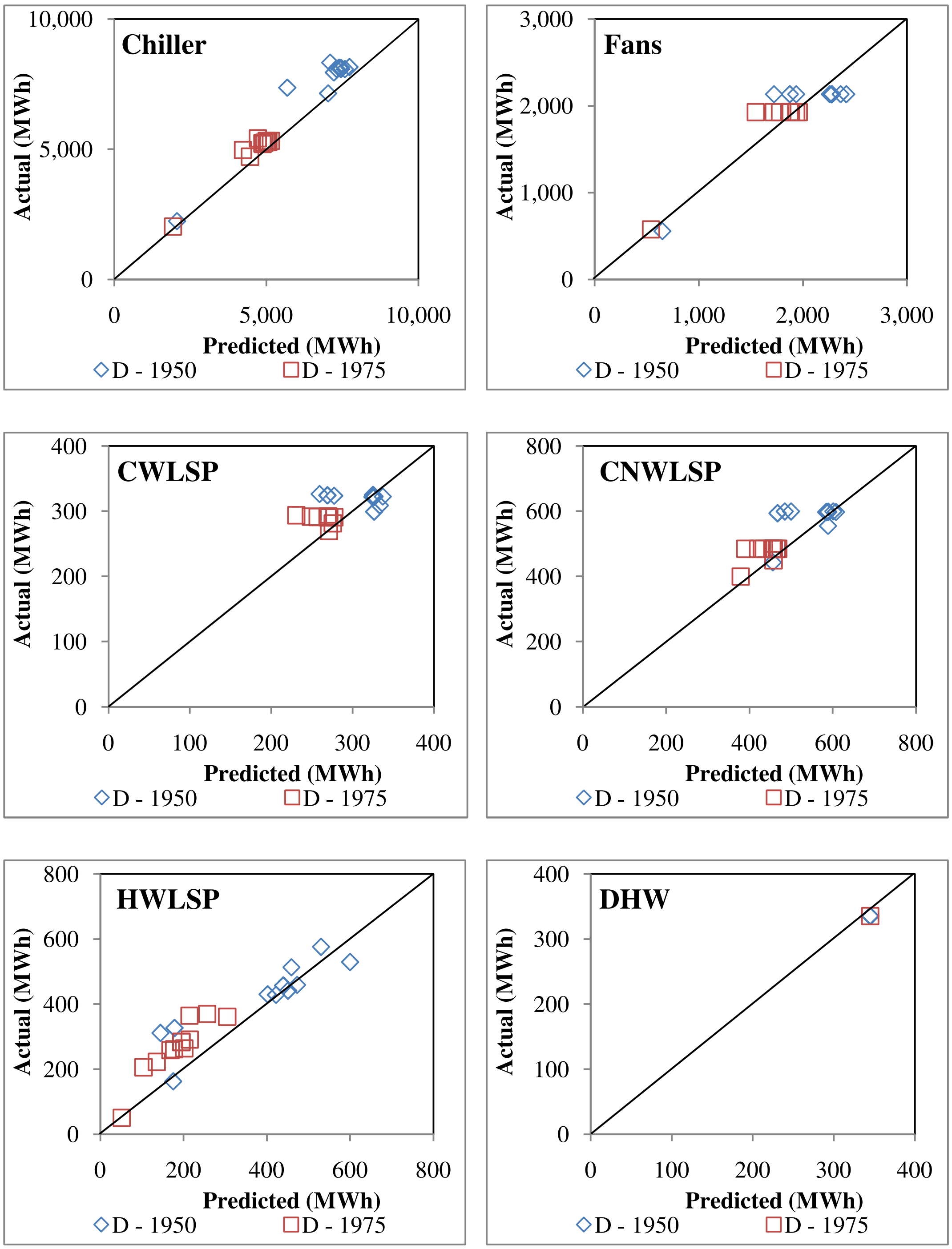


Figure C.11: Building D Energy Prediction Comparison (Ottawa)

C.7.12 Vancouver



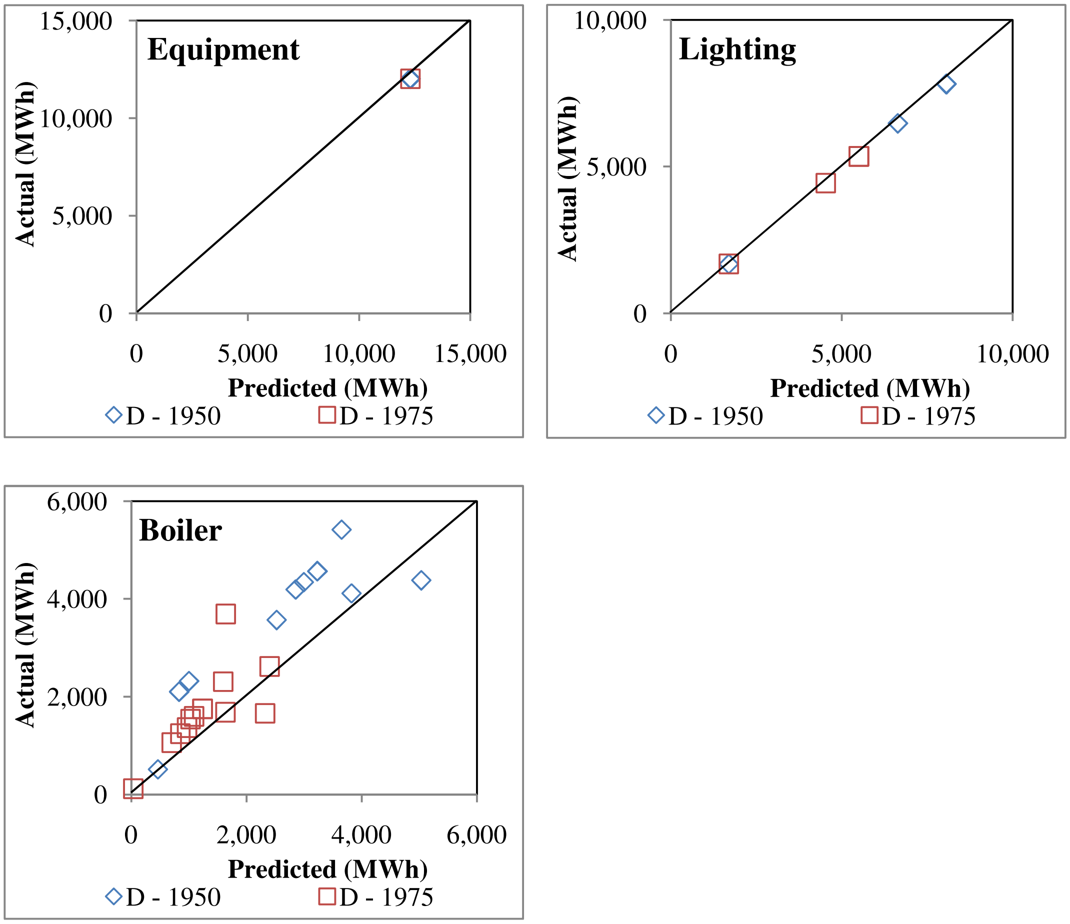
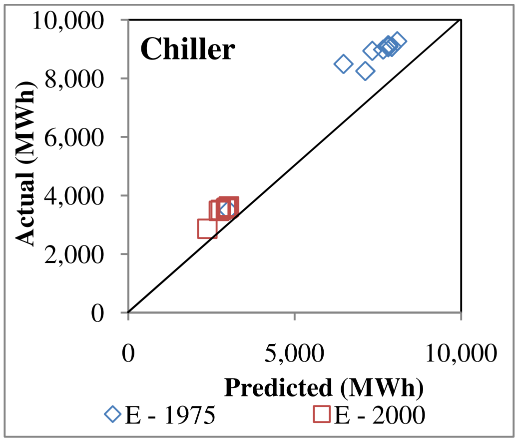
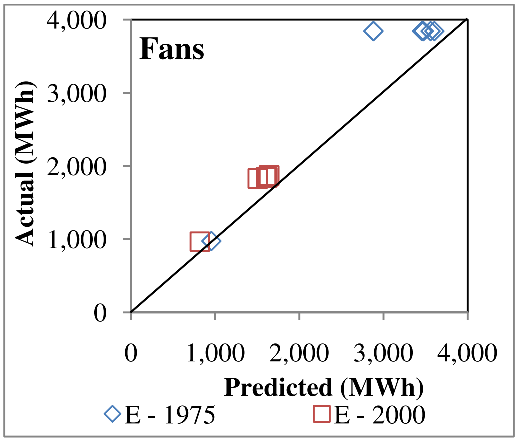


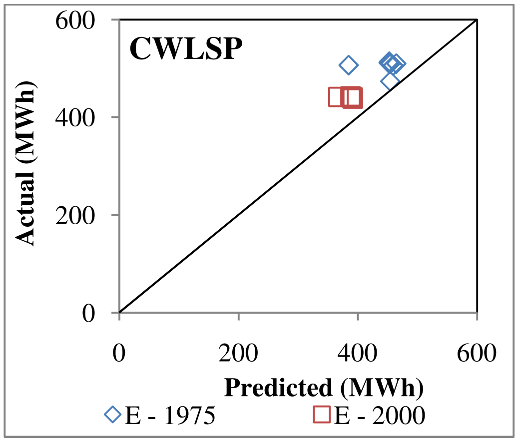
Figure C.12: Building D Energy Prediction Comparison (Vancouver)

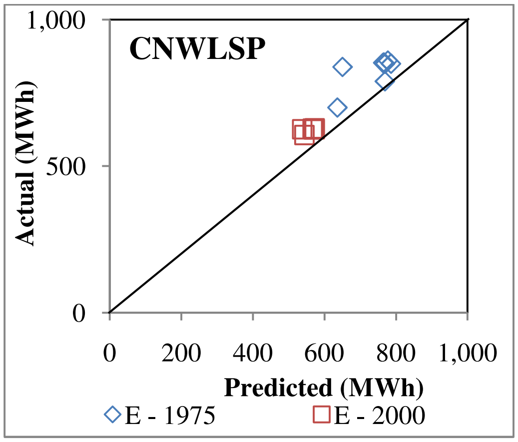
C.8 Building E

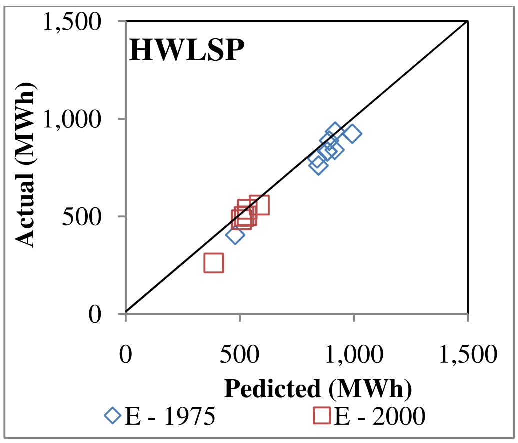
C.8.13 Edmonton

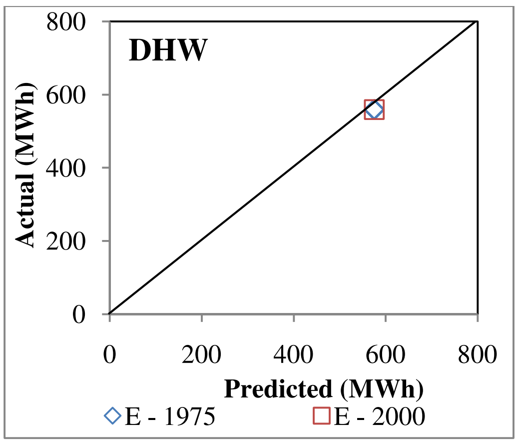












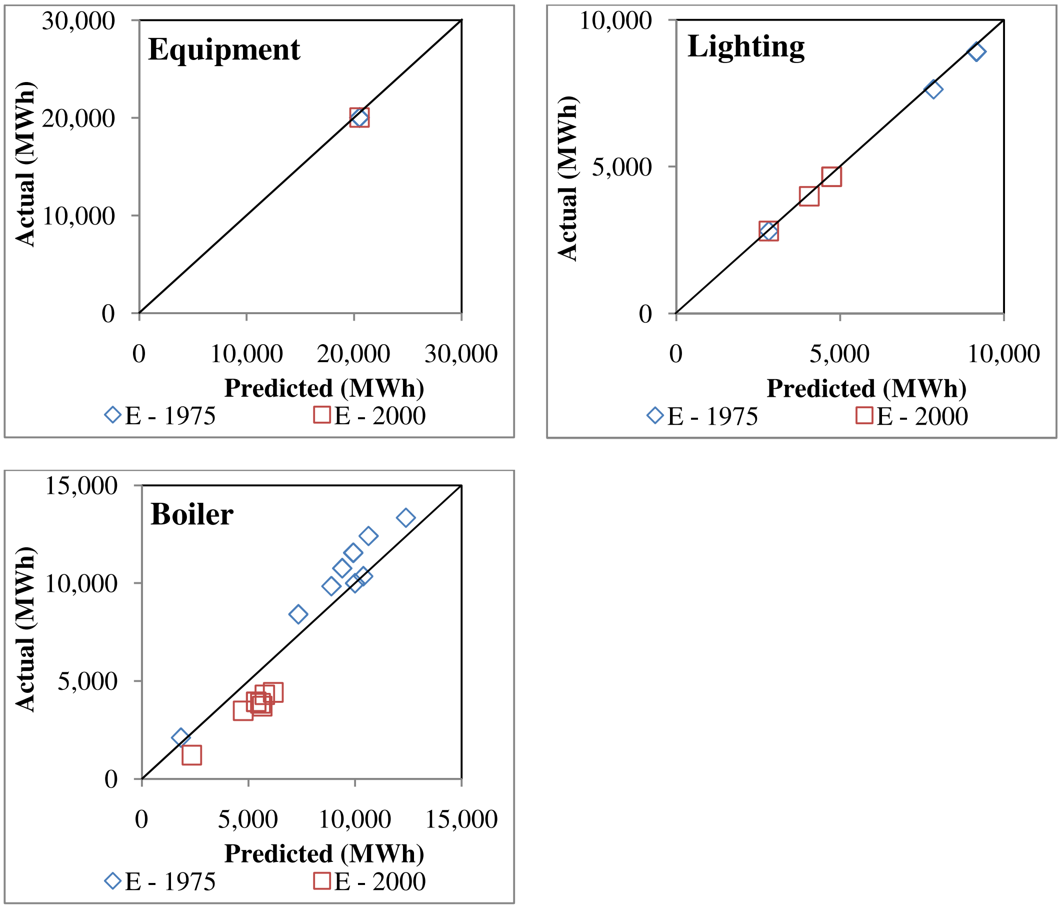
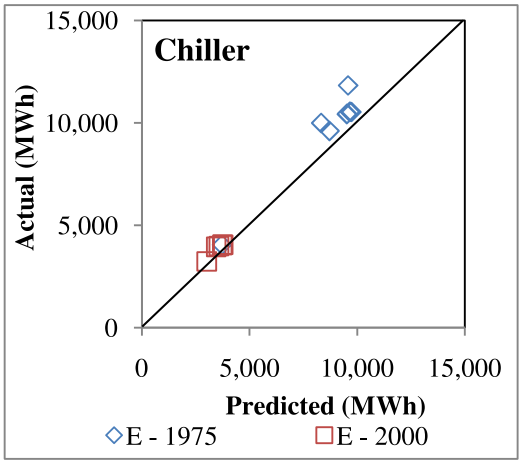
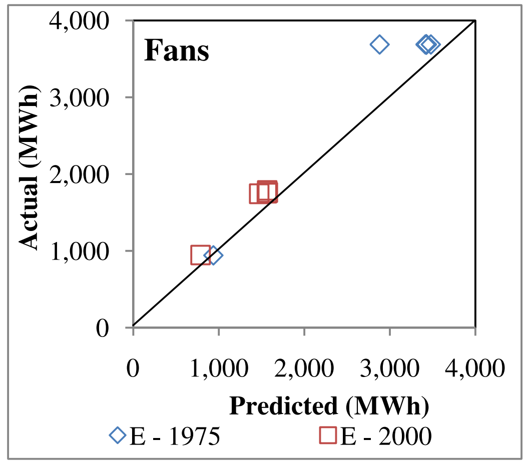
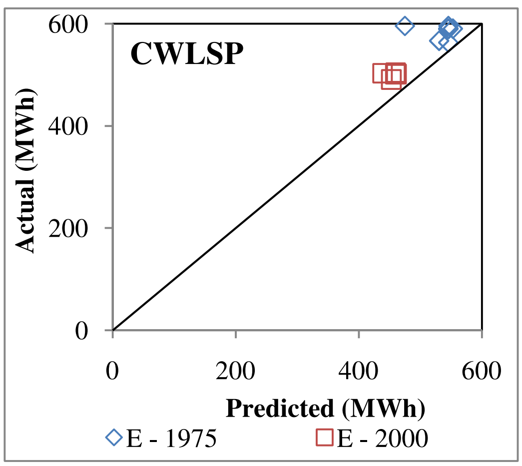


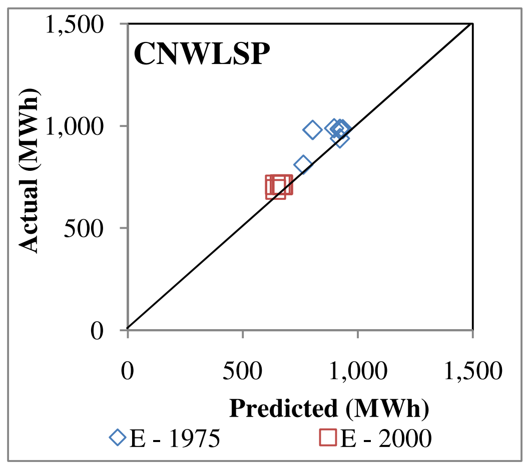
Figure C.13: Building E Energy Prediction Comparison (Edmonton)

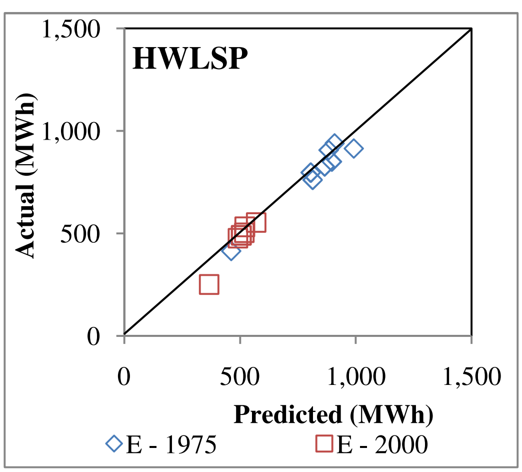
C.8.14 Ottawa

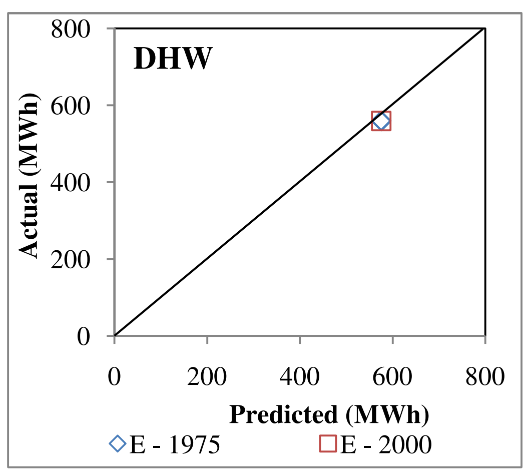

Chiller
Actual (MWh)
15,000
10,000
5,000
0
0
5,000
10,000
15,000
Predicted (MWh)
E - 1975
E - 2000


Fans
Actual (MWh)
4,000
3,000
2,000
1,000
0
0
1,000
2,000
3,000
4,000
Predicted (MWh)
E - 1975
E - 2000


CWLSP
Actual (MWh)
600
400
200
0
0
200
400
600
Predicted (MWh)
E - 1975
E - 2000


CNWLSP
Actual (MWh)
1,500
1,000
500
0
0
500
1,000
1,500
Predicted (MWh)
E - 1975
E - 2000


HWLSP
Actual (MWh)
1,500
1,000
500
0
0
500
1,000
1,500
Predicted (MWh)
E - 1975
E - 2000


DHW
Actual (MWh)
800
600
400
200
0
0
200
400
600
800
Predicted (MWh)
E - 1975
E - 2000

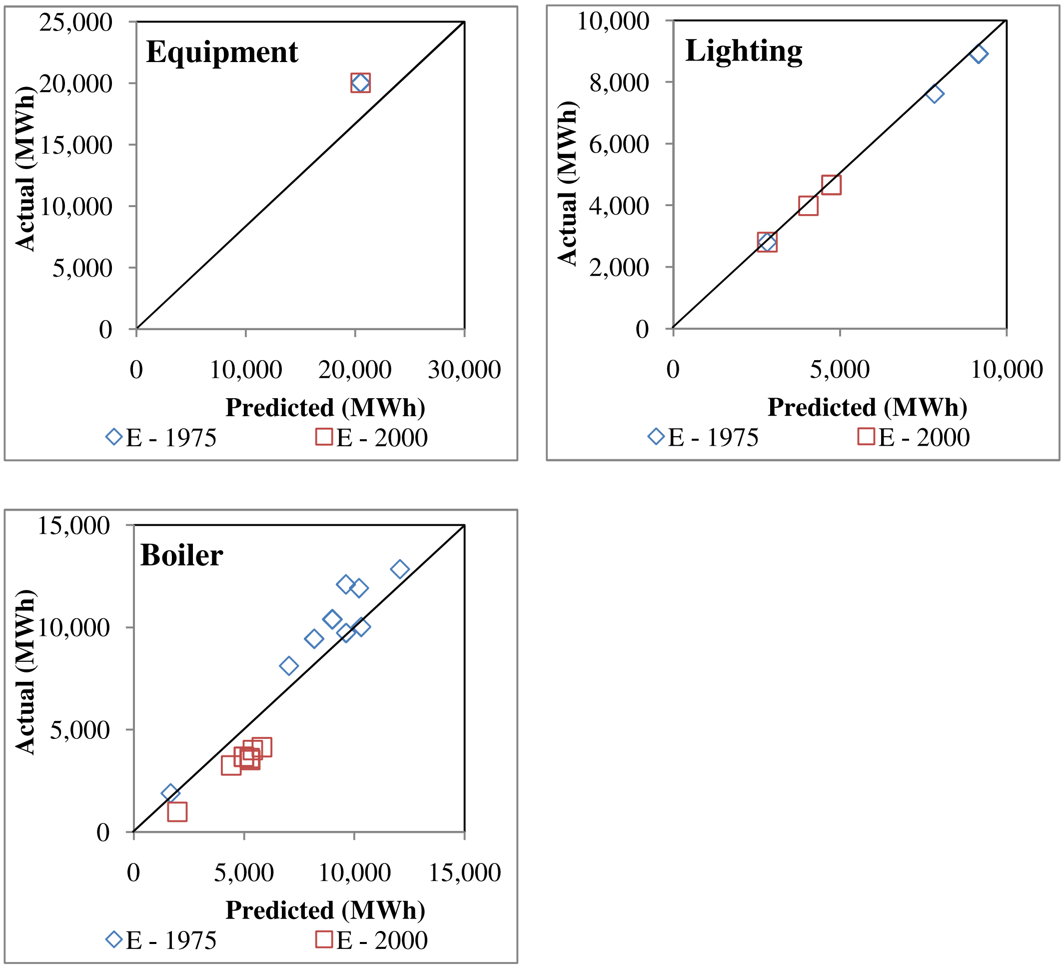
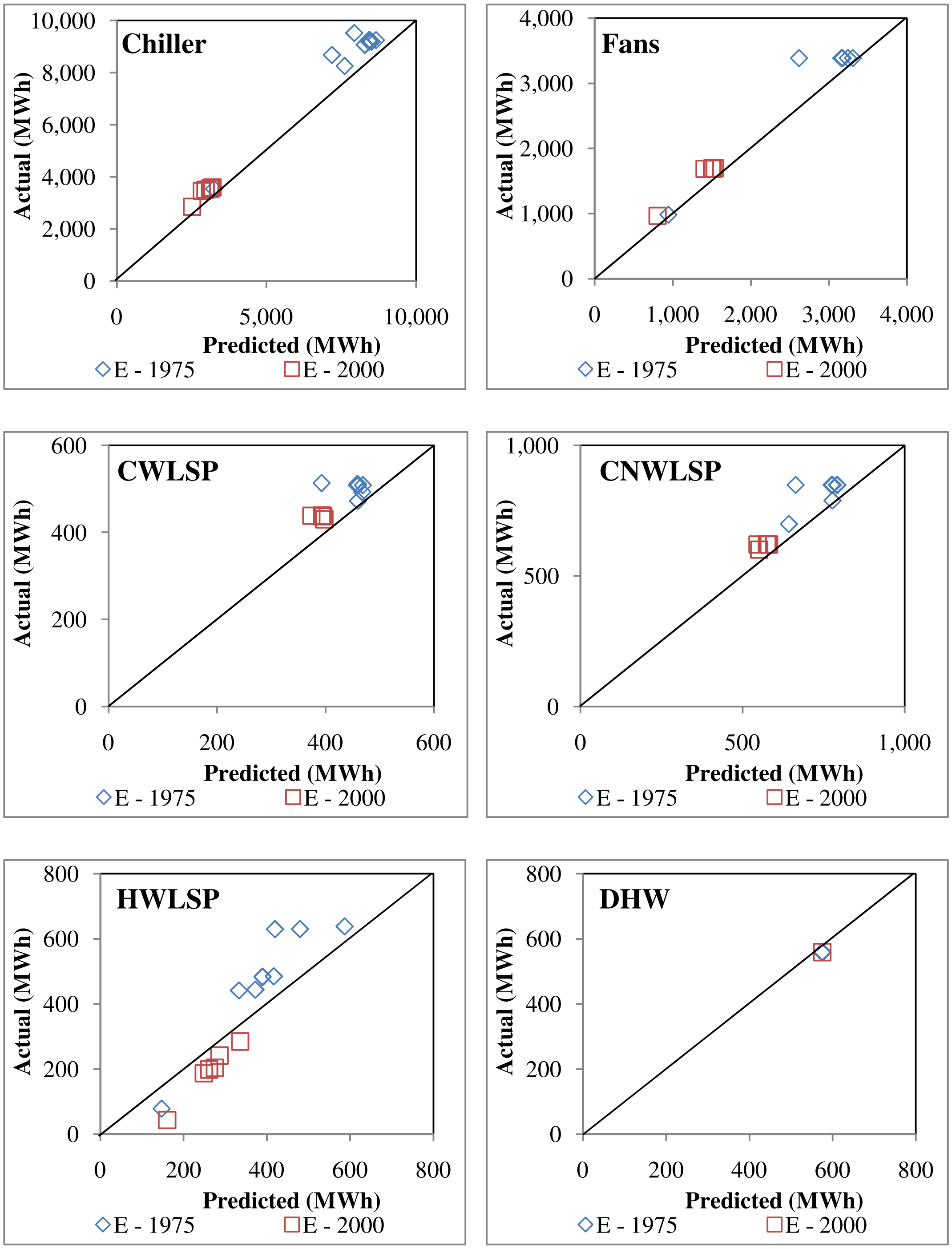


Figure C.14: Building E Energy Prediction Comparison (Ottawa)

C.8.15 Vancouver



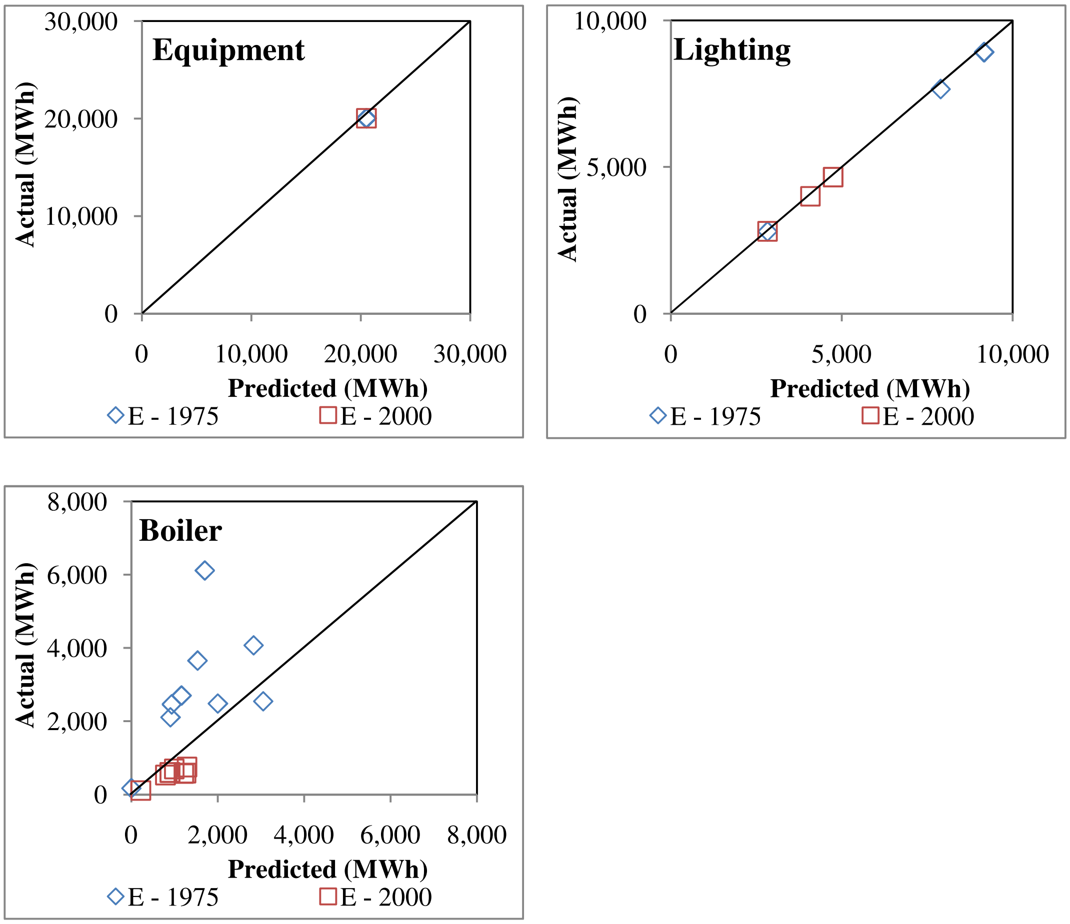


Figure C.15: Building E Energy Prediction Comparison (Vancouver)

Appendix D: ECM Costs of Implementation

Table D.1: ECM Costs of Implementation Building A

ECM	*Archetype*	*Edmonton*	*Ottawa*	*Vancouver*
01-AT	All	$8,938	$9,321	$9,070
02-RI	All	$113,805	$118,033	$121,457
03-WI	All	$113,469	$117,875	$117,306
04-WD	Pre-1950, 1950-1975	$406,429	$482,754	$483,536
05-WT	All	$507,763	$597,278	$595,421
06-EC	Pre-1950, 1950-1975	$11,251	$11,495	$11,553
07-VA	Pre-1950, 1950-1975	$8,614	$9,064	$9,037
	Post-1975	$463	$475	$477
08-HR	Pre-1950, 1950-1975	$110,272	$116,986	$77,592
09-LI	All	$41,171	$45,120	$42,486
10-DL	All	$6,908	$7,555	$7,392
11-CH	All	$82,628	$84,750	$85,169
12-BO	All	$121,188	$124,300	$124,915

Table D.2: ECM Costs of Implementation Building B

ECM	*Archetype*	*Edmonton*	*Ottawa*	*Vancouver*
01-AT	All	$42,076	$43,880	$42,697
02-RI	All	$113,805	$118,033	$121,457
03-WI	All	$534,175	$554,917	$552,240
04-WD	All	$1,913,340	$2,272,655	$2,276,339
05-WT	All	$2,390,389	$2,811,800	$2,803,056
06-EC	All	$11,251	$11,495	$11,553
07-VA	All	$51,685	$54,383	$54,221
08-HR	All	$477,844	$506,940	$426,755
09-LI	All	$247,028	$270,723	$254,919
10-DL	All	$34,540	$37,774	$36,959
11-CH	All	$401,024	$411,320	$413,354
12-BO	All	$181,783	$186,450	$187,372

Table D.3: ECM Costs of Implementation Building C

ECM	*Archetype*	*Edmonton*	*Ottawa*	*Vancouver*
01-AT	All	$116,605	$121,602	$118,325
02-RI	All	$341,415	$354,099	$364,371
06-EC	1950-1975	$11,251	$11,495	$11,553
07-VA	1950-1975	$51,685	$54,383	$54,221
	Post-1975	$2,778	$2,850	$2,864
08-HR	All	$120,049,076	$127,358,908	$1,163,876
09-LI	All	$738,109	$808,907	$761,685
10-DL	All	$34,540	$37,774	$36,959
11-CH	All	$685,266	$702,860	$706,336
12-BO	All	$231,360	$237,300	$238,474

Table D.4: ECM Costs of Implementation Building D

ECM	*Archetype*	*Edmonton*	*Ottawa*	*Vancouver*
01-AT	All	$130,276	$135,859	$132,197
02-RI	All	$341,415	$354,099	$364,371
03-WI	All	$1,653,903	$1,718,125	$1,709,835
04-WD	All	$5,924,050	$7,036,553	$7,047,959
05-WT	All	$7,401,079	$8,705,845	$8,678,773
06-EC	All	$11,251	$11,495	$11,553
07-VA	All	$86,142	$90,638	$90,369
08-HR	All	$1,948,133	$2,066,755	$1,823,406
09-LI	All	$1,230,182	$1,348,179	$1,269,474
10-DL	All	$62,172	$67,994	$66,527
11-CH	All	$1,313,242	$1,346,960	$1,353,622
12-BO	All	$347,040	$355,950	$357,710

Table D.5: ECM Costs of Implementation Building E

ECM	*Archetype*	*Edmonton*	*Ottawa*	*Vancouver*
01-AT	All	$269,096	$280,629	$273,065
02-RI	All	$569,024	$590,165	$607,285
06-EC	1950-1975	$11,251	$11,495	$11,553
07-VA	1950-1975	$86,142	$90,638	$90,369
	Post-1975	$4,631	$4,749	$4,773
08-HR	1950-1975	$3,234,635	$3,431,593	$3,026,079
09-LI	All	$2,048,649	$2,245,152	$2,114,084
10-DL	All	$62,172	$67,994	$66,527
11-CH	All	$1,731,893	$1,776,360	$1,785,146
12-BO	All	$462,719	$474,600	$476,947