SCREENING OFFICE BUILDINGS FOR ENERGY RETROFIT MEASURES

A METHODOLOGY FOR SCREENING OFFICE BUILDINGS FOR ENERGY RETROFIT MEASURES

By

ERIC J. C. CATANIA, B.ENG.

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AUTHOR:	Eric J. C. Catania, B. Eng. (McMaster University)
SUPERVISOR:	Professor Samir E. Chidiac, Ph.D. P.Eng.
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Abstract

Both private and public sectors own and operate an array of office buildings that consume energy and contribute to the emission of greenhouse gases. In an attempt to reduce energy demands, an analysis into the cost/benefit relationship of incorporating energy retrofit measures (ERMs) was carried out. The main objective was to develop a methodology for screening office buildings for both their current level of energy efficiency and their potential for retrofit applications. Optimal retrofit options can be determined by examining how different building characteristics affect the benefits received from improving various components.

By characterizing the office building stock into a manageable set of representative models, it was possible to make estimations on energy consumption for lights, computers, pumps, fans, hot water supply, cooling and heating loads. Employing EnergyPlus, an energy modelling software package, these representative building models were analyzed using three different climate regions for the specific effects that altering building components have on energy consumption. Using a statistical regression analysis, a set of equations was derived for determining the energy consumption based on building-specific variable values.

A life cycle cost analysis was used to obtain the net present value associated with the implementation of various retrofit ERMs. Payback period was adopted to quantify the cost effectiveness of ERMs.

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Chapter 1: Introduction

1.1 Introduction

In the late 20^{th} century, the Canadian government made a commitment to the Kyoto Protocol in which an agreement was signed to reduce the output of greenhouse gases (GHGs) into the atmosphere to a level 6% lower than those recorded in 1990 (United Nations, 1992). In order to achieve this goal, it is necessary for the overall generation of greenhouse gases to be reduced by 25% (ARC Applied Research Consultants, 1999). Reducing the consumption of energy in office buildings is a vital step in lowering these emissions as it is estimated that 12.4% of the total greenhouse gas emissions in Canada are produced by the commercial/institutional sector (ARC Applied Research Consultants, 1999).

Reduction of energy consumption can be achieved through the implementation of energy retrofit measures (ERMs) which range from physical changes to the construction of a building to changes in the operational systems that include climate control and lighting. An approach for optimizing retrofit selection in office buildings is necessary to achieve a cost effective ERM. With this in mind, a method for determining the effects of ERMs on energy consumption while being able to account for the wide variety of building characteristics that are available, was developed. This "methodology of screening" incorporates the building characteristics, climate region, pre and post retrofit energy consumption, ERM implementation and energy costs, as well as interest and inflation rates. The ultimate goal of this study is to develop a standardized process in which general building properties can be used to estimate energy consumption and optimize the selection of the most desirable and cost-effective energy retrofit measures.

1.2 Literature Review

The analysis of energy consumption for retrofit application in buildings is a complex and ever evolving area of study. To date, numerous methods for assessing the impact of ERMs have been developed, each of which vary in application and depth of focus. This includes, examinations into the general levels of energy efficiency for all buildings types, the implications to the emissions of GHGs and the software and analysis programs that are available to assess the cost and payback periods of ERMs. Presentation of the literature is divided into three main components: GHG emission assessment, energy efficiency trend analysis, and ERM cost examination.

1.2.1 GHG Emission

Recognizing that the reduction of greenhouse gas emissions is one of the triggers for improving the energy efficiency of office buildings, it is then important to understand the relationship between the production of GHGs and the source of energy utilized. Different energy sources: coal, natural gas and fuel oil, each contribute in different ways to the levels of greenhouse gases produced. Table 1.1 indicates the quantities of gases that are produced by each of the most common fuel sources in Canada.

Table 1.1: Fuel emissions for greenhouse gases (ARC Applied Research Consultants, 1999)

Greenhouse Gas	*Carbon dioxide (CO_2)*	*Methane (CH_4)*	*Nitrous oxide (N_2O)*
Fuel	**tonnes/terajoule**	**kg/terajoule**	**kg/terajoule**
Natural Gas	49.7	(0.13 – 1.27)	0.62
Light Fuel Oil	73.1	(0.03 – 0.12)	(3.36 – 10.34)
Heavy Fuel Oil	74	(0.01 – 0.21)	(3.11 – 9.59)
Coal – Anthracite	86.2	Varies	Varies
Coal – Canadian Bituminous	(94.3 – 83.0)	Varies	Varies

It can be seen that each type of fuel has its own unique level of contribution to greenhouse gas emissions. This is primarily due to the proportions of hydrogen and carbon that are produced when each is burned (ARC Applied Research Consultants, 1999). The contribution of electrical generation to GHG production depends on the fuel source used, where coal, fuel oil and natural gas have the largest impact and wind, solar and nuclear energy produce negligible amounts of GHGs. Applying an ERM to a building that changes the fuel source used for heating from one that produces high GHG emissions to one with low GHG impacts is a viable option for reducing the overall production of GHGs. A limiting factor is that over 90% of energy consumed in the commercial sector in

Canada is composed of Natural Gas and Electricity (ARC Applied Research Consultants, 1999).

The analysis of the impact of GHG emissions and their relationship to the fuel used in the heating of a building and generation of electricity are generally normalized so that N_2O and CH_4 are equated in terms of equivalent effect of CO_2. This is performed since each of the GHGs impact "global warming" in varying degrees of intensity. Table 1.2 summarizes the factors that can be used in this normalization. The factors were extracted from the National Greenhouse Gas Inventories Programme (1996).

Table 1.2: Global warming potentials of greenhouse gases (National Greenhouse Gas Inventories Programme, 1996)

Greenhouse gas	*GWP*
CO_2	1
CH_4	21
N_2O	310

1.2.2 Energy Efficiency Trends

The trend towards improving or reducing the rate at which energy is consumed in office buildings is an ongoing process and the analysis of energy efficiency can be complicated by factors that are beyond the control of building owners and operators. External influences such as weather, service level and activity within a building can all have an impact on the amount of energy consumed from year to year. As such it is vital, when determining the effects of the implementation of ERMs, to be aware that the estimated benefits received from the reduction in energy consumption may not reflect real world scenarios. The Natural Resouces Canada (2004) report studied the energy efficiency trends in buildings over a 12 year period from 1990 to 2002, in which records were kept for the changes in energy consumption in commercial buildings within Canada. Figure 1.1 illustrates how the savings experienced through the implementation of energy efficiency measures, in the commercial and institutional sector, can be overshadowed by the increases in energy demand due to the effects of activity, service level, structure, weather, and energy efficiency. Activity effect accounts for the increases in occupancy density and floor space usage resulting from improvements in the Canadian economy. Service level effect includes increases in auxiliary equipment loads such as computers, faxes, photocopiers and space cooling demands. The structure effect accounts for changes in the distribution between office and warehouse floor space. The weather effect captures the differences in the average temperature in the winter and summer seasons over the twelve year time span. The energy efficiency effect accounts for the reduction in energy consumption due to the implementation of ERMs (Natural Resouces Canada, 2004).

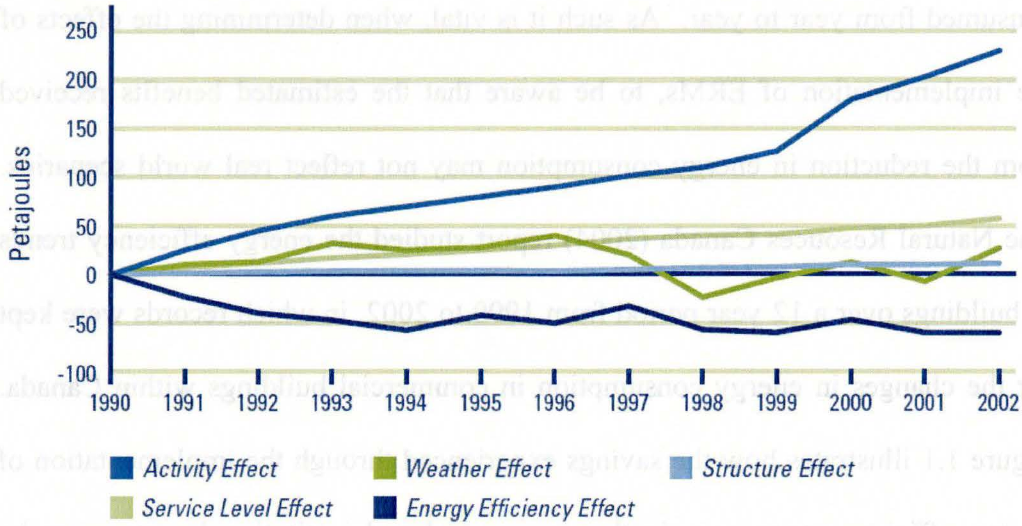

Figure 1.1: Cumulative Changes in Energy Use (Natural Resouces Canada, 2004)

Along with the effects on overall energy efficiency imposed by external sources, lack of knowledge of the possible savings associated with the application of ERMs can be a mitigating factor. Applied Research Consultants (1999) examined how different characteristics affect the energy efficiency of a commercial office building, focusing not only on physical building parameters but primarily on the human aspect of implementing ERMs. The human barriers behind achieving a high level of energy efficiency include the lack of awareness of new technologies and operation practices available. In order to overcome the barriers associated with applying ERMs, several incentive and informational programs have been implemented by the Federal Government of Canada. To promote the need for energy efficient building operation and design, financial incentives are offered to building owners that explore and apply ERMs. On April 1, 2007, an all encompassing energy efficiency analysis action plan entitled ecoACTION was introduced. As part of the ecoACTION program many subsidiaries including ecoAGRICULTURE, ecoENERGY and ecoTRANSPORT were developed to handle the various contributors to energy consumption and GHG emissions. The ecoENERGY retrofit grants and incentives program is scheduled to end on March 31, 2011 and is geared primarily towards residential and small commercial business applications. The funding available from this project includes $10 for each gigajoule of savings in estimated energy consumption, to a maximum of $50,000 or 25% of the eligible project costs. Buildings that are applicable to this program must be limited to a footprint of no more than 10,000 m^2 (Government of Canada, 2007).

Internationally, the European Union has introduced its own efficiency initiative entitled the Energy Performance of Buildings Directive (EPBD) (The European Parliament and the Council of the European Union, 2002) in which both new and existing public and non-public buildings are subject to new regulations regarding energy efficiency and performance. This directive was introduced on January 4th, 2003 and became law on January 4th, 2006 with the goal to reduce the consumption of energy in the over 160 million buildings located in the European Union, accounting for 40% of total energy use. Under this directive, buildings are first classified according to their functional purpose, office, educational, hospital etc., and then evaluated for their current level of energy consumption per unit of floor area in comparison to other buildings under similar classification. The relationship between a given building's energy efficiency status and how it relates to others is then translated into an Energy Performance Certificate which possesses the efficiency status of the building as well as its comparison to the current legal standards and benchmarks that are in place. This certificate program allows the general public to be aware of the current efforts being employed by building operators in achieving a high level of energy efficiency. The goal of the EPBD is to ultimately achieve a cost savings of 22% from the present consumption level as well as to reduce the emission of GHGs by 45 million tonnes by 2010 (The European Parliament and the Council of the European Union, 2002).

1.2.3 Cost Benefit Analysis of ERMs

Several studies have been carried out with a focus on exploring the relationships between cost and ERM application. These projects were geared at improving the knowledgebase associated with various types of ERMs allowing for building owners to gain a better understanding of the possible energy and cost saving options that may be available.

In Caneta Research Inc. (2001), a method for determining the effects of ERMs on the energy consumption of small and large office buildings was developed. The goal of this project was to establish the costs associated with the implementation of retrofit opportunities. This was accomplished by calculating the effects of ERMs on the energy consumption of two different buildings types employing energy consumption modelling software. Building models were developed based on the Model National Energy Code of Canada for Buildings (MNECB) 1997 (National Research Council Canada (NRC), 1997), and were limited to two types, a large building with a floor area of 24,150 m^2 (260,000 ft^2) and a small building with a floor area of 4,200 m^2 (45,000 ft^2). The proposed methodology ranked retrofit measures in terms of simple payback. ERMs were modelled for their effects using the simulation program DOE2.1E (U.S. Department of Energy, 2006) where first, the energy consumption was determined for individual applications and then, using the goal of reducing consumption by 25%, multiple ERMs were simulated. Payback periods were the driving force behind the modelling of multiple retrofits and allowed for the interactive effects of ERMs to be determined.

Caneta Research Inc. (2004) expanded their study to include the application of ERMs to buildings of various ages, allowing for the comparison of the effects on energy consumption based on the type of materials and practices used in the construction of a building. The examination into the effects of a building's construction age was limited to a large building designed in the late 1960's and a small building constructed in the early 1980's. Modelling of the application of ERMs was performed using the simulation tool DOE2.1E and a life cycle cost analysis was used to determine the suitability of retrofit applications. The types of ERMs modelled include building envelope upgrades, HVAC system changes and replacement, and upgrades to the control, pump, and fan systems.

In Marbek Resource Consultants (2000), a plan for reducing the emissions of greenhouse gases, in accordance with the proposed Kyoto protocol, was developed for the Federal Government of Canada. Focus was placed on the eleven largest contributors to the problem. As a result, a plan was developed to determine the capabilities for reducing energy consumption in office buildings. The analysis was divided into the following steps. First, the methodology for accessing office buildings for ERM application was categorized into either a scheme for selecting ERMs based on a simple payback analysis, using a cut off point of 8 years, or a more aggressive approach which employed the use of the maximum acceptable cost willing to be paid per reduced tonne of CO_2 emissions. Second, after choosing the appropriate analysis strategy, buildings were categorized into “archetype” groups based on the characteristics of size and age, then modelled for energy consumption both before and after ERM implementation. Using the building stock information and the archetyping scheme, the Energy Use Intensity (EUI) in kWh/m^2 can then be calculated for a base year of 1998 and a future point of 2010, allowing for the effects of the ERM application strategy to be determined.

A software program entitled RETScreen Clean Energy Project Analysis Software was developed by Natural Resources Canada to determine the implications, both economical and emissions based, of implementing ERMs as well as renewable energy technologies (RETs). ERMs refer to the implementation of devices and equipment which reduce the demand on the power supplied to a building, including improvements to the lighting system, upgrades to the boiler and building envelope enhancements. RETs, on the other hand, are defined as changes to the building that involve the removal of the dependence on non-renewable energy sources. These can include the application of photovoltaic cells for self produced electricity and ground source heat pumps for the supply of natural heating to a building's ventilation system.

The software program developed by RETScreen has five main steps: Energy Modelling, Cost Analysis, GHG Analysis, Financial Summary and Sensitivity and Risk Analysis. Energy modelling is accomplished using basic information about a given building including affected floor area, location, system types and proposed system parameters. Costs are determined from user input cost data for the system being proposed. Greenhouse gas emissions are calculated in one of three methods, simplified, standard and custom. Since GHGs are composed of three main gases, CO_2 N_2O and CH_4, it was proposed that a comparison of each type of gas be performed by first equating the greenhouse effects of each of the gases normalized to those of CO_2 using the factors found in

Table 1.1. The financial summary component determines the total cost and payback associated with a project and included in these calculations are inflation rates, debts and taxes as well as GHG emission reduction credits that may be applicable. GHG credit information is generally applicable on a country by country basis and information on possible credits can be obtained from sources such as the United Nations Framework Convention on Climate Change (UNFCCC) (2006). The sensitivity and risk analysis component assesses the impact of the variability of the key parameters within a project and uses this information to aid in the decision making process (Natural Resources Canada, 2005).

In Coffey (2006), a methodology was developed for assessing the energy efficiency and retrofit potential of office buildings. Focus of the work was divided into three aspects: information collection, calibration and analysis. The collection of accurate and relevant data is vital in the development of a suitable building model, a way of inputting information which is both efficient and easily understood by building managers is essential. Methods for inputting building information have been limited to the use of one of two general modes. First using energy modelling packages such as EE4 (Natural Resources Canada, 2005), eQUEST (Energy Design Resources, 2004) and FEDS (Pacific Northwest National Laboratory, 2002), which are discussed further in Section 2.2, building information can be categorized and subsequently used to determine base level energy consumption statistics. A second method involved the creation of an Excel tool capable of determining the energy consumption of an office building by means of either mathematical formulation or the use of "neural network programming," the energy consumption of a building can then be estimated using known equations of heat transfer combined with the detailed building usage and construction characteristics. As the equations used to determine building consumption were not fully developed it is not possible to examine the validity of this second approach, leaving this methodology of determining energy consumption based on building parameters open to further exploration.

In Fisher & Hand (2006), a method for examining the effects of ERMs on three building types was developed. The focus of the work was expansive and dealt with office, industrial and barrack style buildings. Using the approach of employing energy modelling software to assess the implication of applying ERMs to various types of buildings, the three building models created were analyzed to estimate annual reductions in energy consumption. The objective of the study was to "develop a database of energy savings technologies and measures for government building retrofits with examples of best practices and case-studies." Two different energy simulation tools were employed in this analysis, EnergyPlus and ESP-r, as each program possesses different modelling capabilities. To ensure that equivalent information was being obtained for both software programs, models were first developed using ESP-r then data files were converted into

EnergyPlus compatible formats, simulated again and compared to the result of the ESP-r analysis. Adjustments to the EnergyPlus and ESP-r files were made until the consumption values of the two programs coincided. Cost and technology data was included by examining the estimated costs associated with applying ERMs to each of the three building models developed. Payback periods were determined by dividing the cost of implementation by the estimated annual energy savings (i.e. simple payback). The work involved in applying this methodology is ongoing and the database of the effects on energy consumption of applying a wide variety of ERMs is currently still in development.

As part of the International Energy Agency (IEA), the Energy Conservation in Building and Community Systems (ECBCS) program has developed numerous research projects in the field of energy reduction and cost effective energy efficiency analysis. The IEA ECBCS is currently divided into 50 research Annexes, all of which focus on components ranging from the energy efficiency differences between building types (Office, Institutional, Industrial) to the specific analysis of emerging technologies (Energy Conservation In Buildings And Community Systems, 2007).

In cooperation with the International Energy Agency, IEA ECBCS Annex 36 (2004) worked on the analysis of the application of ERMs in educational buildings. A component of the research performed by Annex 36 was the development of a calculation tool for the evaluation of the many different

ERMs that can be applied to educational buildings such as schools and universities. The calculation tool can be used to assess the most suitable set of ERMs to incorporate This tool, entitled the Energy Concept Advisor (ECA), is composed of four components: Recommendations, Case Studies & Retrofit Measures, Performance Rating and Retrofit Concept. The Recommendations component allows a user to view possible solutions to common issues related to a building's operations including higher than average electrical, heating fuel, and water consumption as well as building specific problems such as air tightness, humidity control and poor insulation. The Case Studies & Retrofit Measures component provides real world examples of the application of the ECA process including the energy consumption before and after retrofit implementation, the actual costs involved and any lessons that were learned in the process of implementing the ERMs. Performance Rating allows a user to enter the energy consumption statistics including floor area and annual fuel consumption for electrical and secondary fuel and provides an instant comparison to the average values for consumption, per unit of floor area, giving feedback on a building's performance. The Retrofit Concept element is the heart of the ECA and is itself composed of three main components: Building Description, Single Retrofit Analysis, and Multiple Retrofit Analyses. The information relating to a building's geometry, age, location, and existing technologies are entered first, allowing for an estimation of the base level energy consumption to be made. This energy consumption is determined using a comparative analysis between a building's specific details to one with similar properties, including size, location, age, constructions, HVAC system properties and lighting technologies. From the base level energy consumption, an analysis of the application of single retrofit measures is performed by determining the possible consumption savings using an alternate set of building variables. The results are displayed graphically allowing for a rapid determination of the benefits received. Expanding on this concept is the application of multiple retrofit measures, which is performed by displaying the linearly added effects of the individual retrofits, to arrive at a total change in consumption. The Annex 36 process has a solid technical backing and with the addition of the numerous case studies, has allowed for the analysis of the ERMs effectiveness. The limitation however, lies in the applicability of this concept to office building analysis, since the database of energy consumption properties and the effects of ERMs are specific to the general design and materials used in the construction of educational buildings.

IEA ECBCS Annex 11 (1987) has already provided an outline of a large database of ERM opportunities that can be applied to office buildings. Each ERM opportunity was categorized based on the building characteristic that was primarily affected. Accordingly, the following categorization scheme was used: Building Envelope, Regulation, Heating, Heating and Cooling, Cooling, Ductwork, Pipe work, Demand Hot Water, Lighting, Electrical Systems and

Miscellaneous. A total of 231 energy retrofit measures were suggested and a segment of this list is presented in Table 1.3 to illustrate the types of ERMs that could be explored.

Table 1.3: Example of ERMs identified in IEA ECBCS Annex 11 (1987)

Retrofit Category/Description
Building Envelope
Add attic insulation
Add insulation to exterior wall externally
Correct excessive envelope air leakage
Install shutters, blinds, shades, screens or drapes
Use double or triple glaze replacement
Regulation
Maintain proper space set points
Air economizer
Conversion to VAV
Heating
Repair or upgrade insulation on boiler/furnace
Replace obsolete heating plant
Use of exhaust air as heat source for heat pumps
Combined Heating and Cooling
Improve capacity control
Replace or upgrade cooling equipment and heat pumps
Air to air heat recovery techniques
Cooling
Raise chilled water temperature and suction gas pressure
Lower condensing water temperature and head pressures
Lighting
Use task lighting
Install more efficient light source
Install lighting control to maximize day light usage
Electrical System/Ductwork/Pipework/Demand Hot Water
High efficiency motors
Reduce air flow rate

1.3 Objective and Scope

A brief review of the literature on the subject of evaluating the effectiveness of ERMs has revealed that there is a variety of strategies available that can be used for determining the effects of ERM implementation in office buildings. All of the approaches proposed in the literature for this analysis consist of three main components: First, a method is used to collect the building information that is subsequently used in the creation of an energy modelling data file; Second, an estimate of the energy consumption is made both pre and post retrofit based on the derived energy model; Third, the effects of the retrofit opportunities on consumption through the iterative modelling of an adjusted simulation file are determined. Using this approach, it is possible to gain accurate predictions of the energy usage characteristics of a building, but the time, effort and background knowledge required to develop and assess the accuracy of each model can be problematic. The user needs to be knowledgeable of the energy simulation software package including its limitations, and needs to carry out the analysis for a large array of office buildings.

It was observed through this review that although a large amount of research has gone into analyzing the effects of ERMs, there are several key factors that require further exploration. Through the modelling of representative buildings, it is possible to determine the base level energy consumption statistics for specific building archetypes as explored in Caneta (2004). Buildings constructed during different eras were found to experience variations in the effects of ERM implementation. On the basis of these two observations, a revised methodology is proposed in this study that adapts the concept of representative building modelling for the development of a database on the effects of ERMs on energy consumption. The goal behind the development of this database is to formulate a set of mathematical equations that can be used for estimating the energy consumption of office buildings based on a set of key variables. This approach will allow for the rapid estimation of a building's energy consumption before and after the implementation of ERMs. By combining the energy calculation model with an economical analysis, a screening methodology can be developed to determine the feasibility of implementing ERMs in office buildings.

1.4 Thesis Outline

Chapter 1 presents a brief summary of the research and methodologies that have been developed to date, and includes an examination of the theories and common practices adopted for the evaluation of ERM applications. Specifically considered were energy modelling, building representation strategies and approaches for cost analyses. Chapter 2 describes, in detail, some of the energy modelling tools that are used today. From a list of more than ten simulation software options, two programs were selected for further evaluation. Data from nine office buildings were used to evaluate the adequacy of the programs in predicting energy consumption.

In Chapter 3, a set of representative buildings were proposed to group into archetypes, many different office buildings for the purpose of modelling. This was proposed in order to generate energy consumption data pertaining to the implementation of ERMs. The energy consumption data, which were generated using EnergyPlus, were used to develop a set of regression equations in Chapter 4. The proposed model has the capability of estimating the energy consumption of an office building based on building properties and characteristics.

The screening methodology is developed in Chapter 5 and it includes the cost of implementing ERMs. In addition, a set of cost equations are given to determine payback periods and the cost effectiveness of implementing ERMs. Chapter 6 provides conclusions as well as suggestions for future research work.

Chapter 2: Energy Modelling: Software Tools and Validation

2.1 Introduction

In order to develop a calculation tool for estimating the energy consumption of a building, one must first select an appropriate energy modelling software package. The modelling package needs to be adaptive to many different office-building configurations, as well as accepted by the industry for its robustness and accuracy in estimating energy consumption. There are a wide variety of software programs currently available which have the capability of modelling the energy consumption of various types of buildings. As such, it becomes necessary to establish the positive and negative characteristics of each in order to make an informed choice of the optimal program to use. A review of 20 different energy modelling programs was performed and each tool was analyzed for the general features pertaining to each of the individual programs (Crawly, et al, 2005). This included an analysis of how building characteristics are defined as well as an examination of how each program handles economic assessments, environmental emissions, weather characteristics and results reporting. Accordingly, five different software packages were initially considered for application in this analysis, namely, eQUEST, ESP-r, EE4, EnergyPlus and FEDS. eQUEST was developed by the California based "Energy Design Resources Program" in cooperation with the US Department of Energy and has been approved for use by the California Energy Commission (Energy Design Resources, 2004). ESP-r, used primarily in Europe and Asia (U.S. Department of Energy, 2006), was developed by the University of Strathclyde's Department of Mechanical Engineering. EE4 was developed and used extensively by Natural Resources Canada. EnergyPlus was developed by the U.S. Department of Energy and used by an extensive audience for modelling the energy consumption of buildings. FEDS was developed by the Pacific Northwest National Laboratory in cooperation with the U.S. Department of Energy. Details and evaluation of the five software programs are presented in this chapter.

2.2 Examination of Energy Modelling Tools

The five energy simulation programs selected as potential energy simulation tools for this study are examined for their suitability. The criterion for program selection are: 1) ease of use; 2) acceptance by the industry; 3) pre and post processing capabilities; and, 4) accuracy of the predictions.

2.2.1 eQUEST (Energy Design Resources, 2004)

eQUEST is a software program which was developed around the popular DOE2.1E energy simulation tool (U.S. Department of Energy, 2006) and consists of three main processing stages:

Stage 1 – A Building Simulation Wizard, used to create a detailed description of the building in question. It is composed of two different building creation tools, Schematic Design and Design Development. The Schematic Design component creates a description of the building using various characteristics, including HVAC description, wall construction, and general sizing parameters. The Design Development component is more comprehensive and allows for the input of detailed information, including in-depth internal loads and HVAC system descriptions.

Stage 2 – The Energy Efficiency Measures Wizard which allows for the quick analysis of the energy savings attained by applying various changes to the energy profile of a building.

Stage 3 – Presentation of graphical results which are combined with the DOE2.1E energy simulation tool.

In order for eQUEST to provide useful simulation results of a building, a large amount of information about the architectural design, usage, and central system must be known. eQUEST functions by taking the data input by the user and creates a DOE2.1E model of the building. This model is then run through a DOE2.1E analysis in order to assess a building's energy consumption rate. These rates can be divided on a month-to-month basis and are presented with a clear indication of the sources of the energy consumption, i.e. the energy consumption is broken down into the individual components such as lighting use, ventilation equipment, space heating/cooling and water temperature controls. This segregation of the energy consumption is quite useful since it can make apparent the components which may be consuming higher than desired levels of electricity or gas. As a result, the number of choices for possible retrofit selection may be refined to focus primarily on these problem areas.

One component of interest within the eQUEST package is the Energy Efficiency Measure Tester. This component allows the user to adjust various characteristics of the building model such as, lighting power density or wall insulation, and then instantly view the effects that these changes have on energy consumption. It functions by altering the values in the initial building model and performing subsequent DOE2.1E runs. This component can provide further detail when the parametric element is used. It allows for parametric analysis of numerous retrofits to be performed and analyzed simultaneously. This more detailed analysis makes it possible to test a large number of building retrofits and determine the combination of applications which would result in the lowest energy consumption rates.

There are three main advantages to the eQUEST program. First, it utilizes a simple user interface which allows building models to be created rapidly even where limited information is available. This aspect is highly attractive since there may be a large number of buildings where only a partial list of attribute details are available. Second, the DOE2.1E simulation engine on which eQUEST is based is widely accepted for modelling the energy consumption of office buildings.

Finally, the Energy Efficiency Measure Tester included allows for a rapid determination of the effect of both single and multiple retrofit applications.

The primary disadvantage is related to the DOE2.1E simulation component on which eQUEST is based. Energy consumption of a building is determined using a sequential time step approach. As such, the loads are determined by calculating the heat balance of the zones within a building, these loads are then utilized to assess the output requirements of the HVAC system. This modelling approach lacks feedback to the original heat balance calculation which can result in energy consumption estimations that may not accurately represent the demand requirements (Lawrence Berkeley National Laboratory, 2006). The ability of the simulation engine DOE2.1E to model newer more complex ERMs may be hindered by the fact that the last update was published in 1998 (U.S. Department of Energy, 2006).

2.2.2 **ESP-r** (Energy Systems Research Unit, 2002) (Hand, 2006)

ESP-r is a modelling and simulation tool that is capable of simulating and assessing a building's thermal performance, energy usage and gaseous emissions by using information associated with a building's environmental control systems as well as the construction materials used. The processing algorithm used by ESP-r is illustrated in Figure 2.1. ESP-r does not require a large amount of detailed building specifications to perform an analysis and the information required by the program includes the following:

Geometrical data – Dimensions of walls, number of floors, etc.

Scheduling information – Hours and days of operation

Construction materials

Environmental controls – Heating patterns and cooling demands

Plant information – Heating, cooling, water, and ventilation systems

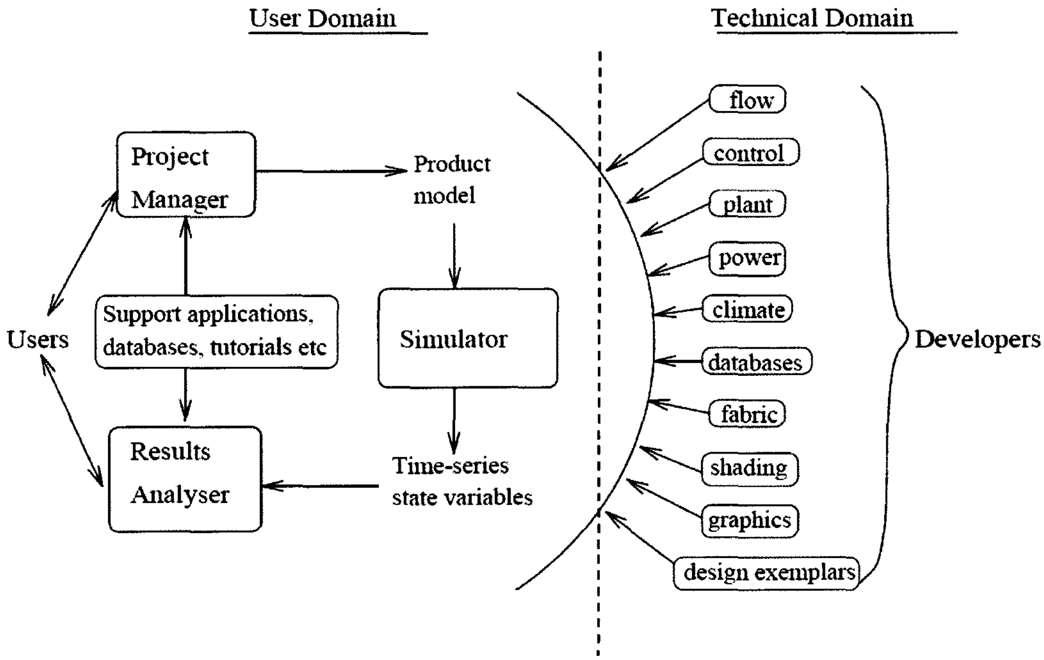

Figure 2.1: ESP-r processing algorithm (Energy Systems Research Unit, 2002)

ESP-r is capable of simulating both the energy consumption of a building as well as the fluid flow components. The modelling of a building is defined by first dividing the building up into zones which possess similar temperature, systems, and airflow characteristics. Zones are then defined by their geometric characteristics, construction materials and usage profiles. These three categories are essential in order for ESP-r to perform a simulation of a building. There are also many optional components which can be modelled in ESP-r. By including information on utilities, shading/insulation, blind/shutter control, air flow, casual gains, convection coefficients and transparent multi-layered construction, the level of detail of the output is increased.

As seen in Figure 2.1, there are two main components to the running of ESP-r, a user interface side in which project and building information can be entered into the system and a technical domain where the calculation modules reside. The project management side of the program appears to be quite diverse in its range of manipulation and it can be used in conjunction with the user interface side to allow for the definition of building components to be made and can provide the user with pre-developed building databases.

The zones within the building are connected by modelling the network which supplies the electrical, water and airflow components. In order for the airflow components to be simulated, information about the building leakage distribution must be known.

The advantages of ESP-r lie in its ability to model a building without the need for an overly complex building data file to be created first. Building geometry can be defined using computer aided design tools (CAD) and the models which are developed can be extracted to conform to alternative energy simulation tools such as EnergyPlus. Also, the calculation strategy employed is adaptive enough to handle many different types of building systems and as such can handle the numerous ERMs to be studied.

The input strategy is a major deterrence in the use of ESP-r. The creation of building data files is not an overtly user friendly process as it requires the development of a text based building definition. As well, although the usage of ESP-r is primarily focused on the European market it is adaptive enough to handle Canadian building specifications.

2.2.3 EE4 (Natural Resources Canada, 2005)

This program was developed primarily to assess the energy performance of a building's design while ensuring compliance with the Model National Energy Code of Canada for Buildings 1997 (National Research Council Canada (NRC), 1997). EE4 uses a graphical interface in which building information is input using a series of "Building Trees" which are organized in a hierarchical format. The building information handled by EE4 includes some of the following:

Plant:	Heating, cooling and water systems
System:	HVAC system types, and fan information

Zone:	Zone heating, cooling, airflow and lighting and occupancy schedules
Space:	Floor area, occupancy density, outdoor air flow rates, process and receptacle loads, and demand hot water loads
Envelope Components:	Wall, floor, roof, below grade and interior partition areas and construction types, specific light fixture characteristics, windows, doors, and skylights

After inputting all desired building information, EE4 creates two input files, one which is used to determine compliance with the MNECB and the other is used in a DOE2.1E simulation of the system. After the simulation is run, the results are then displayed in tabular format.

An advantageous aspect of EE4 is that it allows for the manual modification of various building components which is useful when specific energy efficiency retrofits are studied. The use of EE4 is wide spread in the Federal administration and commercial industry sectors within Canada and is therefore known to be accepted for its building modelling capabilities.

The disadvantages in EE4 are similar to those inherent to DOE2.1E and not related to the system specific design strategy of the program but to the limitations associated with the sequential simulation engine.

2.2.4 EnergyPlus (Lawrence Berkeley National Laboratory, 2006)

EnergyPlus is an energy analysis and thermal load simulation program that uses many modelling methods similar to those developed by programs such as Building Loads Analysis and System Thermodynamics (BLAST) and DOE2.1E. EnergyPlus calculates the heating and cooling loads necessary to maintain a user defined thermal control set-point from the description of a building and it includes construction, usage, HVAC systems, external environment values, thermostatic control set-points and type of central power plant.

The program schematic illustrated in Figure 2.2 demonstrates how EnergyPlus uses an integrated solution manager to determine the energy consumption of a building based on the inputs provided by the user. It is composed of individual calculation modules which are used to determine all aspects of a building's energy consumption components.

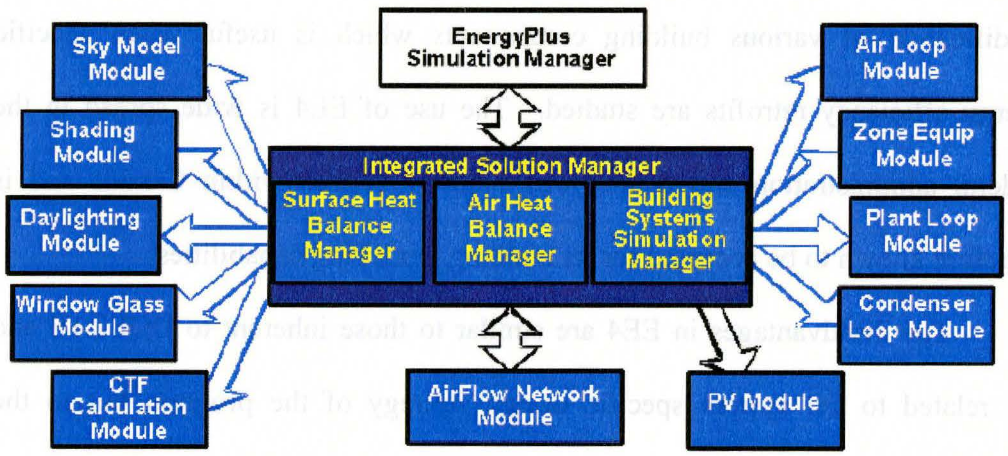

Figure 2.2: EnergyPlus program schematic (Lawrence Berkeley National Laboratory, 2006)

EnergyPlus uses the concept of integrated simulation to perform its analysis on building information. Simulations are divided into the calculations of three major building components which are analyzed simultaneously: Surface Balance, Air Heat Balance and Building Systems. This parallel approach to the simulation results in a quicker and more accurate solution. A greater level of accuracy implies that the results produced are more physically realistic. The integrated approach is one of the key aspects which separate EnergyPlus from other simulation tools such as BLAST and DOE2.1E. Figure 2.3 illustrates how EnergyPlus uses information during all phases in the calculation process to model a building's behaviour.

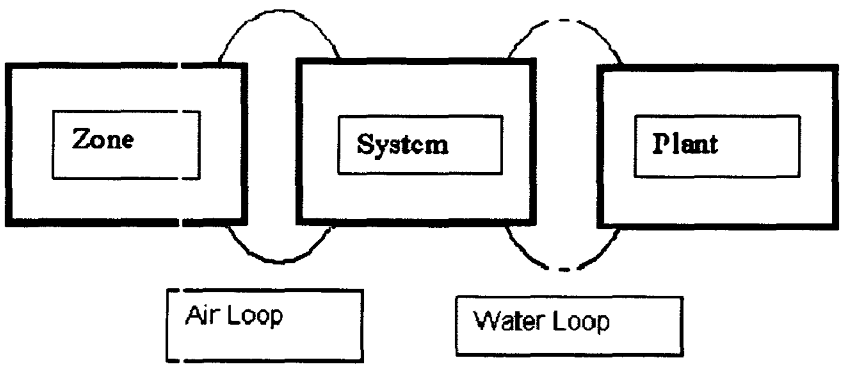

Figure 2.3: Schematic of Simultaneous Solution Scheme (Lawrence Berkeley National Laboratory, 2006)

Programs such as BLAST and DOE2.1E simulate all essential aspects of a building such as occupancy, equipment zones, air handling systems, and the central plant using a sequential simulation process. This sequential approach to analyzing a building's energy consumption is typically best suited to systems with well-defined supply and demand characteristics without the need for external factors to be taken into consideration. This type of design lacks feedback from all stages in the calculation. An example of this inadequacy is the simulation behaviour when performing a heat balance on a specific zone of a building. Information is passed on sequentially to calculate the heating and cooling requirements, which are then used to determine the necessary load on the air handling system(s). However, the information corresponding to the system loads is not re-entered into the calculation of the original heat balance performed and may result in values which don't predict the actual physical results.

An aspect of interest of EnergyPlus as a simulation tool is the method it uses to input data. Detailed information of a building's description and system components is entered using a text file written with all information presented in code form. The methods for creating this input file are quite diverse and can be performed through the use of many third party programs and user interfaces. For example ESP-r described in section 2.2.2, can be used to create input files for EnergyPlus. Although the input method may be time-consuming it is very adaptive to the sometimes limited information available for a given building.

EnergyPlus' advantages lie in its capability for modelling a large number of different building configurations, making it highly adaptive to the various types of ERMs which may be studied. The simultaneous simulation strategy employed may provide a more realistic estimation of the actual building heat gain distribution. One of the more notable benefits to the high degree of adaptability of EnergyPlus is reflected in the capacity for developing and applying specific weather characteristics to building models as Canadian climate data is limited in the EnergyPlus and DOE databases.

The input strategy used to develop EnergyPlus simulation files is a large drawback to the usability of the program. The definition of building geometry and material properties is complex and time consuming depending largely on the complexity of the building model.

2.2.5 FEDS (Pacific Northwest National Laboratory, 2002)

The primary function of FEDS is not to only calculate the actual energy consumption of a building, but instead to suggest retrofit opportunities that may reduce energy demands. FEDS takes minimal information about a building and creates a corresponding DOE2.1E data file. The data file created is run through several analyses where implementations of numerous retrofit possibilities are assessed. These retrofit scenarios are then analyzed for cost and energy savings and a list of optimal retrofit possibilities is presented.

The FEDS process is divided into the following steps: Archetype Classification, Minimum Detailed Information Collection, Maximum Detailed Information Collection, Energy Consumption Estimation and Retrofit Assessment.

Buildings are first grouped into an archetype category, the purpose of which is to minimize the number of calculations involved when large databases of buildings are examined. Building sets can consist of single and multiple grouping strategies and are usually broken down into vintage and sizing archetypes. The "Minimum Detail Requirements" component allows for basic building information to be entered and is limited to the percentage use of the heating, cooling and hot water fuel sources and the lighting technologies present. FEDS uses this minimum building information, combined with the archetyping scheme and location, and makes assumptions regarding a building's construction and HVAC characteristics based on an extensive internal database. Following the input of a building using the minimum detailed level of information, "Maximum Detail Mode" becomes available allowing for adjustments to be made to the numerous assumption that were made initially. Estimations about the energy consumption and the effects retrofit changes have on this consumption are then determined by employing an iterative calculation scheme in which the maximum reduction in the consumption of energy is used as the goal for the iteration procedure.

A useful aspect is FEDS' ability to suggest optimal retrofit options while rapidly determining energy consumption. The ability of FEDS to rapidly model both individual buildings as well as multiple buildings grouped into archetype sets which possess common HVAC system types, wall constructions, age and sizes, is also an attractive feature. The rapid definition of building properties, combined with a large database of building material and component specifications, allows for estimations of consumption to be made without performing complex time step based energy simulations.

FEDS' more simplistic input method limits its ability to model complex ERMs. Furthermore, FEDS lacks the ability to define weather characteristics beyond those included in the program database, as such restricting its applicability to Canadian buildings. Finally, the detail of the output of building consumption information is limited to annual estimations, thus reducing the ability to examine monthly energy consumption patterns.

2.2.6 Summary

From the evaluation of the features of the five energy modelling software packages and recalling the selection criteria, it was determined that EnergyPlus and FEDS are worthy of further examination. EnergyPlus was selected because it was found to be the most developed and complete software tool in comparison to others that employ ESP-r and DOE2.1E calculation engines. On the other side, FEDS was chosen because it provides the user with an easy and quick method, based on the minimum detail requirement, to calculate the energy consumption and iteratively determine the effectiveness of energy retrofit measures. The next step in the evaluation of these two programs was carried out by comparing the calculated results of energy consumption to actual data collected for nine office buildings.

2.3 Case Studies

In order to further validate the adequacy of the two modelling programs, EnergyPlus and FEDS, comparisons between the simulated and measured energy consumption of existing buildings was performed. Information on both the energy consumption characteristics and detailed building traits were gathered for nine office buildings located within the province of Quebec.

In order to develop simulation models, information on these nine buildings was first divided into groups. Available data was separated into five general building categories: building envelope, ventilation system type, electrical and secondary fuel systems and occupancy characteristics. The vintage of a building can be used to make estimations about construction materials and Heating Ventilation and Air Conditioning (HVAC) system configurations. A building's size (gross or rentable area), number of floors and location can provide links to many other characteristics such as general design and operational traits. This includes envelope materials, heating and cooling system types, electrical equipment loadings as well as any occupancy characteristics it may have been designed for. Table 2.1 gives the year of construction for each of the buildings, beginning with the oldest. The labelling system used will aid in the discussion to follow. The construction dates for all nine buildings cover a wide range of years (1931 to 1986). This broad period is beneficial because it will aid in exposing weaknesses in both the simulation software and the screening methodology proposed.

Table 2.1: Building label and year of construction

Building	*Year of Construction*
CS1	1931 – 1933
CS2	1958
CS3	1958 – 1960
CS4	1963 and 1970
CS5	1970
CS6	1974
CS7	1976
CS8	1981
CS9	1985 – 1986

2.3.1 Building Data

Dividing each building into separate key components allows for a better understanding of the type of building system possessed by each, and can expose any interactivity that may be present. Table 2.2 illustrates the categorization method that was used, and contains a brief description of each grouping. Data used to define each of the buildings were provided by (Public Works and Government Services Canada, 2007). Assumptions made to account for any information that was lacking within this report were based on other documents, such as the guides published by American Society of Heating Refrigeration and Air-Conditioning Engineers (ASHRAE) and the American Society of Heating and Ventilating Engineers (ASHVE) (American Society of Heating Refrigeration and Air-Conditioning Engineers. Inc., 1962, American Society of Heating Refrigeration and Air-Conditioning Engineers. Inc., 1977, American Society of Heating Refrigeration and Air-Conditioning Engineers. Inc., 1961, American Society of Heating and Ventilating Engineers, 1939, American Society of Heating and Ventilating Engineers, 1950). To be specific, the following parameters were not usually defined in the reported documents; infiltration rate, chiller Coefficient of Performance (COP = ratio of the output of cooling energy to the work energy input), boiler efficiency, supply hot water consumption rate, occupancy density, floor heights/total volume, geometry, and equipment and appliance loads. To overcome this problem it was assumed that these buildings were designed and built in accordance with the standards of the time. Thus knowing the date of construction, one was able to determine the most likely values for these variables. Furthermore, some of the variables were assumed constant for all nine buildings and are given in Table 2.3.

Table 2.2: Building characteristics

Category	*Description*
Building envelope	• U-values and construction characteristics of the walls, roof and windows • Insulation properties and characteristics of below grade floors • Gross area • Volume
Distribution	• Type of distribution system present, CAV, VAV • Capacities and air flow volumes • Infiltration rates
Electrical Systems	• Air conditioning and cooling systems • Computer and appliance loads • Elevator loads • Service hot water equipment (If applicable) • Miscellaneous
Secondary Fuel Systems	• Heating systems type and capacity • Service hot water equipment (If applicable)
Occupancy	• Occupancy schedule • Occupancy density • Temperature set-points • Fresh air requirements • Weather and location statistics

Table 2.3: Building data assumed to be constant

Building Parameters	***Value***
Minimum fresh air per person (l/s/person)	10
Temperature set-point for heating (°C)	21.1
Temperature set-point for cooling (°C)	23.3
Luminescence (Lux)	500
Average Floor Height (m)	3.5
Below Grade Wall Details	No Insulation
Perimeter Floor Details	No Insulation
Service Hot water Consumption (l/day/person)	3.8

A brief description of the nine case study buildings is given next. Included with each is a depiction of the building simulation model which was created for use in EnergyPlus and FEDS. To develop the EnergyPlus simulation files, a third party pre-possessing tool "DesignBuilder" was used (DesignBuilder, 2006). DesignBuilder allows for rapid development of the complex EnergyPlus input files.

2.3.1.1 Building CS1

Building CS1 was constructed between 1931 and 1933 and possesses an area of 59,185 m^2. Its early vintage means that it will be used to represent the oldest building archetype that exists in the case study catalogue. The building details are summarized in Table 2.4. It shows that the percentage of windows and U-values for the envelope materials were modelled using assumed quantities. This was due to the lack of information present within the reported documents.

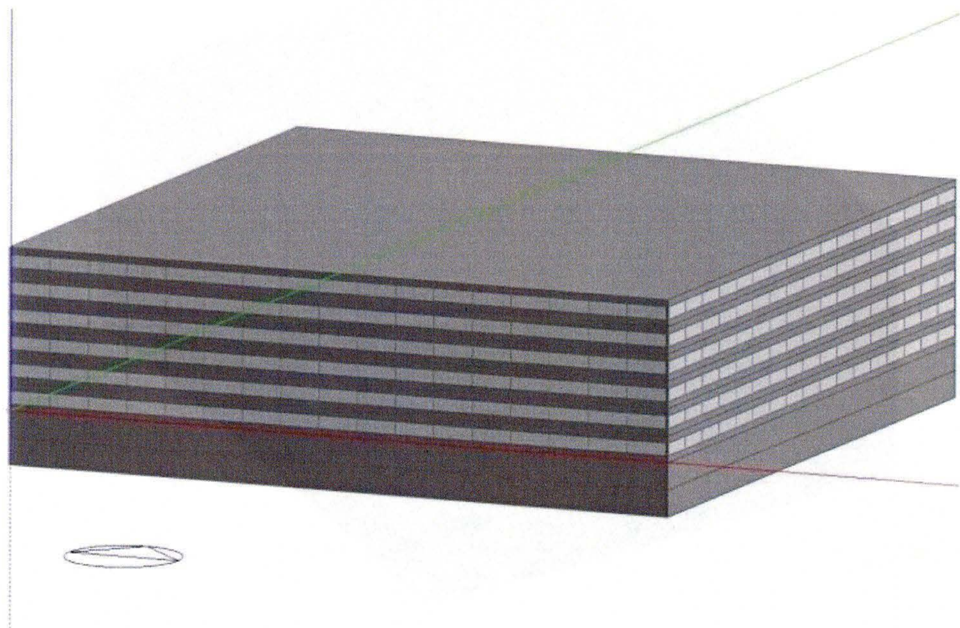

Figure 2.4: Grapical representation of the model used to simulate energy consumption of Building CS1

2.3.1.2 Building CS2

Building CS2 was constructed in 1958 and possesses an internal floor area of 12,184 m^2. Two natural gas powered steam boilers provide the heat for the building and a direct expansion chiller cools the air in the summer. Details of the building are given in Table 2.4.

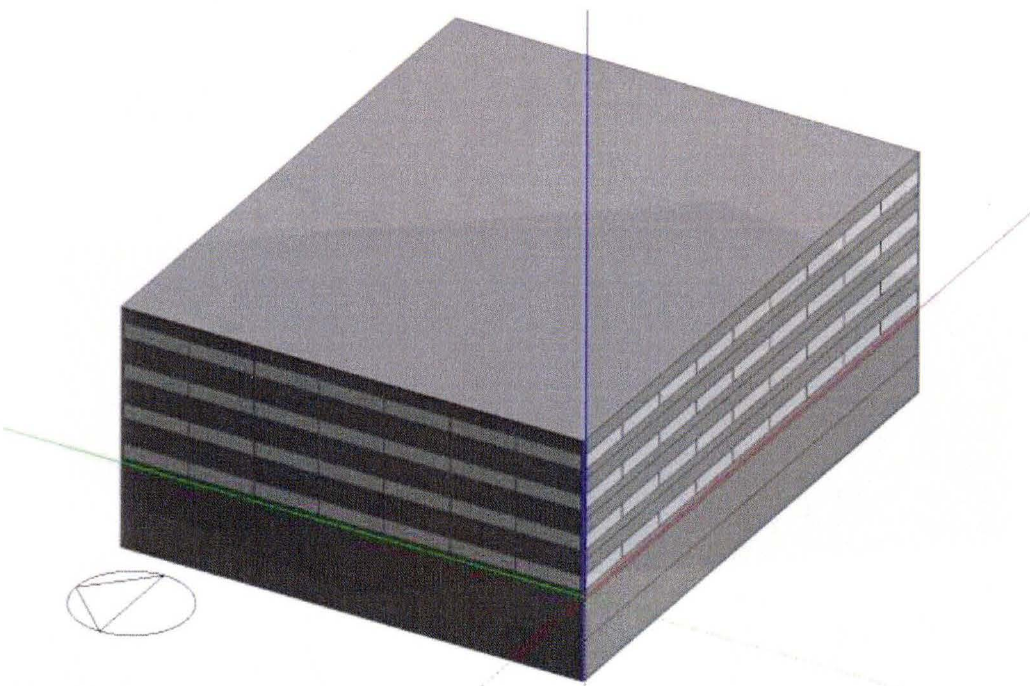

Figure 2.5: Grapical representation of the model used to simulate energy consumption of Building CS2

Table 2.4: General Building Information: Buildings CS1 and CS2

Characteristic	*Building CS1*	*Building CS2*
General Information		
Vintage	1931- 1933	1958
Number of Floors	5 above grade + 2 below	4 above grade + 2 below
Gross Area (m^2)	59,185	12,184
Gross Volume (m^3)	207,148	46,644
Building Envelope		
Walls	brick/terracotta, granite/terracotta	granite panelling and brick
Roof	Elastomer DL membrane	granite panelling
Windows	double glazed	double glazed
Windows to Wall (%)	40	20
U-values (W/m²•C)		
Walls	0.55 [1]	0.342
Roof	0.47 [1]	0.346
Windows	3.2 [1]	2.89
Infiltration Rate (ach)	0.1 [2]	0.8 [2]
Distribution System		
Description	Combination AHU and Pumps	Combination AHU and Pumps
Electrical Systems		
Lighting (W/m^2)	11.5	8.0
Equipment (W/m^2)	40 [2]	20
Chiller Type	Chiller Water	Direct Expansion
Capacity	3830 kW	50 Tons
COP	1.73 [2]	5.2 [2]
Secondary Fuel Systems		
Boiler Fuel	Natural Gas	Natural Gas
Capacity	5690 kW	2(150HP)
Type	Hot water	Hot water
Efficiency	0.65 [2]	0.66
Service Hot Water Fuel	Electricity	Electricity
Occupancy Characteristic		
Occupancy Schedule	8:00 – 18:00	6:30 – 17:30
Density (m^2/person)	20 [1]	30
System Schedule	Constant Operation	18°C Setback, Off Eve. & WE

1 American Society of Heating and Ventilating Engineers, 1939

2 Value adjusted to optimize consumption results

2.3.1.3 Building CS3

Building CS3 was constructed between 1958 and 1960. It is composed of 12 storeys including 2 below grade. A natural gas powered steam boiler provides the heat for the building and a chilled water system provides cooling in the summer. Details of the building are given in Table 2.5.

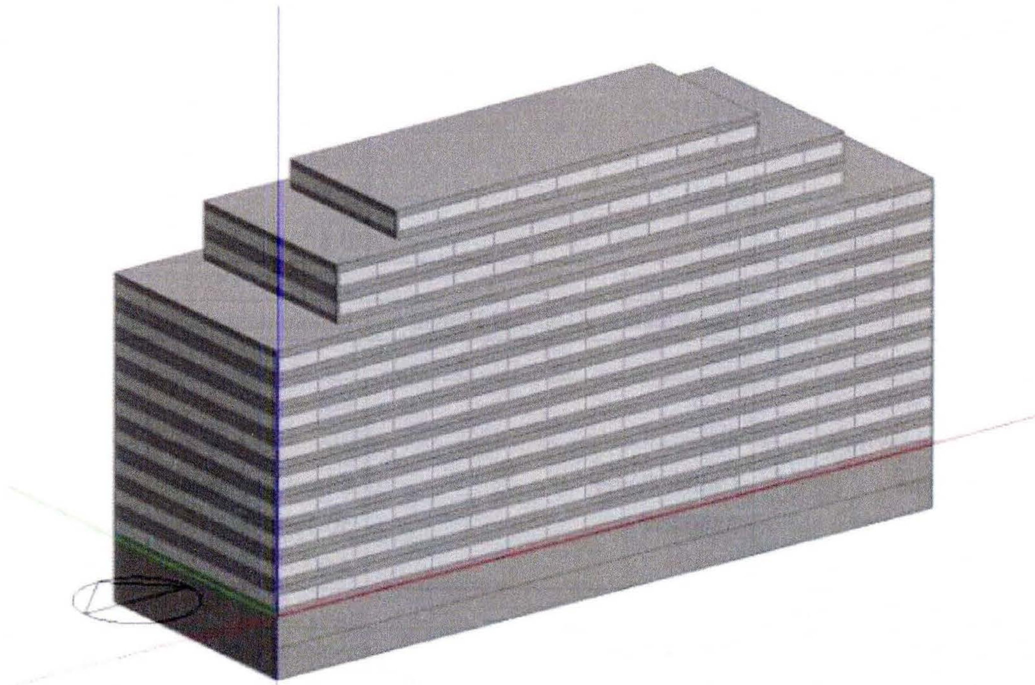

Figure 2.6: Grapical representation of the model used to simulate energy consumption of Building CS3

2.3.1.4 Building CS4

Building CS4 is composed of two separate structures that are connected through the use of a basement level access way. The two buildings were constructed at different times. The first was built in 1963 and it possesses two floors above ground and one below and consists of 3,732 m^2 of floor space. The second building built in 1970, is composed of five floors above ground and one floor below and has 7,928 m^2 of floor space. The key point to note for these buildings is that although they are two separate structures, they are both fed by the same heating and cooling system allowing the two buildings to be modelled as one. Details of the building are given in Table 2.5.

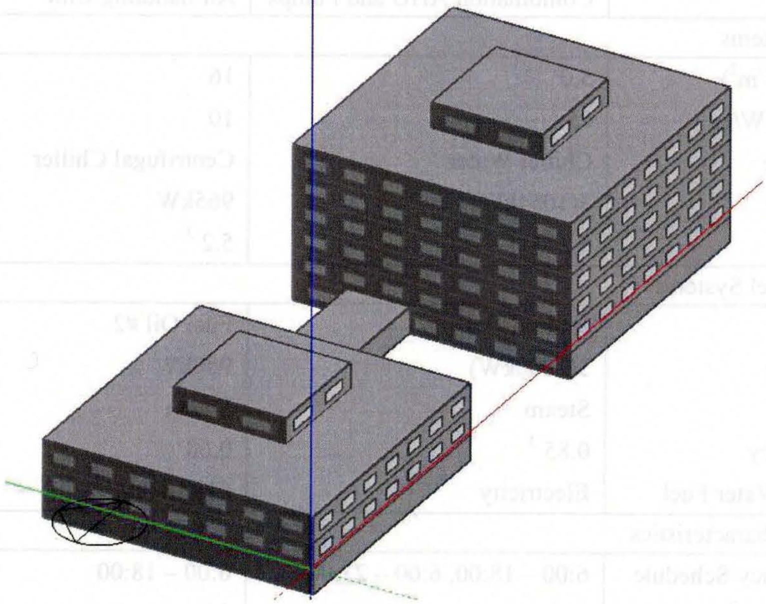

Figure 2.7: Grapical representation of the model used to simulate energy consumption of Building CS4

Table 2.5: General Building Information: Buildings CS3 and CS4

Characteristic	*Building CS3*	*Building CS4*
General Information		
Vintage	1958 - 1960	1963 and 1970
Number of Floors	10 above grade and 2 below	2+ 5 above grade and 1 below
Gross Area (m^2)	36,700	11,760
Gross Volume (m^3)	128,450	41,160
Building Envelope		
Walls	Brick, granite/ Gypsum panels	Brick on Concrete Block
Roof	Built-up Concrete roofing	Built-up Concrete roofing
Windows	Double glazed	Double glazed
Windows to Wall (%)	40	24 and 27
U-values (W/m^2•C)		
Walls	0.61	0.48
Roof	0.55	0.289
Windows	3.57	3.44
Infiltration Rate (ach)	1 [3]	1 [3]
Distribution System		
Description	Combination AHU and Pumps	Air handling Unit
Electrical Systems		
Lighting (W/m^2)	5.0	16
Equipment (W/m^2)	25 [3]	10
Chiller Type	Chiller Water	Centrifugal Chiller
Capacity	3(1054kW)	965kW
COP	5.2 [3]	5.2 [3]
Secondary Fuel Systems		
Boiler Fuel	Natural Gas	Fuel Oil #2
Capacity	3(2000kW)	980kW
Type	Steam	Steam
Efficiency	0.85 [3]	0.60
Service Hot Water Fuel	Electricity	Electricity
Occupancy Characteristics		
Occupancy Schedule	6:00 – 18:00, 6:00 – 23:00	6:00 – 18:00
Density (m^2/person)	43.2	25
System Schedule	No Setback, Off Eve. & WE	No Setback, Off Eve. & WE

3 Value adjusted to optimize consumption results

2.3.1.5 Building CS5

Built in 1970, Building CS5 primarily houses office space but also has a small post office operating within it. The building has an interior surface area of 11,185 m^2 spread over 13 floors. Details of the building are given in Table 2.6.

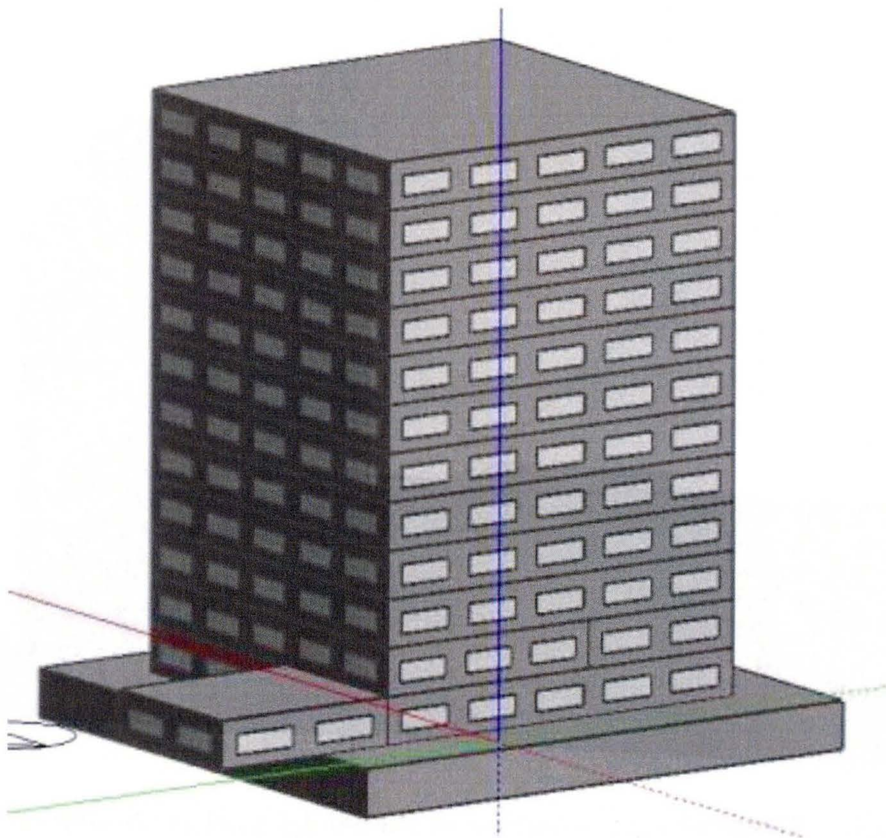

Figure 2.8: Grapical representation of the model used to simulate energy consumption of Building CS5

2.3.1.6 Building CS6

This building was constructed in 1974. It is built primarily out of reinforced concrete and has a rough area of 24,600 m^2 divided into a combination of 4 shared levels and a 12 story office tower. Details of the building are given in Table 2.6.

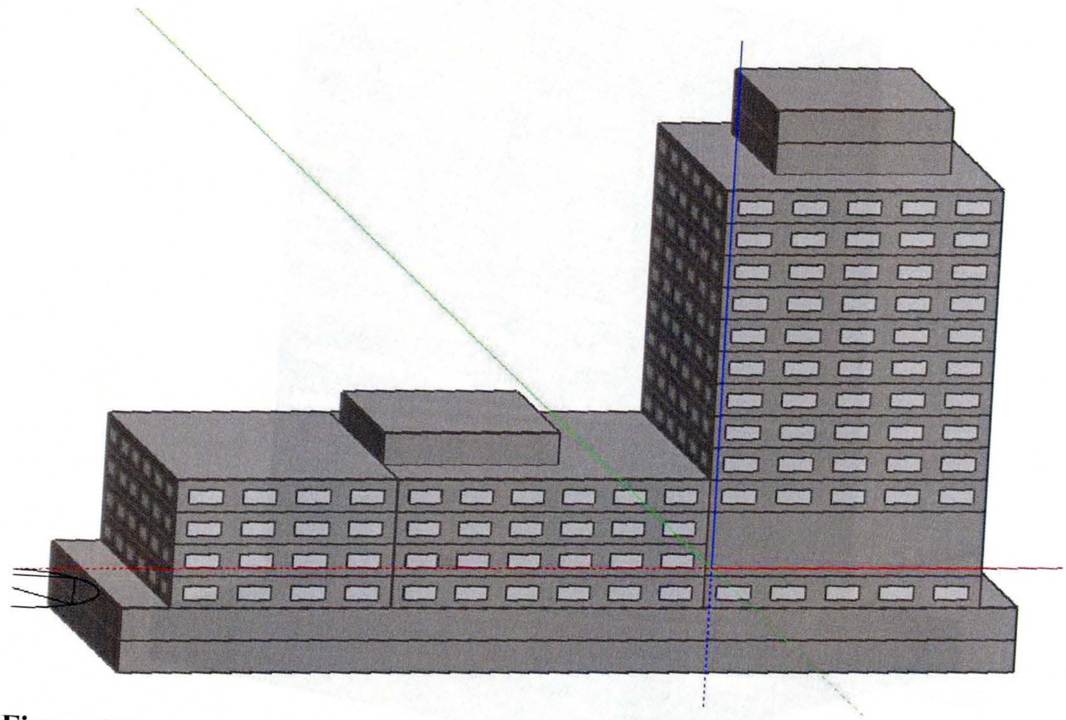

Figure 2.9: Grapical representation of the model used to simulate energy consumption of Building CS6

Table 2.6: General Information: Buildings CS5 and CS6

Characteristic	***Building CS5***	***Building CS6***
General Information		
Vintage	1970	1974
Number of Floors	12 Above ground and 1 Below	12, 4 above ground + 2 Below
Gross Area (m^2)	11,185	24,600
Gross Volume (m^3)	39,148	86,100
Building Envelope		
Walls	Concrete on Concrete Blocks	Concrete on Concrete Blocks
Roof	Elastomer/ Granite Flagstones	Built-up Concrete
Windows	Double Glazed	Double Glazed
Windows to Wall (%)	40 [4]	24
U-values (W/m^2•C)		
Walls	0.278	0.43
Roof	0.356	0.289
Windows	3.33	2.78
Infiltration Rate (ach)	0.95 [5]	0.4 [5]
Distribution System		
Description	Combination AHU and Pumps	Combination AHU and Pumps
Electrical Systems		
Lighting (W/m^2)	8.44	17.5
Equipment (W/m^2)	20 [5]	55 [5]
Chiller Type	Chiller Water	Absorption Cooler
Capacity	248 Tons	2263kW
COP	5.2 [5]	5.2 [5]
Secondary Fuel Systems		
Boiler Fuel	Natural Gas	Fuel Oil #2
Capacity	100BHP	2(2451)kW
Type	Hot Water	Steam
Efficiency	0.70 [5]	0.65
Service Hot Water Fuel	Electricity	Electricity
Occupancy Characteristics		
Occupancy Schedule	6:00 – 18:00	6:00 – 18:00
Density (m^2/person)	43.2	38
System Schedule	No Setback, Off Eve. & WE	No Setback, Off Eve. & WE

4 American Society of Heating Refrigeration and Air-Conditioning Engineers. Inc., 1977

5 Value adjusted to optimize consumption results

2.3.1.7 Building CS7

Building CS7 was built in 1976 and is composed of office space, conference rooms, data processing facilities and storage. It has an internal area of approximately 12,322 m^2 distributed over 4 floors. Details of the building characteristics are given in Table 2.7.

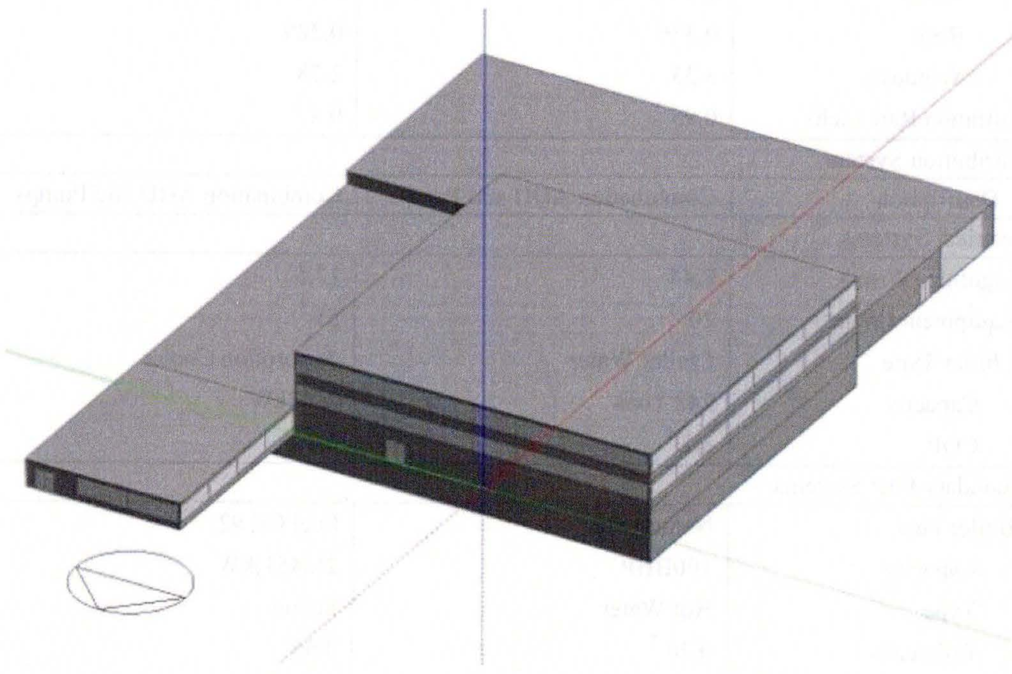

Figure 2.10: Grapical representation of the model used to simulate energy consumption of Building CS7

2.3.1.8 Building CS8

Building CS8 described in Table 2.7 was built in 1981 and has an area of approximately 20,000 m^2. Office space comprises 90% of the usable space within the building. The heating and cooling systems of this building are fed by natural gas and electricity, respectively.

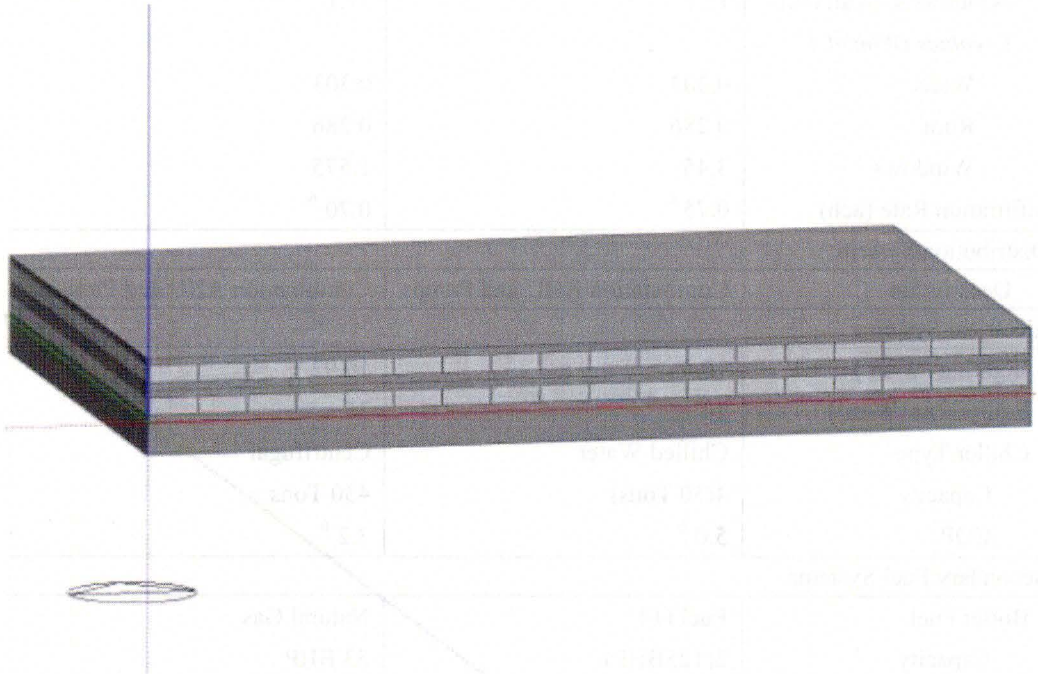

Figure 2.11: Grapical representation of the model used to simulate energy consumption of Building CS8

Table 2.7: General Information: Buildings CS7 and CS8

Characteristic	*Building CS7*	*Building CS8*
General Information		
Vintage	1976	1981
Number of Floors	3 above ground + 1 below	2 above ground + 1 below
Gross Area (m^2)	12,322	19,510
Gross Volume (m^3)	43,127	68,285
Building Envelope		
Walls	Prefabricated Concrete	Brick on Concrete Block
Roof	Membrane/asphalt and gravel	Concrete flagstones on steel
Windows	Double Glazed	Double Glazed
Windows to Wall (%)	17.7	37.1
U-values (W/m^2•C)		
Walls	0.303	0.303
Roof	0.286	0.286
Windows	3.45	1.575
Infiltration Rate (ach)	0.75 [6]	0.70 [6]
Distribution System		
Description	Combination AHU and Pumps	Combination AHU and Pumps
Electrical Systems		
Lighting (W/m^2)	16.4	10.92
Equipment (W/m^2)	20	36
Chiller Type	Chilled Water	Centrifugal
Capacity	4(50 Tons)	430 Tons
COP	5.0 [6]	3.2 [6]
Secondary Fuel Systems		
Boiler Fuel	Fuel Oil	Natural Gas
Capacity	2(125BHP)	53 BHP
Type	Hot water	Hot Water
Efficiency	0.65	0.60
Service Hot Water Fuel	Electricity	Electricity
Occupancy Characteristics		
Occupancy Schedule	8:00 – 18:00	6:00 – 18:00, 6:00 – 24:00 (3 mo)
Density (m^2/person)	70.4	20
System Schedule	Constant Operation	No Setback, Off Eve. & WE

6 Value adjusted to optimize consumption results

2.3.1.9 Building CS9

Building CS9 is the only building in the case study set which has electricity as its only source of fuel. Its small footprint of 3,456 m^2 is heated by a radiant hot water system and a DX Chiller provides air conditioning in the summer. Detail of the building characteristics are given in Table 2.8

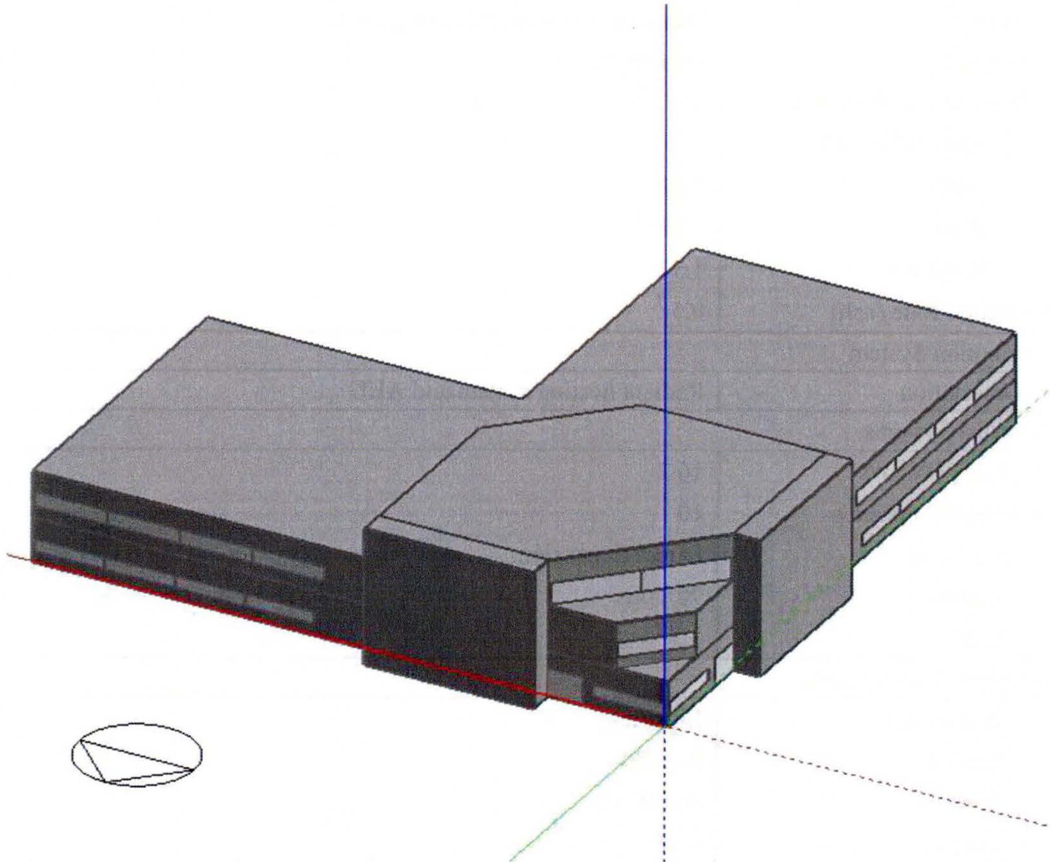

Figure 2.12: Grapical representation of the model used to simulate energy consumption of Building CS9

Table 2.8: General Information: Building CS9

Characteristic	*Building CS9*
General Information	
Vintage	1985 – 1986
Number of Floors	2 above grade
Gross Area (m^2)	3,456
Gross Volume (m^3)	12,096
Building Envelope	
Walls	Anodized Aluminum
Roof	Membrane with asphalt and gravel
Windows	Double glazed
Windows to Wall (%)	30
U-values ($W/m^2 \cdot C$)	
Walls	0.213
Roof	0.284
Windows	1.57
Infiltration Rate (ach)	0.5 [7]
Distribution System	
Description	Radiant heating system and AHU
Electrical Systems	
Lighting (W/m^2)	16.2
Equipment (W/m^2)	10 [7]
Chiller Type	Direct Expansion
Capacity	90 Tons
COP	3.5 [7]
Secondary Fuel Systems	
Boiler Fuel	Electricity
Capacity	246.5kW
Type	Hot Water
Efficiency	0.95 [7]
Service Hot Water Fuel	Electricity
Occupancy Characteristics	
Occupancy Schedule	8:00 – 18:00
Density (m^2/person)	20
System Schedule	Setback 18°C, Off Eve. and Weekends

7 Value adjusted to optimize consumption results

2.3.2 Energy Consumption

Energy consumption data which are vital in the validation of energy simulation programs, for each of the nine buildings, was obtained from the PWGSC. Information was listed based on fuel source, period of consumption, consumption in kWh, power, percent utilization and occasionally cost per kWh.

2.3.3 Energy Consumption Simulations

The simulation results were presented in two different methods; monthly and annually. EnergyPlus permits the presentation of the consumption values monthly and annually where as the Facility Energy Decision System (FEDS) only presents the consumption values annually.

The simulation program EnergyPlus was used to model all nine buildings. Subsequently, the FEDS models were developed using the same variable values. The purpose of modelling in this fashion was to gain an understanding of how FEDS and EnergyPlus differ in their ability to handle similar data.

2.3.4 Component Effects

In order to gain an understanding of how some of the variables affect the building models and how best to calibrate each model to mirror the utility consumption, one of the buildings was selected for an examination into what each incremental change has on the overall energy consumption. For this, the variables; chillers COP, boiler efficiency, infiltration rate, equipment and appliance loads, were varied individually and the results were graphed to illustrate the effects on monthly consumption. The aim was to determine the level of effect each variable has on the energy consumption and to explore the type of relationship that exists between the variables and energy consumption, i.e. a linear or non-linear variation.

The building selected for in this process was building CS4 which was assumed to be located in Montreal. A base model was first created using information reported in the literature. The assumptions made during the development of the base model were incrementally adjusted and the results were plotted. The development of the building model itself along with the energy simulation results are discussed next.

2.3.4.1 Chiller COP Value

The range for chiller COP values was chosen between 1.4 and 5.0 since this range represents low and high efficiency units. From Figure 2.13 and Figure 2.14 it can be seen that the change in chiller COP only effects the electrical consumption during the summer months. This effect is dependant only on the COP value and the difference decreases with improving COP. No interactive effects on secondary fuel consumption were observed. The conclusion that can be made here is that improving the efficiency of the chiller within a building will serve to reduce significantly, the electrical consumption. However, the benefit experienced by further improving the Chiller COP has an apparent feasible limitation. This is observed through the asymptotical decrease in slope that occurs as the COP is increased.

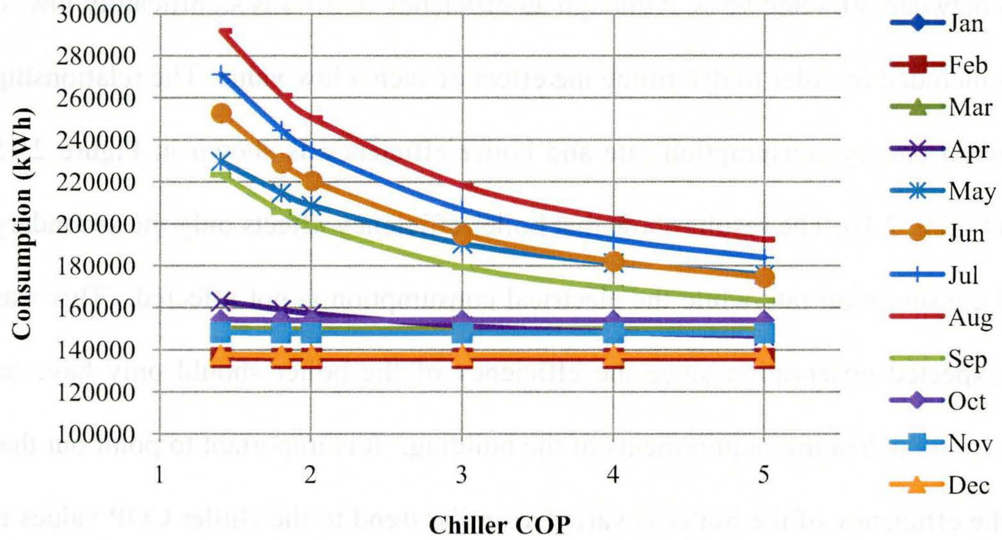

Figure 2.13: Electrical Consumption vs. Chiller COP

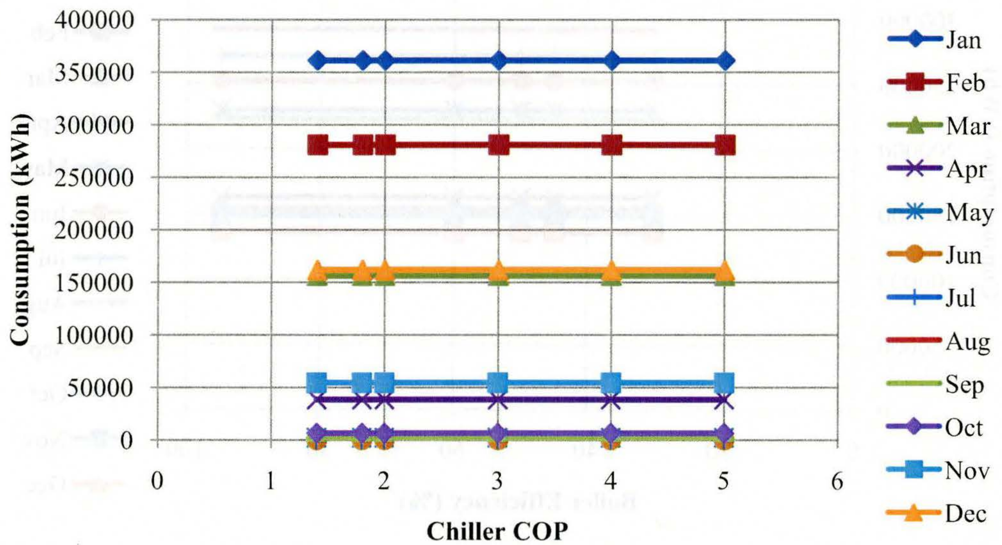

Figure 2.14: Secondary Fuel Consumption vs. Chiller COP

2.3.4.2 Boiler Efficiency

The range chosen to examine the effects of altering the boiler efficiency was between 30% and 95%. Although an efficiency of 30% is significantly low, it was included in order to determine the effect of such a low value. The relationship between energy consumption rate and boiler efficiency is shown in Figure 2.15 and Figure 2.16. The results show that boiler efficiency affects only the secondary fuel consumption rate while the electrical consumption is not affected. This was an expected observation since the efficiency of the boiler should only have an effect on the heating requirements of the building. It is important to point out that as the efficiency of the boiler is varied a similar trend to the chiller COP values is observed. As the efficiency improves, the impact of the improvement decreases.

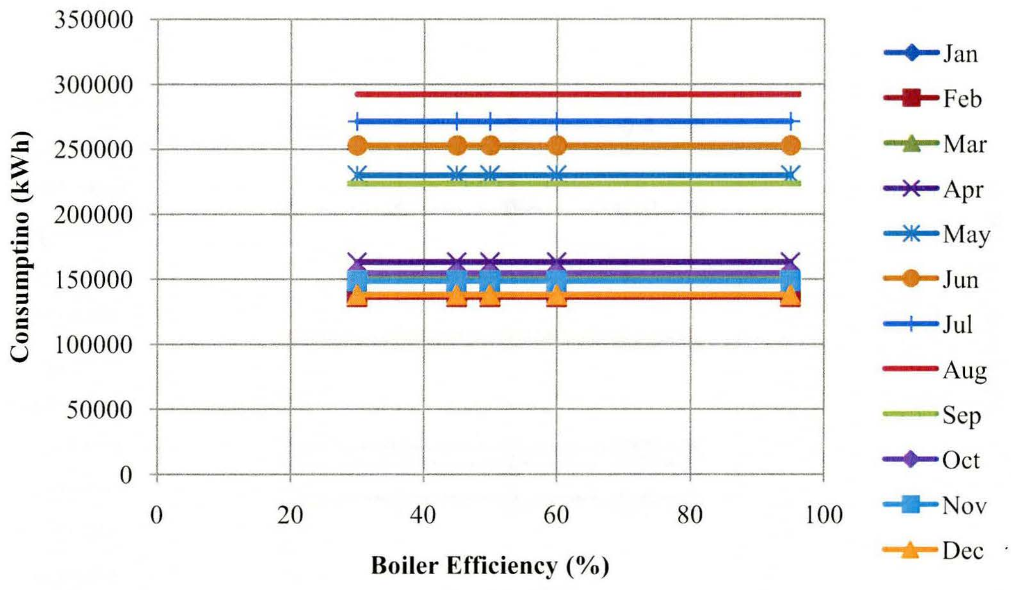

Figure 2.15: Electrical Consumption vs. Boiler Efficiency

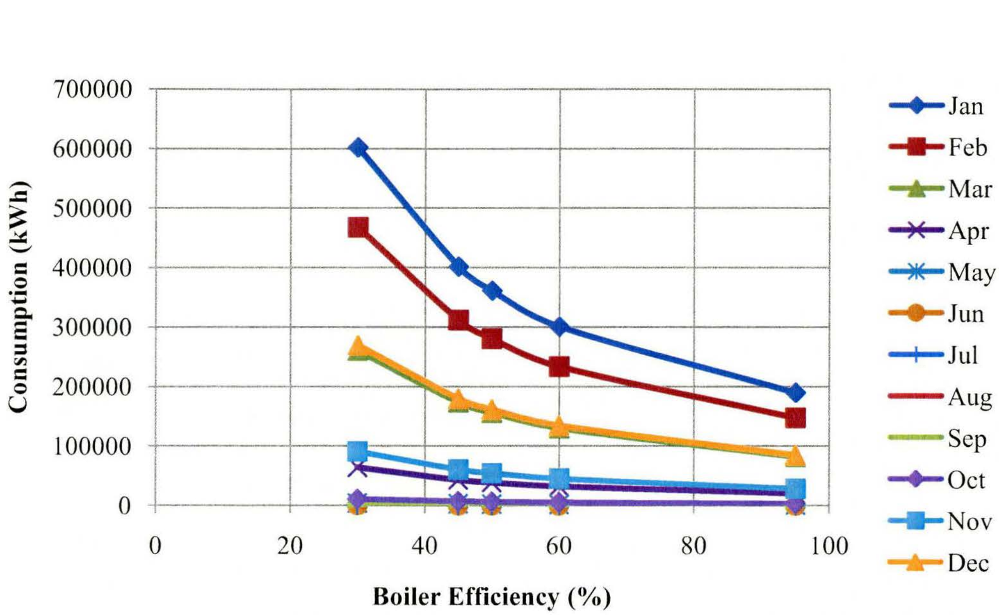

Figure 2.16: Secondary Fuel Consumption vs. Boiler Efficiency

2.3.4.3 Infiltration Rate

The infiltration rate of a building can have large implications on a building's energy consumption and choosing a suitable range on which to base the modelling was vital in obtaining accurate results. The range of acceptable infiltration rates chosen was between 0.1 and 1.0 air changes per hour. This range was selected based on two factors, the minimum required fresh air flow rate and the ventilation air flow rate requirements provided by the American Society of Heating Refrigeration and Air-Conditioning Engineers. Inc. (1962). As a constant, the ventilation air flow was set to 10 litres/second per person. From Figure 2.17 and Figure 2.18 one can observe that the infiltration rate has a positive impact on the electrical consumption over the summer months. However, a drastic increase in the winter secondary fuel consumption rate occurs as a result.

The effects of infiltration can be used in a two-fold attempt to improve energy simulation results both reducing summer consumption and increasing winter consumption rates.

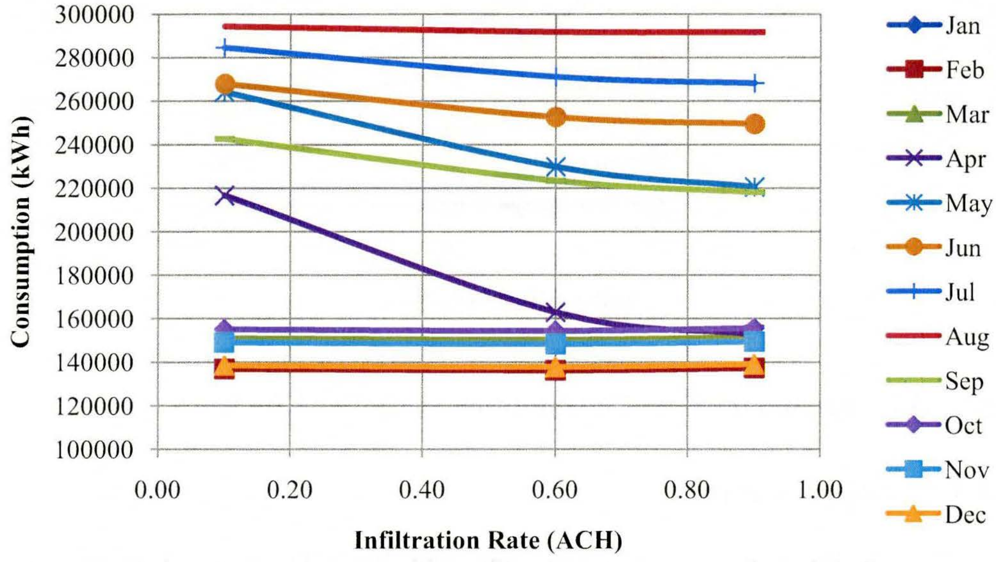

Figure 2.17: Electrical Consumption vs. Infiltration Rate

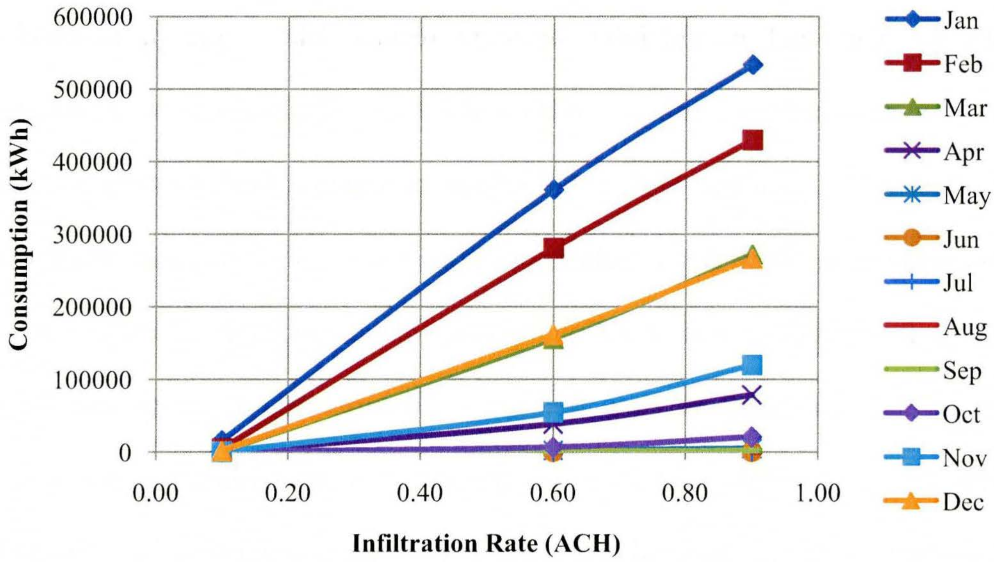

Figure 2.18: Secondary Fuel Consumption vs. Infiltration Rate

2.3.4.4 Equipment and Appliance Load

Equipment and Appliance loads are comprised of the various pieces of electrical equipment used during the daily operating schedule of a building. They include computers, photocopiers, fax machines and various kitchen appliances. The assumption made was to vary these loads between 0 and 50 W/m^2 to give a wide range of loading possibilities, thus representing the pre-1950 and post-1975 office load requirements.

From Figure 2.19 and Figure 2.20, two different trends can be seen. For the electrical consumption, the effects are purely linear and depend only on the overall change in direct energy consumption. However, it is apparent that the summer electricity consumption is increased according to the production of heat generated by each piece of electrical equipment. The reverse can be seen in the winter months for the secondary fuel consumption. Here the increased gains experienced by the additional internal heat produced by increased equipment usage help to reduce the overall heating requirements of the building. However, this effect is not linear, with increasing use the reduction amount 'flattens out' and as a result we see that there is a limitation to the benefits experienced in the reduction of secondary fuel.

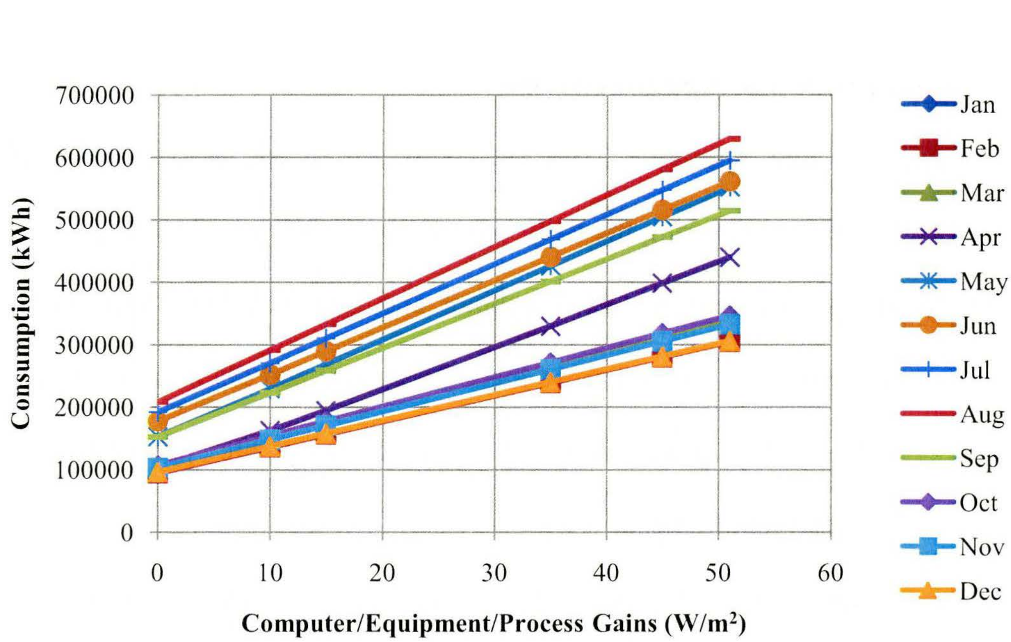

Figure 2.19: Electrical Consumption vs. Equipment and Appliance Loads

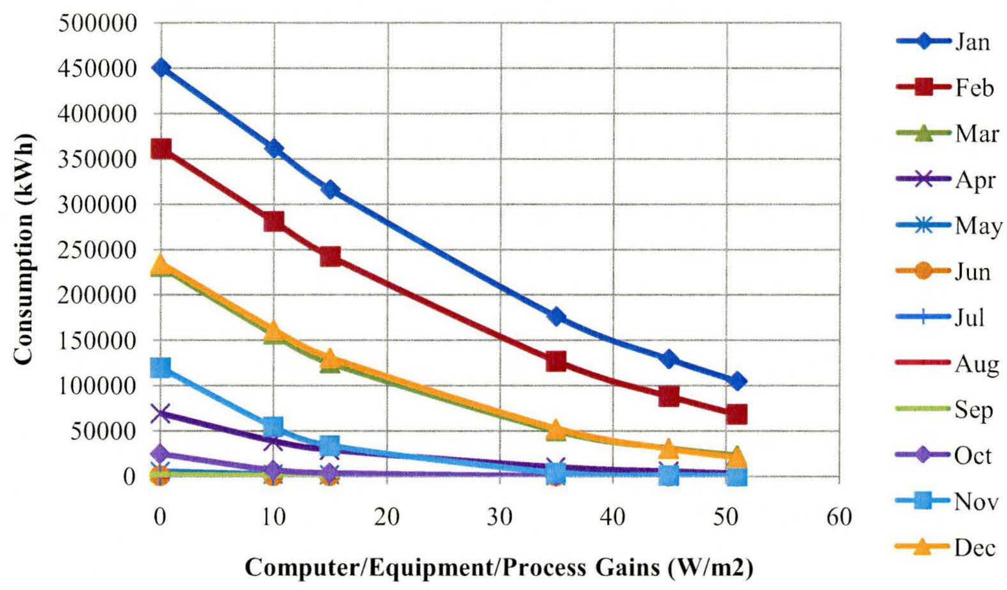

Figure 2.20: Secondary Fuel Consumption vs. Equipment and Appliance Loads

The results presented in Figure 2.13 to Figure 2.20 provide basic information that was used to calibrate the models of the nine office buildings for the purpose of calculating the energy consumption. Although the presented data does not reveal the potential synergistic effect of varying more than one variable, one can use it to select which variable needs to be modified to obtain an improved estimation of the building energy consumption.

2.3.5 EnergyPlus vs. FEDS

A comparative analysis was carried out to evaluate the adequacy of the complex simulation software, namely EnergyPlus, and a simpler simulation tool namely FEDS, in simulating the energy consumption of office buildings. Nine office buildings were used to evaluate the simulated versus metered values. Figure 2.21 to Figure 2.29 display the results obtained using EnergyPlus, FEDS, and metered values. It should be noted that the FEDS models were created using the same simulation parameters applied in the optimized EnergyPlus models. However, the weather data used in the simulations is not the same, as FEDS has a limited amount of Canadian weather data. This is a known source of error that is due to the apparent limitation of the software.

By examining the results obtained from the simulations, it becomes evident that FEDS is consistently under-predicting the energy consumption results. This is most noticeable for the secondary fuel consumption levels. As noted earlier, one of the reasons for this consistent under-prediction can be due to the fact that FEDS does not possess the weather files for all nine cities and the closest matching city was selected for the simulations.

A more detailed exploration into the modelling results will allow for a better understanding of the possible reasons for the inaccuracy of the programs. Table 2.9 summarizes the modelling results obtained and confirms that the error between the metered values and EnergyPlus are significantly lower than that of FEDS. From the results obtained it can be seen that the annual modelling results for EnergyPlus are consistent with the metered values and that the associated error values appear unaffected by size, number of storeys, fuel source, or ventilation type. When FEDS is examined more closely however, a trend is observed between the volume of the building and the error with the metered value. The buildings with a large conditioned volume of air are associated with a larger error in the calculation of the secondary fuel consumption. This suggests that the error is not only due to the differences in weather data, but also in the approach used to calculate the energy consumed. According to the results it was decided to further study the adequacy of EnergyPlus by examining the monthly prediction of energy.

Table 2.9: Summary of errors associated with EnergyPlus, FEDS and metered values

Case #	*Volume (m^3)*	*# of Storeys*	*Heating Fuel*	*Vent. Type*	*% Error EnergyPlus*		*%Error FEDS*	
					Elec.	*Fuel #2*	*Elec.*	*Fuel #2*
CS1	226800	8	Natural Gas	VAV	-7%	-3%	-50%	-61%
CS2	49596	6	Natural Gas	CAV	7%	-10%	-6%	-13%
CS3	119248	13	Natural Gas	CAV	1%	-5%	-27%	-46%
CS4	42935	5	Fuel Oil	CAV	4%	-15%	5%	-49%
CS5	40832	13	Natural Gas	CAV	7%	-10%	-17%	-11%
CS6	88772	10	Natural Gas	CAV	-5%	-14%	-46%	-79%
CS7	46679	4	Fuel Oil	CAV	9%	-7%	-52%	-22%
CS8	61845	3	Natural Gas	CAV	5%	0%	-3%	-74%
CS9	14327	2	Electricity	CAV	7%	-3%	-13%	n/a

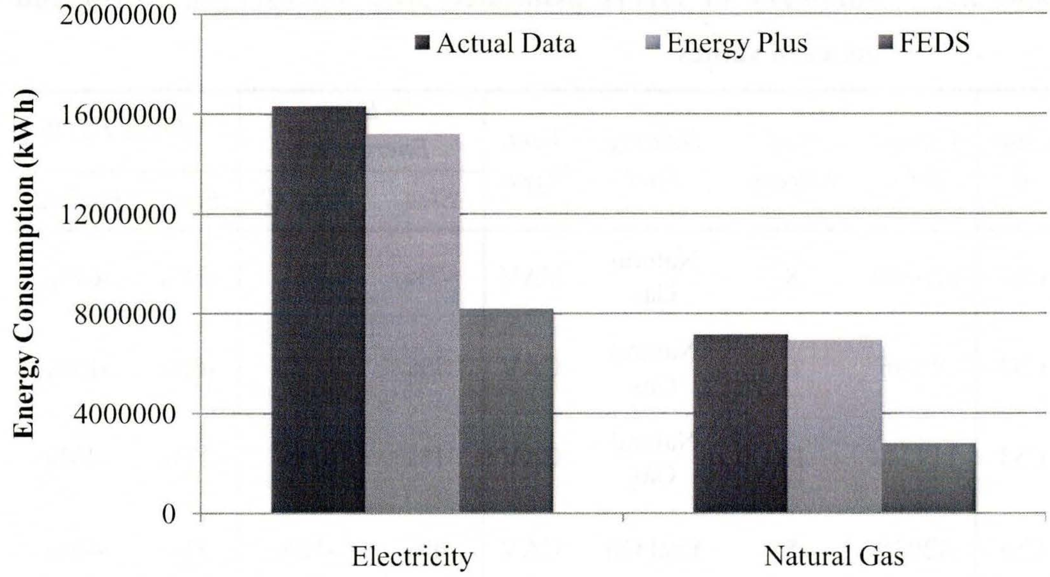

Figure 2.21: Building CS1: Energy consumption obtained from EnergyPlus, FEDS and meters

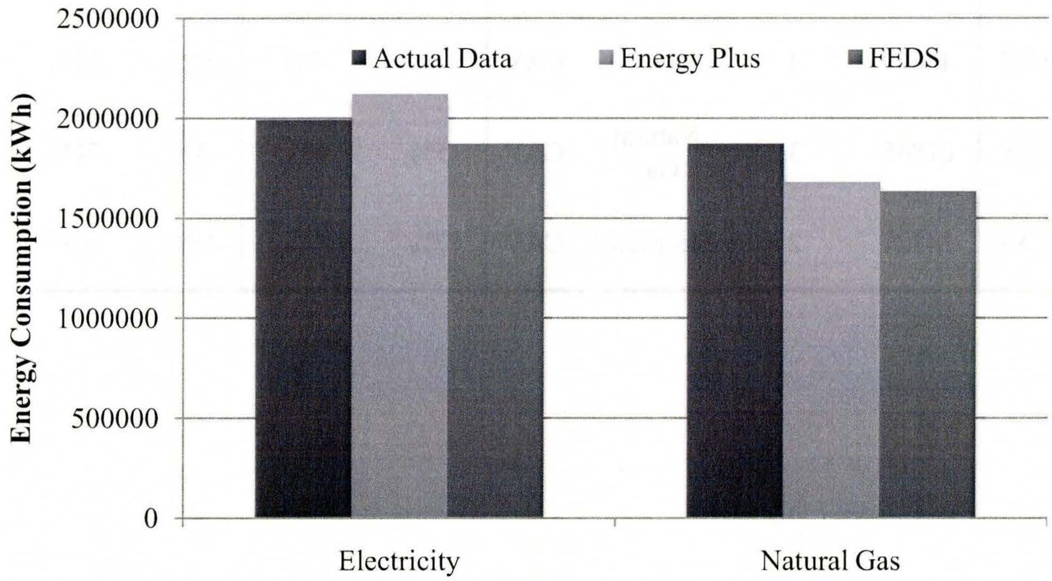

Figure 2.22: Building CS2: Energy consumption obtained from EnergyPlus, FEDS and meters

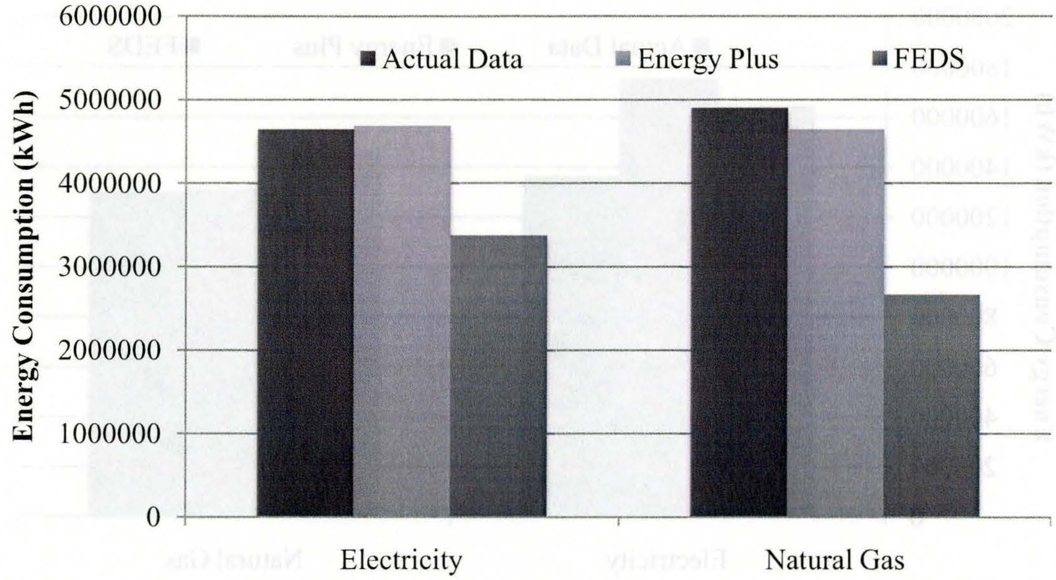

Figure 2.23: Building CS3: Energy consumption obtained from EnergyPlus, FEDS and meters

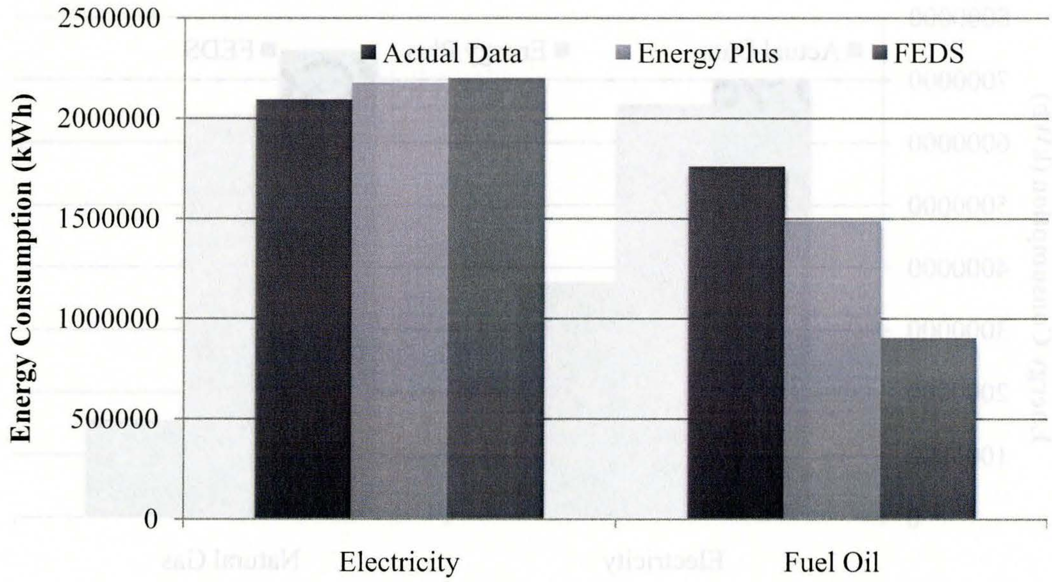

Figure 2.24: Building CS4: Energy consumption obtained from EnergyPlus, FEDS and meters

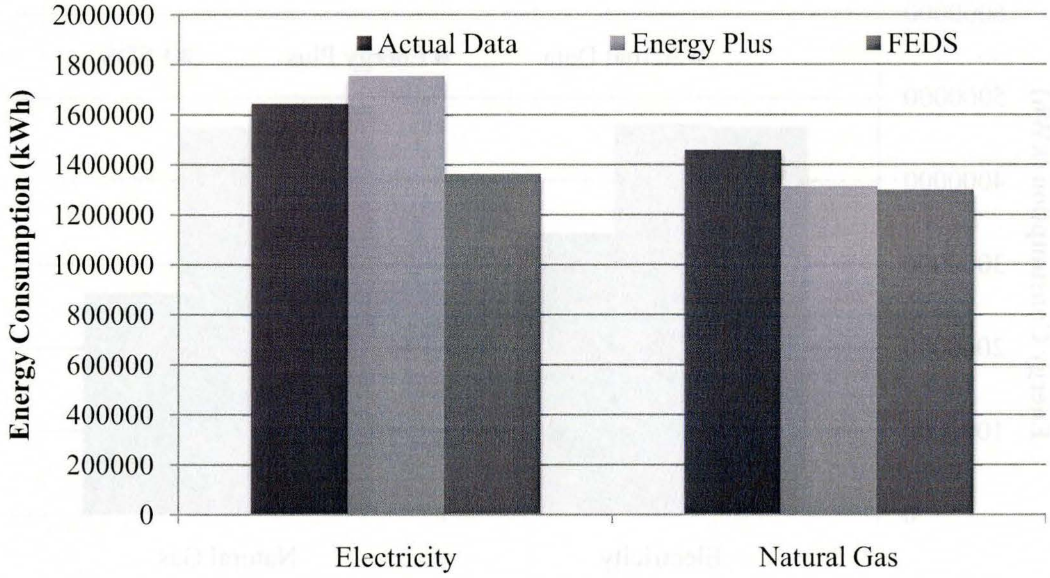

Figure 2.25: Building CS5: Energy consumption obtained from EnergyPlus, FEDS and meters

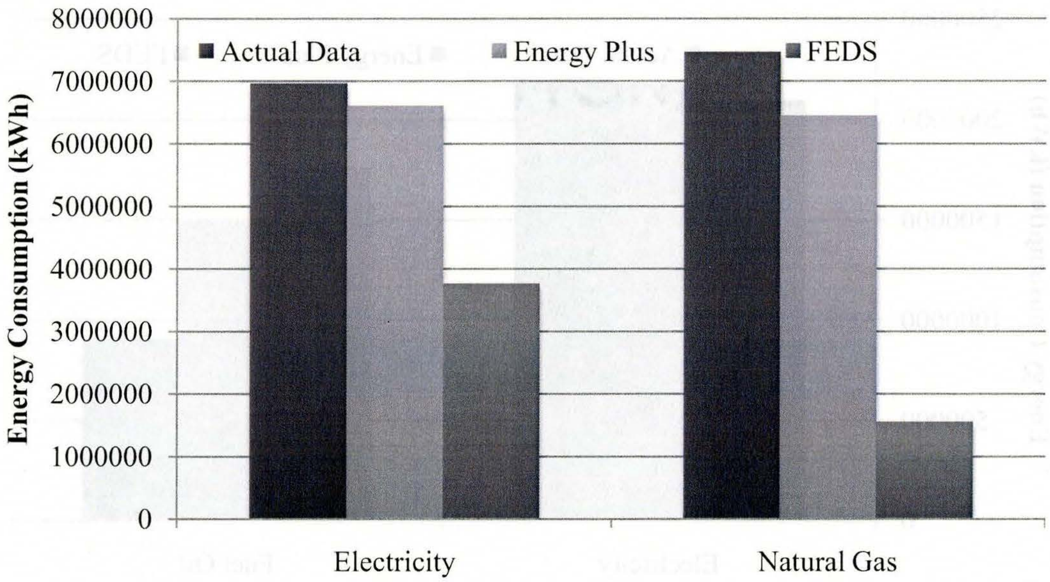

Figure 2.26: Building CS6: Energy consumption obtained from EnergyPlus, FEDS and meters

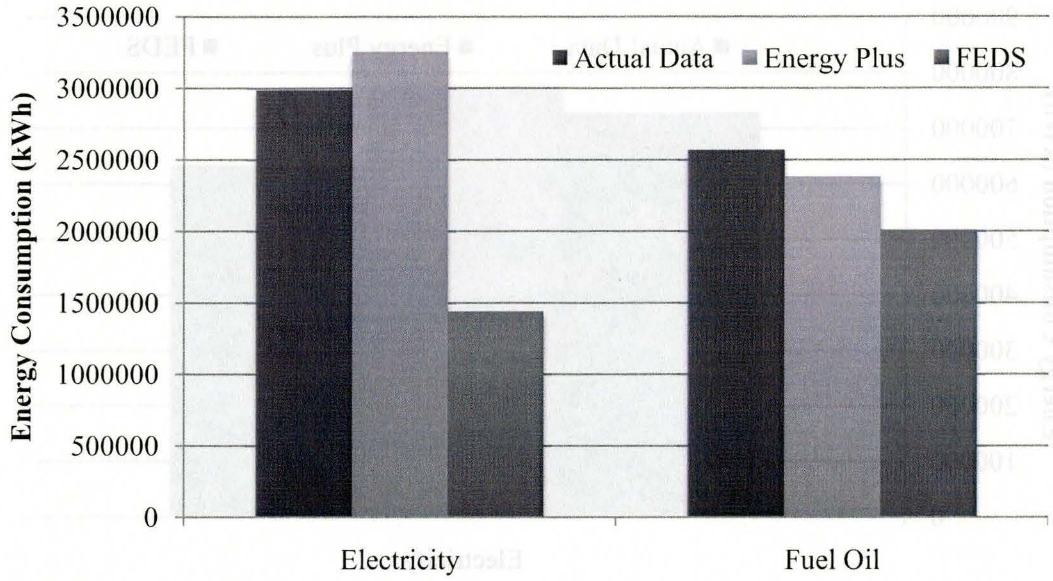

Figure 2.27: Building CS7: Energy consumption obtained from EnergyPlus, FEDS and meters

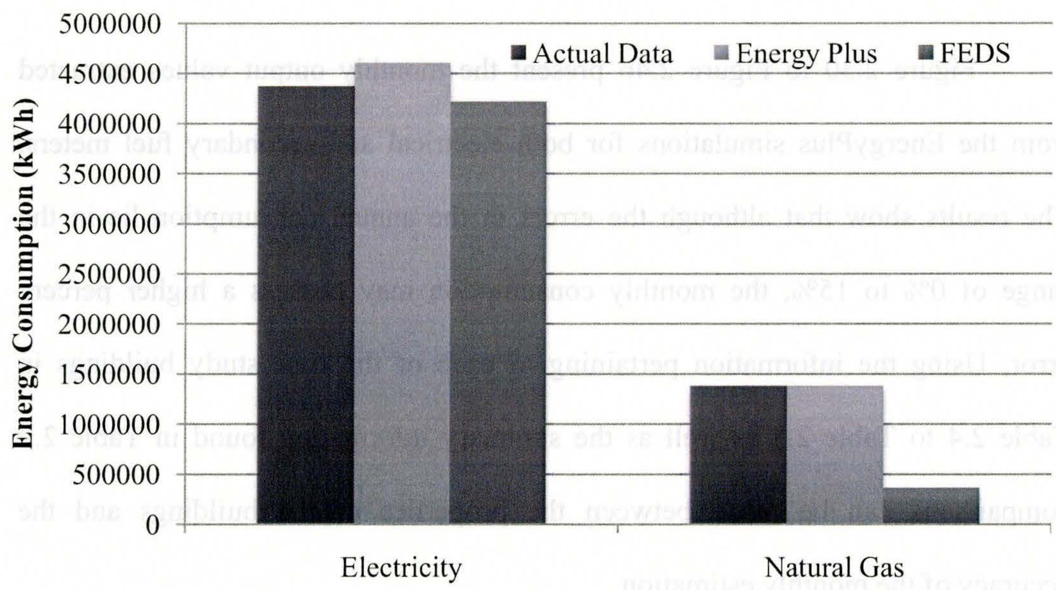

Figure 2.28: Building CS8: Energy consumption obtained from EnergyPlus, FEDS and meters

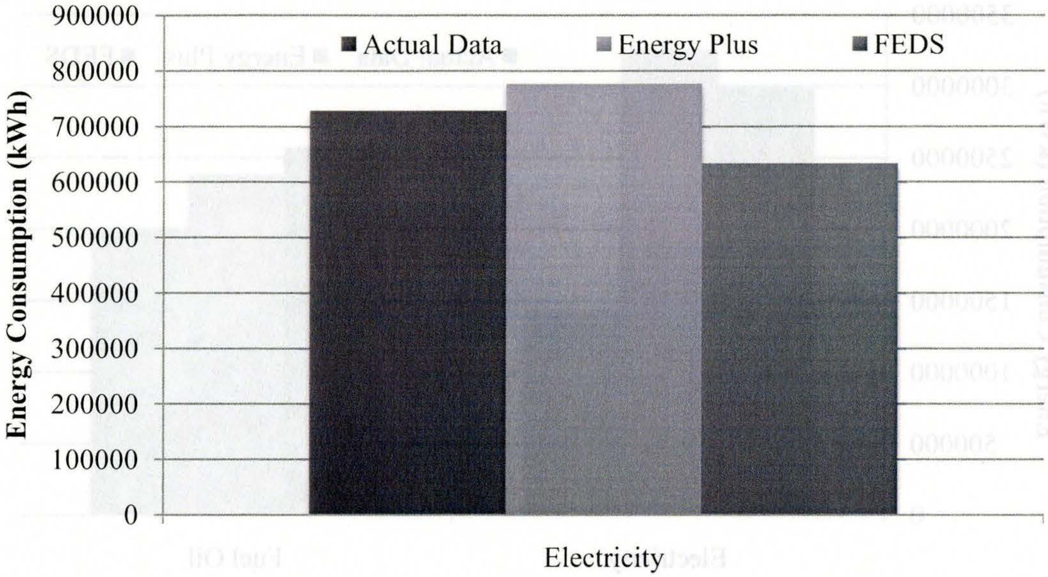

Figure 2.29: Building CS9: Energy consumption obtained from EnergyPlus, FEDS and meters

Figure 2.30 to Figure 2.46 present the monthly output values extracted from the EnergyPlus simulations for both electrical and secondary fuel meters. The results show that although the errors in the annual consumption lie in the range of 0% to 15%, the monthly consumption may possess a higher percent error. Using the information pertaining to each of the case study buildings in Table 2.4 to Table 2.8 as well as the summary information found in Table 2.9 comparisons can be made between the properties of the buildings and the accuracy of the monthly estimation.

Building CS1 is the largest building in the case study set with a volume of 226,800 m^3. The inadequacies of the monthly consumption occur both in electrical and natural gas estimations. In the winter months the consumption of electrical energy is underestimated where as in the summer months it is over estimated. This indicates that there is an aspect of the building's electrical demand that is not being captured adequately. The natural gas consumption is appropriately determined for the winter months (September to March) but there is a significant loss of precision in April and in the summer period.

Building CS2 is of average to small volume as it possesses six storeys. Setting this building apart from the others in the case study set is the distribution of floor heights, as each floor possessed its own unique floor to ceiling measurement. As well, this building employs the use of air to air heat recovery to reduce heating requirements. The inadequacies of the modelling are prominent in the summer months for the electrical demand where over estimation occurred. The supply of natural gas during the month of April is the most divergent from the otherwise accurate results.

Consumption for Buildings CS3, CS4 and CS5 were well predicted for both electrical, natural gas and fuel oil for building CS4 for all seasons. Each of these buildings possess similar ventilation systems and infiltration rates. Since the variation in size and number of floors among these buildings was significant 119,247 m^3 to 40,831 m^3 and 13 to 5, respectively, it becomes apparent that neither size or floor height are governing factors in the accuracy of EnergyPlus simulations.

Building CS6 was the most interesting building for determining energy consumption levels. The electrical demand was accurately estimated, however the natural gas consumption posed difficulties. When examining the metered consumption for building CS6 in Figure 2.41, an uncharacteristic consumption pattern emerged. This pattern for consumption indicates that there is likely an undefined piece of natural gas consuming equipment that is in operation over the summer months. As such, it was difficult for EnergyPlus to estimate, with a high level of accuracy, the consumption during this season.

Building CS7 was the second of two buildings that were supplied with fuel oil to heat the building during the winter months. It possesses a small number of floors (four) and also contains a large warehouse facility. The inadequacies of the modelling of this building are found in the overestimation of electrical demand in the summer period between May and September and the underestimation of the natural gas consumption in the month of April.

Building CS8, as in CS7, is a smaller building possessing three storeys. Predictions obtained using EnergyPlus are accurate for the electrical demands. However, there are significant errors in the estimations of the winter heating requirements. Overestimating in the January to March period and underestimating in the September to December period.

Building CS9 is the only building in the case study portfolio that is heated by radiant electrical baseboards. It is well modelled for all seasons with the one exception of the month of April, where consumption was underestimated.

For these results the following conclusions can be made about the modelling capabilities of EnergyPlus:

1. The volume and number of storeys possessed by a building are well captured by EnergyPlus.
2. EnergyPlus modelling for the consumption of secondary fuel during the month of April may be under-predicted as it was a consistent trend associated with the majority of the buildings studies.
3. Ventilation system configurations such as variable or constant air volume and heat recovery capabilities must be well defined/known in order for the model to adequately predict energy consumption.

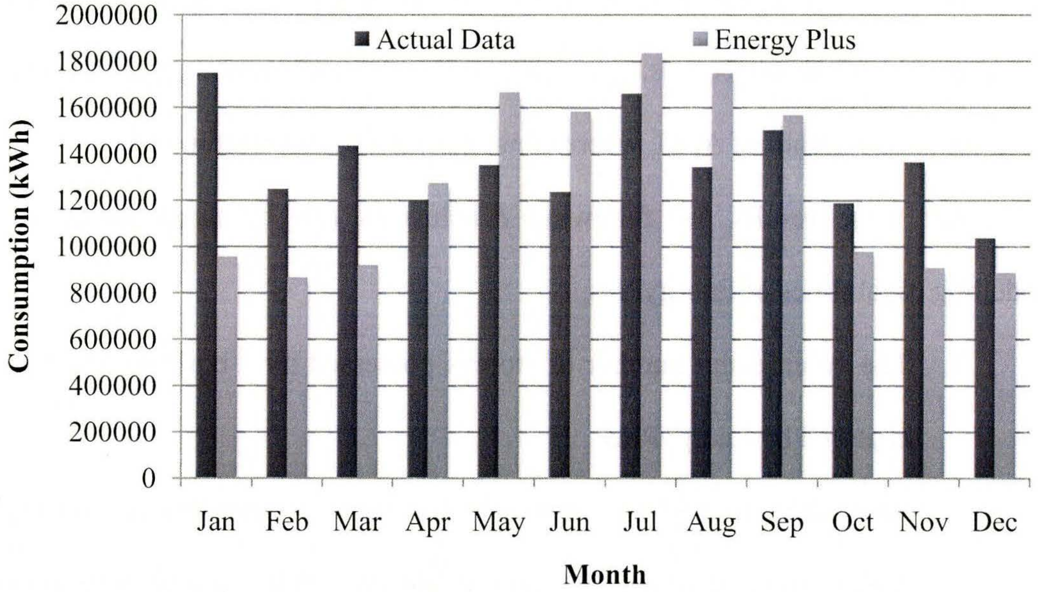

Figure 2.30: Calculated versus measured electrical consumption for building CS1

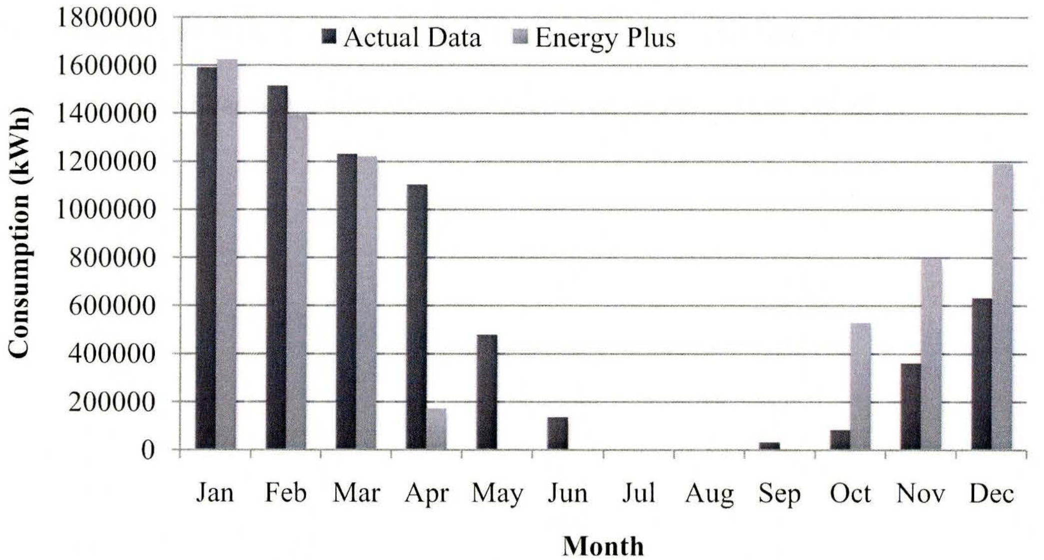

Figure 2.31: Calculated versus measured natural gas consumption for building CS1

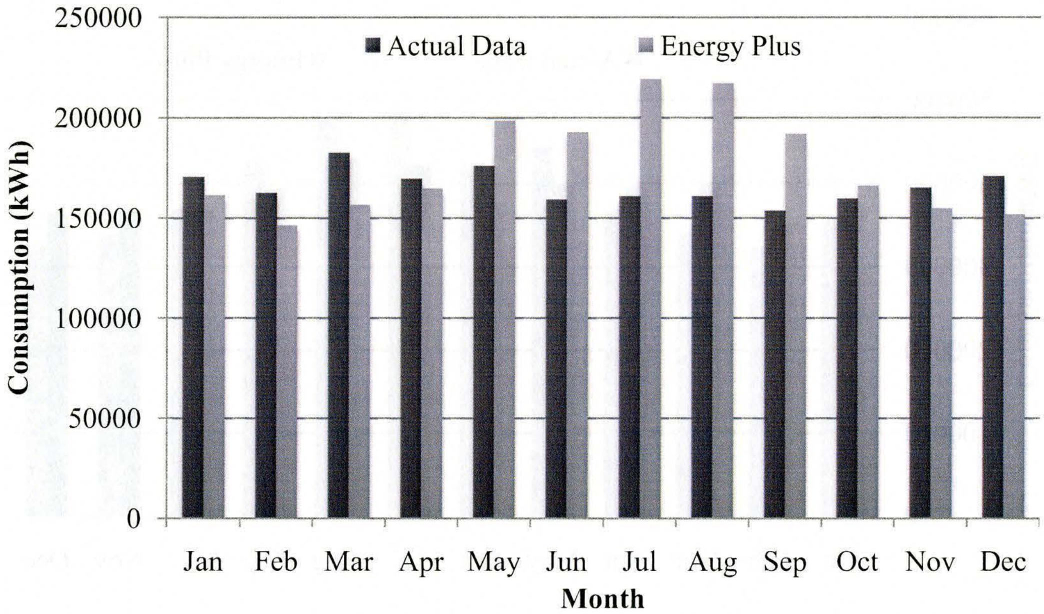

Figure 2.32: Calculated versus measured electrical consumption for building CS2

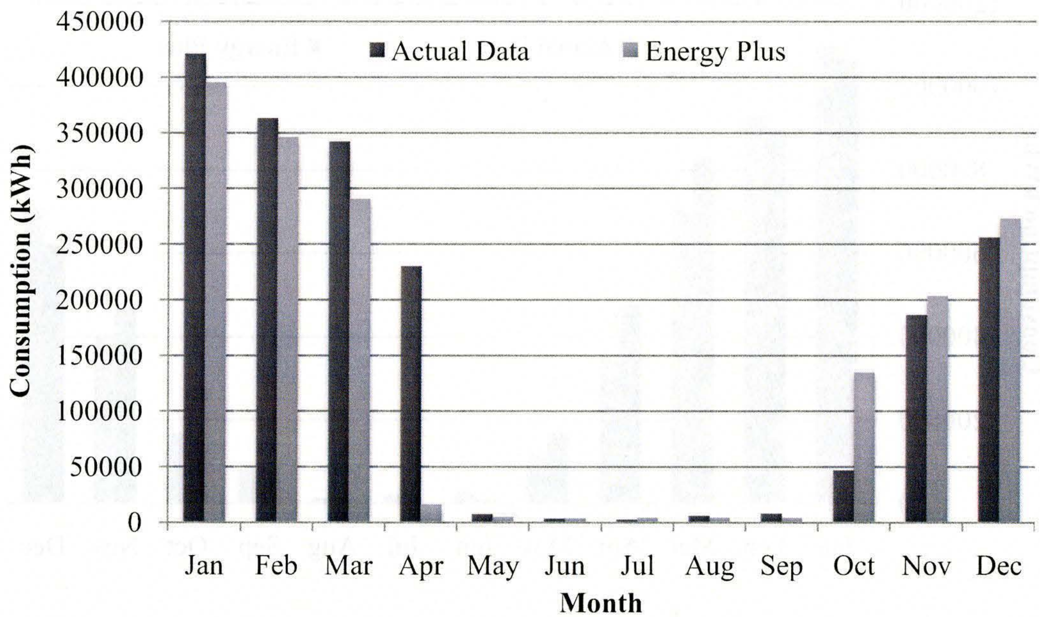

Figure 2.33: Calculated versus measured natural gas consumption for building CS2

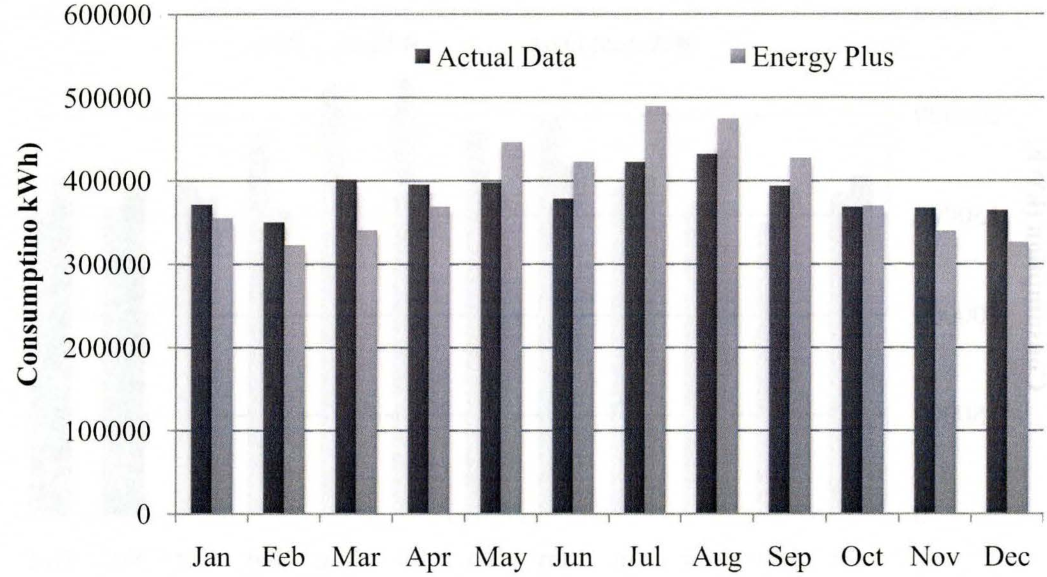

Figure 2.34: Calculated versus measured electrical consumption for building CS3

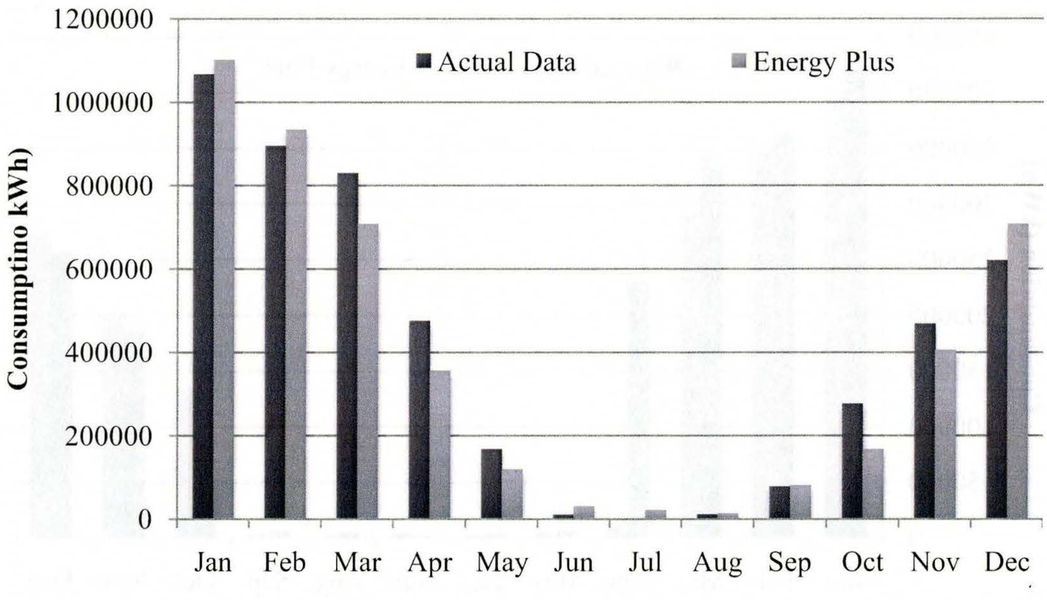

Figure 2.35: Calculated versus measured natural gas consumption for building CS3

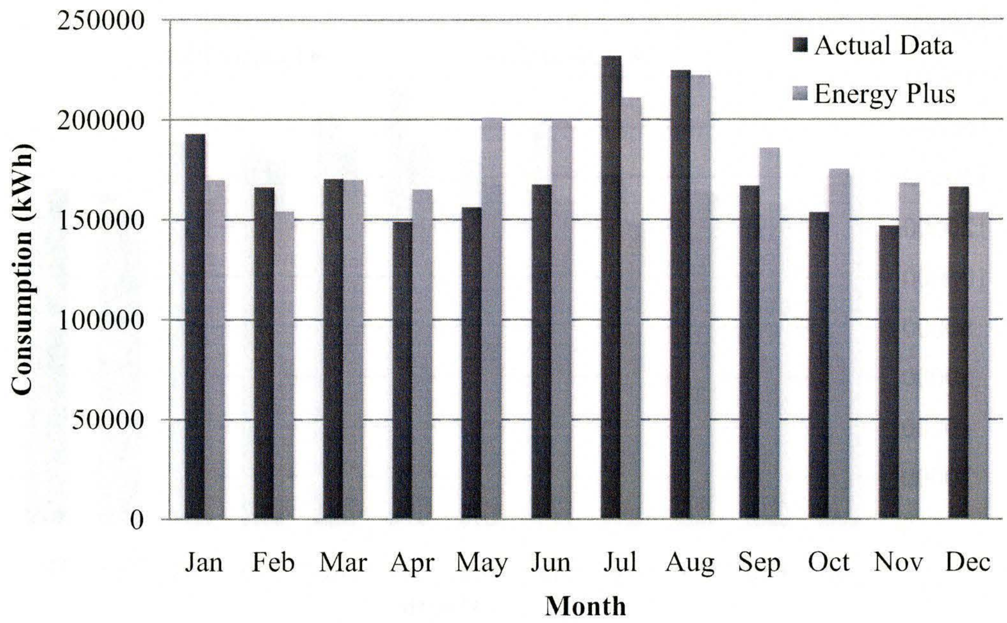

Figure 2.36: Calculated versus measured electrical consumption for building CS4

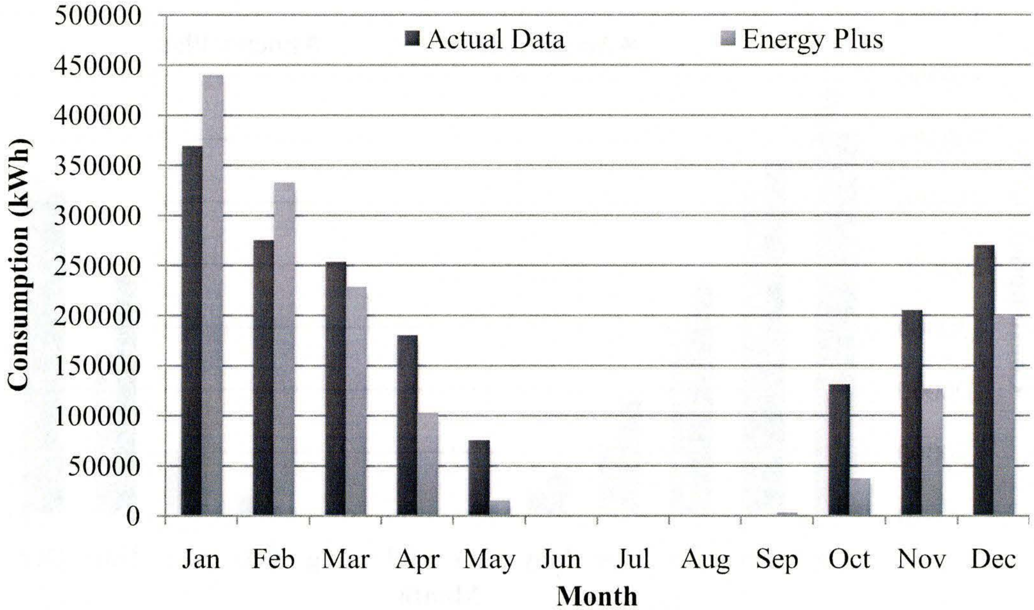

Figure 2.37: Calculated versus measured fuel oil consumption for building CS4

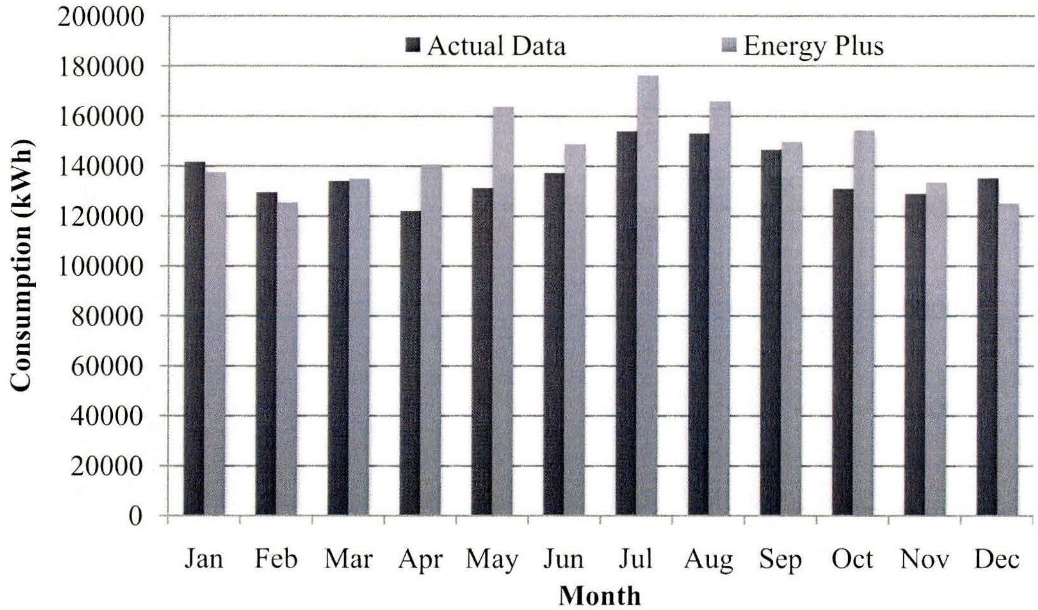

Figure 2.38: Calculated versus measured electrical consumption for building CS5

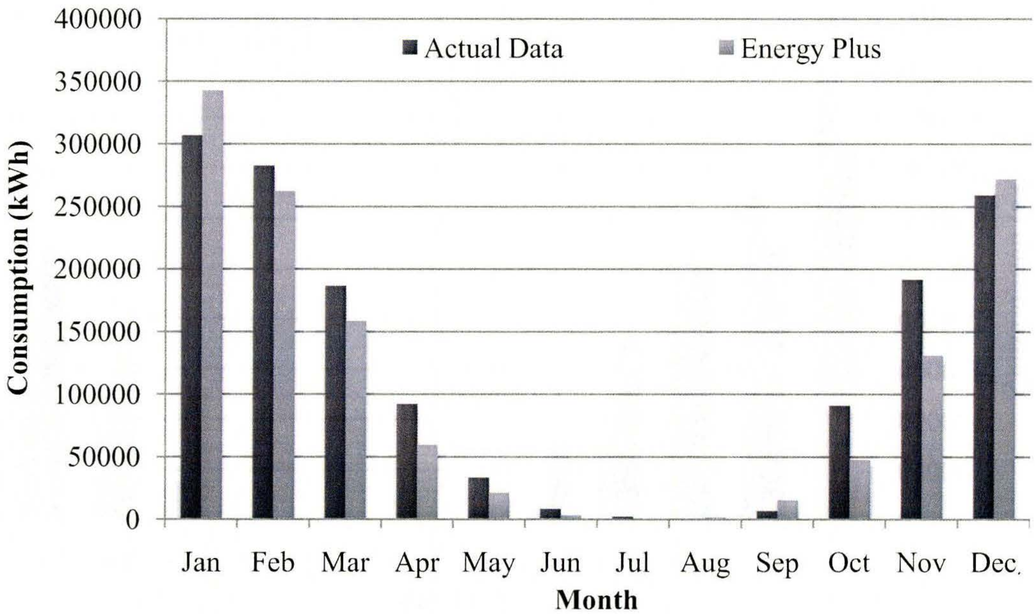

Figure 2.39: Calculated versus measured natural gas consumption for building CS5

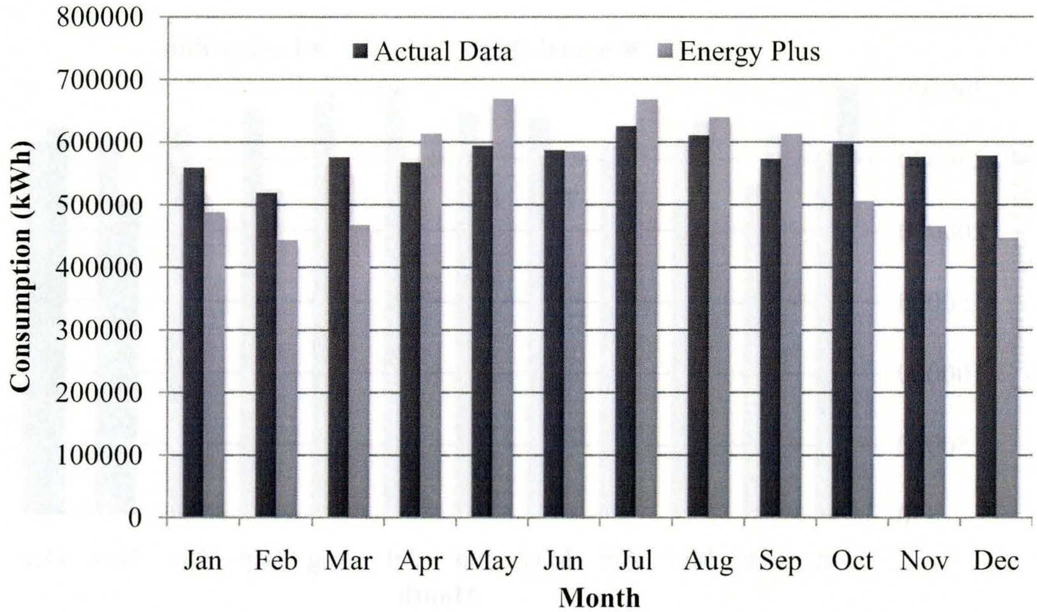

Figure 2.40: Calculated versus measured electrical consumption for building CS6

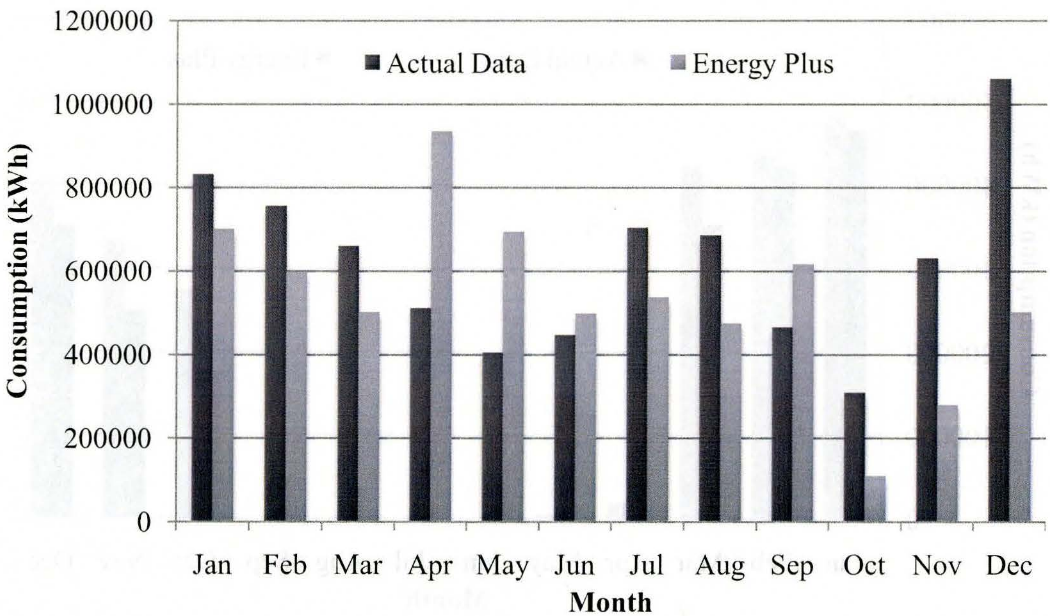

Figure 2.41: Calculated versus measured natural gas consumption for building CS6

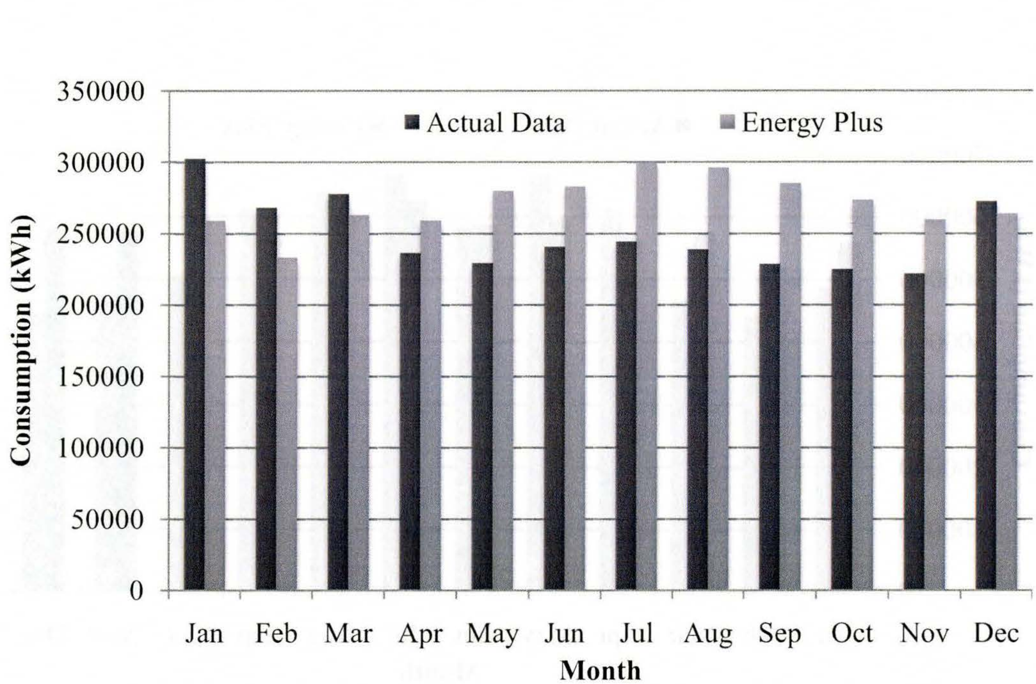

Figure 2.42: Calculated versus measured electrical consumption for building CS7

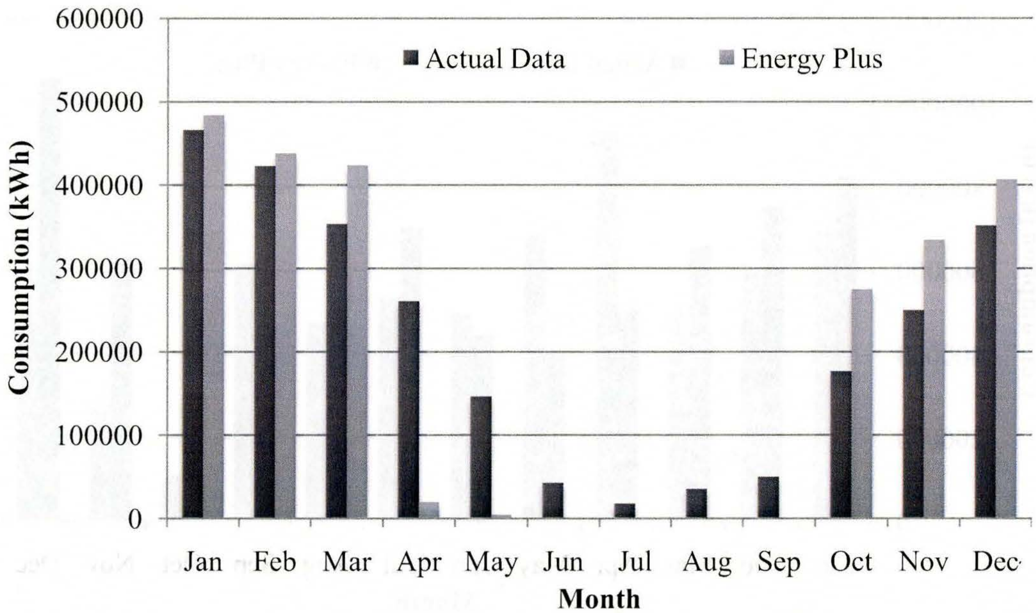

Figure 2.43: Calculated versus measured fuel oil consumption for building CS7

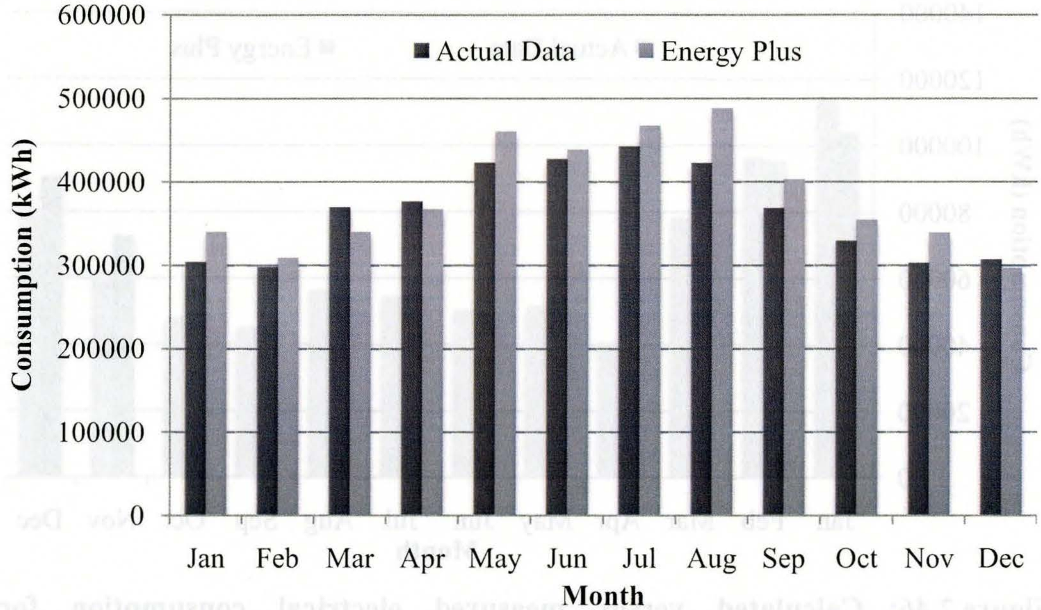

Figure 2.44: Calculated versus measured electrical consumption for building CS8

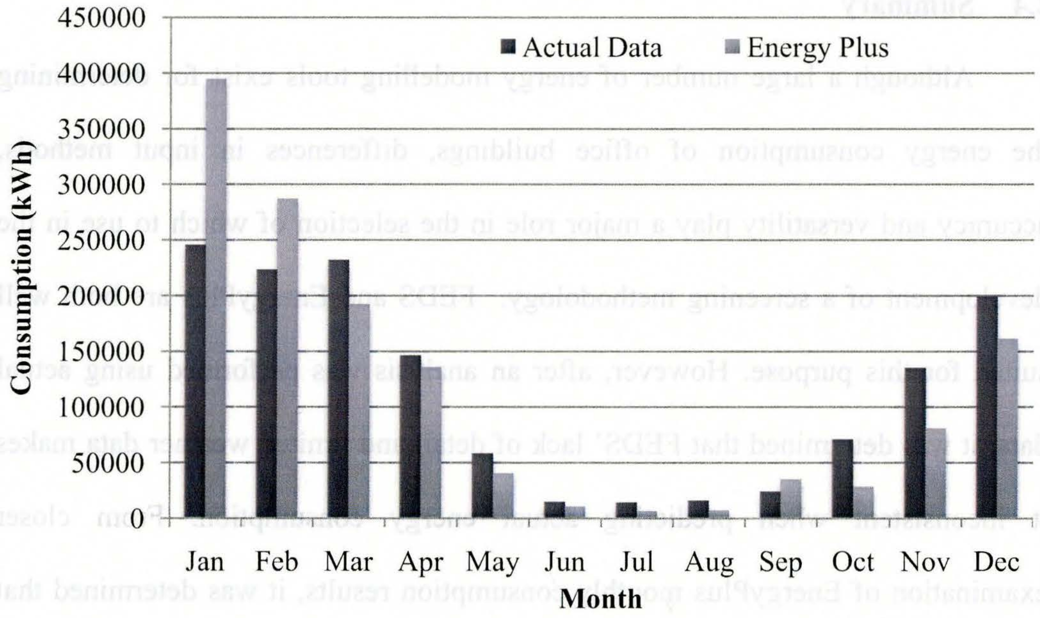

Figure 2.45: Calculated versus measured natural gas consumption for building CS8

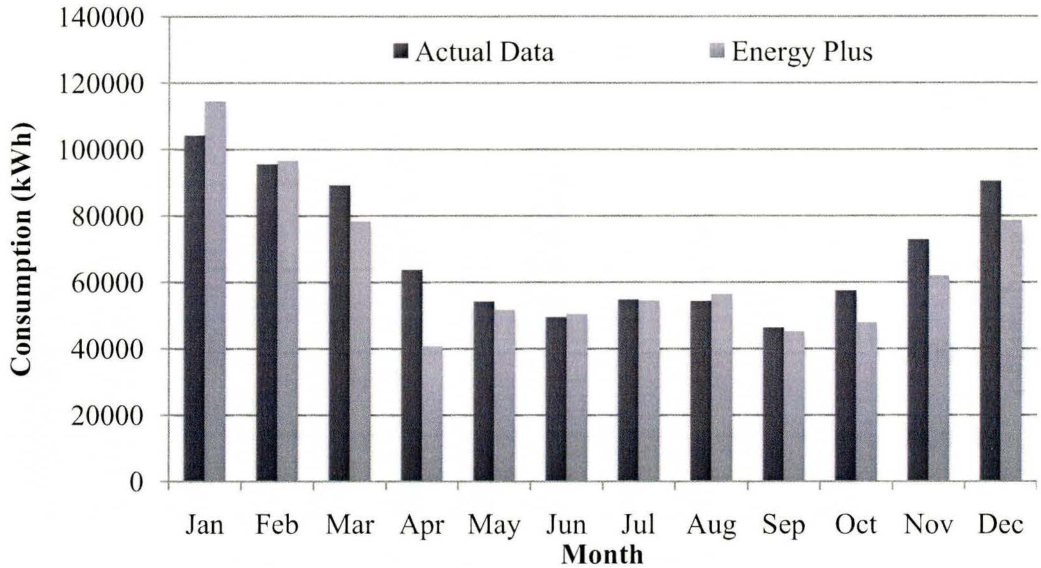

Figure 2.46: Calculated versus measured electrical consumption for building CS9

2.4 Summary

Although a large number of energy modelling tools exist for determining the energy consumption of office buildings, differences in input methods, accuracy and versatility play a major role in the selection of which to use in the development of a screening methodology. FEDS and EnergyPlus are both well suited for this purpose. However, after an analysis was performed using actual data, it was determined that FEDS' lack of detail and limited weather data makes it inconsistent when predicting actual energy consumption. From closer examination of EnergyPlus monthly consumption results, it was determined that EnergyPlus was an adequate program to use for simulating the energy consumption of office buildings.

Chapter 3: Representative Buildings

3.1 Introduction

Office buildings vary in terms of fuel source used, age, size, occupancy characteristics, HVAC system, location and building envelope construction practices. To group these buildings in an organized way the concept of a representative building set was created to capture the majority of construction possibilities. This was achieved by grouping buildings into archetypes reflecting the age, size, type of construction, and location. Accordingly, three building archetypes were proposed. They were based on varying years of construction using eras of distinct points in time for which major changes in construction practices occurred. For each of the archetype classifications a set of defined building types was also assigned. These building types were chosen with the goal of capturing the three main types of structures that are prevalent in the office building stock. Two of the buildings possess brick veneer/concrete block walls and have a low window to wall percentage. These buildings are typical for low-rise structures and are more common in older medium-rise structures. A third building type, which is composed primarily of curtain-walls with a high window to wall percentage, was chosen to represent the majority of newer high-rise office buildings. Figure 3.1 illustrates the archetype scheme chosen. Thus, three archetype vintages were adopted and consists of Archetype #1 – Buildings which were constructed prior to 1950, Archetype #2 – Buildings constructed between 1950 and 1975 and Archetype #3 – Buildings constructed post 1975. Moreover, conforming with the age of the buildings, three building types were selected, Building Type R1 – Large w/concrete wall exterior representing buildings that posses a brick veneer attached to a concrete block backup wall, Building Type R2 – Large w/curtain wall exterior representing buildings with curtain walls and Building Type R3 – Small w/concrete wall exterior. Detailed descriptions of these representative buildings are given in section 3.2.

Canadian weather consists of several climatic regions including dry, humid mesothermal, humid microthermal and polar climates (Natural Resources Canada, 2005). To capture the effects of the differences in the weather experienced in Canada due to these climactic variations three distinct weather locations were chosen to model the energy consumption of the representative buildings: Ottawa, Edmonton and Vancouver.

An energy consumption database was developed by simulating the representative building archetypes for base level energy consumption and the effects of implementing retrofit options. Chapter 4 will discuss how this database was used to make predictions of the energy consumptions of existing buildings.

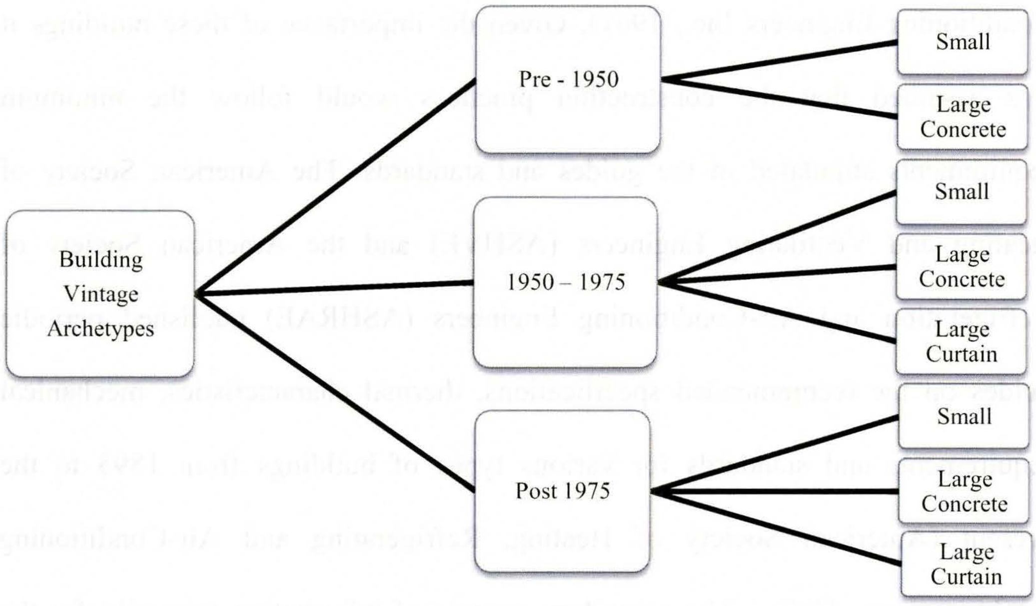

Figure 3.1: Archetype Diagram

3.2 Definition of Representative Buildings

The parameters of the representative models were chosen based on data obtained from a combination of sources. The primary source of information concerning the construction characteristics of the walls, roof and fenestration came from guidelines available at the time of construction, namely ASHVE (American Society of Heating and Ventilating Engineers, 1939), (American Society of Heating and Ventilating Engineers, 1950) and ASHRAE guides (American Society of Heating Refrigeration and Air-Conditioning Engineers Inc., 1962), (American Society of Heating Refrigeration and Air-Conditioning Engineers Inc., 1977), (American Society of Heating Refrigeration and Air-

Conditioning Engineers Inc., 1961). Given the importance of these buildings it was assumed that the construction practices would follow the minimum requirements stipulated in the guides and standards. The American Society of Heating and Ventilating Engineers (ASHVE) and the American Society of Refrigeration and Air-Conditioning Engineers (ASHRAE) published periodic guides on the recommended specifications, thermal characteristics, mechanical requirements and standards for various types of buildings from 1895 to the present (American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc, 2007). The secondary sources of information primarily for the electrical, lighting and elevator loading specifications were taken from Morofsky & Cane (2003) and Caneta Research Inc. (2001) as well as through conversations with the PWGSC. Table 3.1 to Table 3.7 detail the parameters used to define each building type for all applicable archetype periods and Figure 3.2 to Figure 3.4 give a schematic representation of the buildings extracted from the EnergyPlus simulation files. Building types R1 and R3 both possess variations on concrete wall configurations. The changes that occur between archetype vintages are primarily due to improvements in insulation techniques and window construction practices that occurred with time. Building type R2 includes a curtain wall representation in the modelling scheme as curtain wall construction became more prevalent in the years following 1950 and the HVAC systems that were used to control the building were representative of this fact. The primary HVAC system for all representative buildings consists of a chilled water cooling system and a hot water heating distribution network, where the chilled water is cooled using electrical chillers and the water is heated using natural gas boilers.

Table 3.1: Parameters used in the modelling of the office buildings assumed constant for all archetypes

Parameter	***Value***
Floor to ceiling height (ft)	3.5 m
Operation schedule (occupancy)	6:00 AM – 6:00 PM
Lighting target luminescence	500 Lux
Elevator load	30 kW/elevator
Holidays per year	8
Hot water consumption rate	3.8 l/person/day
Temperature set points	Heating: 21.1°C, Cooling: 23.5°C
Heating fuel source	Natural Gas
Cooling fuel source	Electricity
Hot water heating source	Electricity

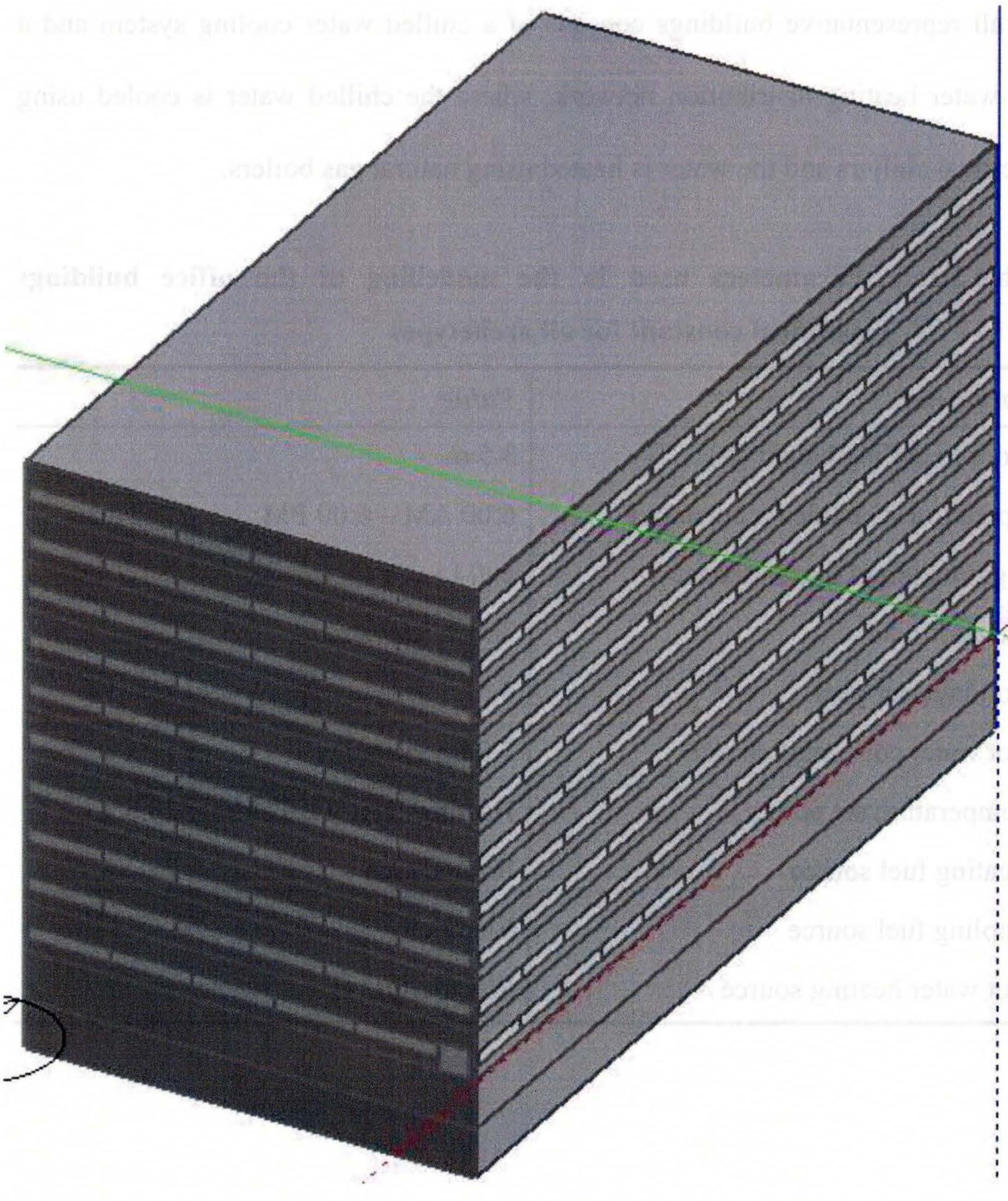

Figure 3.2: Building R1 - Large archetype with concrete block walls and brick veneer

Table 3.2: Building R1 - Pre 1950 and 1950 - 1975 archetype descriptions

Item	*Pre – 1950*	*1950 – 1975*
Description of building: *# of storeys:* *10 above and 2 below ground* *Floor area: 24,150 m²* *Volume: 84,525 m³*	Heating fuel: natural gas Cooling fuel: electricity External wall: Brick veneer on concrete block with ½ plaster, rigid insulation Roof: Metal roofing deck Windows: Single glazed No blinds	Heating fuel: natural gas Cooling fuel: electricity External wall: Brick veneer on concrete block with ½ plaster, rigid insulation Roof: Metal roofing deck Windows: Double glazed Medium reflectivity blinds
Guides/standards	ASHVE – 1939	ASHVE – 1950, ASHRAE 1961
Lighting load (W/m^2)	26	17.8
Lighting level (Lux)	500	500
Equip/appliance load (W/m^2)	10	20
Elevator load (kW)	4 x 30	4 x 30
Occupant density (m^2/person)	30	25
Fenestration (%)	30	40
Fenestration U-value (W/m^2.C)	6.42 (SGHC = 0.81)	4.50 (SGHC = 0.68)
Wall U-value (W/m^2. C)	1.21	1.21
Roof U-value (W/m^2.C)	1.41	0.74
Below grade wall (RSI)	No insulation	No insulation
Perimeter floor insulation (RSI)	No insulation	No insulation
Floor on ground	Tile on 8 in. Concrete slab	Tile on 8 in. Concrete slab
Infiltration (ACH)	1.0	0.75
Outdoor air (l/sec/person)	10	10
HVAC system	Ventilation type: CAV Heating efficiency: 0.75 Cooling COP: 1.8 Cooling type: chilled water	Ventilation type: CAV Heating efficiency: 0.75 Cooling COP: 2.5 Cooling type: chilled water
SHW system	Electric storage heater	Electric storage heater

Table 3.3: Building R1 – Post-1975 and current levels

Item	*Post 1975*	*Current*
Description of building: *# of storeys:* *10 above and 2 below ground* *Floor area: 24,150 m^2* *Volume: 84,525 m^3*	Heating fuel: natural gas Cooling fuel: electricity External wall: Brick veneer on concrete block with 2.5 in air space ½ plaster, rigid insulation Roof: Metal roofing deck Windows: Double glazed Medium reflectivity blinds	Daylighting with light dimming 60% air to air heat recovery
Guides/standards	ASHRAE – 1977, MNECB – 1997	ASHRAE – 1977 MNECB – 1997
Lighting load (W/m^2)	17.8	10.0
Lighting level (Lux)	500	500
Equip/appliance load (W/m^2)	30	30
Elevator load (kW)	4 x 30	4 x 30
Occupant density (m^2/person)	20	18
Fenestration (%)	50	50
Fenestration U-value ($W/m^2 \cdot C$)	3.40 (SGHC = 0.47)	1.8 (SGHC = 0.41)
Wall U-value ($W/m^2 \cdot C$)	1.16	0.55
Roof U-value ($W/m^2 \cdot C$)	0.64	0.47
Below grade wall (RSI)	No insulation	No insulation
Perimeter floor insulation (RSI)	No insulation	No insulation
Floor on ground	Tile on 8 in. concrete slab	Tile on 8 in. concrete slab
Infiltration (ACH)	0.5	0.5
Outdoor air (l/sec/person)	10	10
HVAC system	Ventilation type: VAV (turndown ratio = 0.3) Heating efficiency: 0.75 Cooling cop: 5.2 Cooling type: chilled water	Heating Efficiency 0.95 w/ gas preheat Add economizer
SHW system	Electric storage heater	Electric storage heater

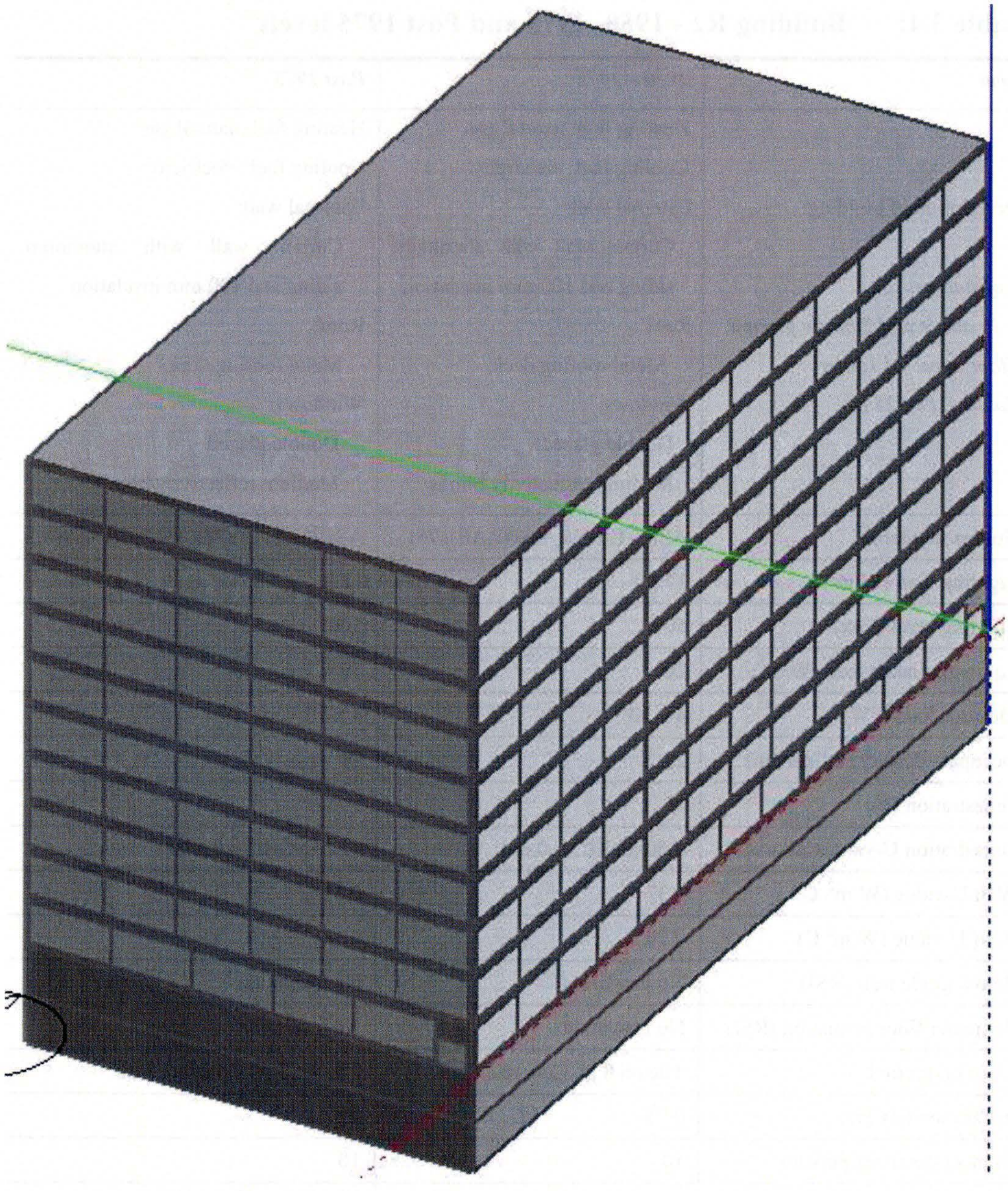

Figure 3.3: Building Type R2 – Large building with aluminum curtain wall construction

Table 3.4: Building R2 - 1950- 1975 and Post 1975 levels

Item	*1950 – 1975*	*Post 1975*
Description of building: *# of storeys:* *10 above and 2 below ground* *Floor area: 24,150 m^2* *Volume: 84,525 m^3*	Heating fuel: natural gas Cooling fuel: electricity External wall: Curtain wall with aluminum siding and 100 mm insulation Roof: Metal roofing deck Windows: Double glazed Medium reflectivity blinds	Heating fuel: natural gas Cooling fuel: electricity External wall: Curtain wall with aluminum siding and 100 mm insulation Roof: Metal roofing deck Windows: Double glazed Medium reflectivity blinds
Guides/standards	ASHVE 1950, ASHRAE 1961	ASHRAE – 1977, MNECB - 1997
Lighting load (W/m^2)	17.8	17.8
Lighting level (Lux)	500	500
Equip/appliance load (W/m^2)	20	30
Elevator load (kW)	4 x 30	4 x 30
Occupant density (m^2/person)	25	20
Fenestration (%)	85	100
Fenestration U-value ($W/m^2.C$)	4.50 (SGHC = 0.68)	3.40 (SGHC = 0.47)
Wall U-value ($W/m^2. C$)	0.37	0.37
Roof U-value ($W/m^2.C$)	0.74	0.64
Below grade wall (RSI)	No insulation	No insulation
Perimeter floor insulation (RSI)	No insulation	No insulation
Floor on ground	Tile on 8 in. Concrete Slab	Tile on 8 in. Concrete Slab
Infiltration (ACH)	0.75	0.5
Outdoor air (l/sec/person)	10	10
HVAC system	Ventilation Type: CAV Heating Efficiency: 0.75 Cooling COP: 2.5 Cooling Type: Chilled Water	Ventilation Type: VAV (Turndown Ratio = 0.3) Heating Efficiency: 0.75 Cooling COP: 5.2 Cooling Type: Chilled Water
SHW system	Electric Storage Heater, 95% Efficiency	Electric Storage Heater, 95% Efficiency

Table 3.5: Building R2 - Current levels

Item	***Current***
Description of building: *# of storeys:* *10 above and 2 below ground* *Floor area: 24,150 m^2* *Volume: 84,525 m^3*	Daylighting with light dimming 60% air to air heat recovery
Guides/standards	ASHRAE – 1977, MNECB - 1997
Lighting load (W/m^2)	10.0
Lighting level (Lux)	500
Equip/appliance load (W/m^2)	30
Elevator load (kW)	4 x 30
Occupant density (m^2/person)	18
Fenestration (%)	100
Fenestration U-value (W/m^2·C)	1.8 (SGHC = 0.41)
Wall U-value (W/m^2· C)	0.37
Roof U-value (W/m^2·C)	0.47
Below grade wall (RSI)	No insulation
Perimeter floor insulation (RSI)	No insulation
Floor on ground	Tile on 8 in. Concrete Slab
Infiltration (ACH)	0.5
Outdoor air (l/sec/person)	10
HVAC system	Heating Efficiency 0.95 w/ Gas Preheat Add Economizer
SHW system	Electric Storage Heater, 95% Efficiency

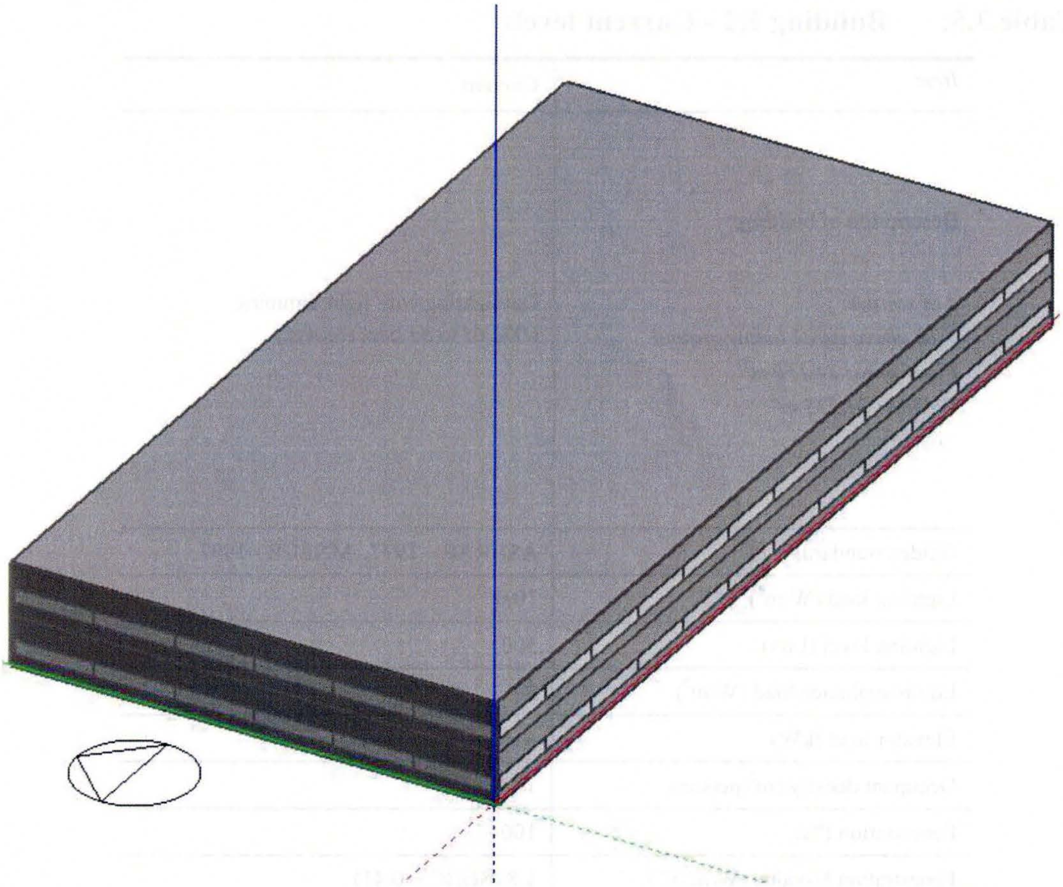

Figure 3.4: Building Type R3 Small Archetype

Table 3.6: Building R3 – Pre 1950 and 1950 - 1975

Item	*Pre – 1950*	*1950 – 1975*
Description of building: *# of storeys:* *2 above ground* *Floor area: 4,200 m^2* *Volume: 14,700 m^3*	Heating fuel: natural gas Cooling fuel: electricity External wall: Brick veneer on concrete block with ½ plaster, rigid insulation Roof: 2 in. Built-up concrete on 1 in. Rigid insulation Windows: Single glazed	Heating fuel: natural gas Cooling fuel: electricity External wall: Brick veneer on concrete block with ½ plaster, rigid insulation Roof: 2 in. Built-up concrete on 1 in. Rigid insulation Windows: Double glazed Medium reflectivity blinds
Guides/standards	ASHVE – 1939	ASHVE – 1950, ASHRAE 1961
Lighting load (W/m^2)	26	17.8
Lighting level (Lux)	500	500
Equip/appliance load (W/m^2)	10	20
Elevator load (kW)	1 x 30	1 x 30
Occupant density (m^2/person)	30	25
Fenestration (%)	30	40
Fenestration U-value (W/m^2·C)	6.42 (SGHC = 0.81)	4.50 (SGHC = 0.68)
Wall U-value (W/m^2· C)	1.21	1.21
Roof U-value (W/m^2·C)	1.36	0.74
Below grade wall (RSI)	No insulation	No insulation
Perimeter floor insulation (RSI)	No insulation	No insulation
Floor on ground	Tile on 8 in. Concrete Slab	Tile on 8 in. Concrete Slab
Infiltration (ACH)	1.0	0.75
Outdoor air (l/sec/person)	10	10
HVAC system	Ventilation type: CAV Heating efficiency: 0.75 Cooling cop: 1.8 Cooling type: chilled water	Ventilation type: CAV Heating efficiency: 0.75 Cooling cop: 2.6 Cooling type: chilled water
SHW system	Electric storage heater	Electric storage heater

Table 3.7: Building R3 – Post 1975 to current levels

Item	*Post 1975*	*Current*
Description of building: *# of storeys:* *2 above ground* *Floor area: 4,200 m²* *Volume: 14,700 m³*	Heating fuel: natural gas Cooling fuel: electricity External wall: Brick veneer on concrete block with 2.5 in air space ½ plaster, rigid insulation Roof: 2 in. Built-up concrete on 1 in. Rigid insulation Windows: Double glazed Medium reflectivity blinds	Daylighting with light dimming 60% air to air heat recovery
Guides/standards	ASHRAE – 1977 MNECB – 1997	ASHRAE – 1977 MNECB – 1997
Lighting load (W/m^2)	17.8	10.0
Lighting level (Lux)	500	500
Equip/appliance load (W/m^2)	30	30
Elevator load (kW)	1 x 30	1 x 30
Occupant density (m^2/person)	20	18
Fenestration (%)	50	50
Fenestration U-value ($W/m^2 \cdot C$)	3.40 (SGHC = 0.47)	1.8 (SGHC = 0.41)
Wall U-value ($W/m^2 \cdot C$)	1.16	0.55
Roof U-value ($W/m^2 \cdot C$)	0.64	0.47
Below grade wall (RSI)	No insulation	No insulation
Perimeter floor insulation (RSI)	No insulation	No insulation
Floor on ground	Tile on 8 in. Concrete Slab	Tile on 8 in. Concrete Slab
Infiltration (ACH)	0.5	0.5
Outdoor air (l/sec/person)	10	10
HVAC system	Ventilation type: VAV Heating efficiency: 0.75 Cooling cop: 2.6 Cooling type: chilled water	Heating efficiency 0.95 w/ gas preheat And economizer
SHW system	Electric storage heater	Electric storage heater

3.3 Simulation Strategy

The variables, defined in Table 3.2 to Table 3.7 were used to develop a parametric analysis for systematically determining the effects of changes in construction practices. Of specific interest are the changes to the building envelope, HVAC system, and usage characteristics. Table 3.8 provides a list of these parameters and their respective range investigated in this study.

Table 3.8: Parameter range

Parameters	*Range*
Lighting load (W/m^2)	10 to 26 W/m^2
Equipment load (W/m^2)	15 to 65 W/m^2
Occupancy density (m^2/person)	18 to 30 m^2/person
Fenestration %	85% - 100% (Large curtain wall building) 30% - 50% (Large concrete panel building) 30% - 50% (Small building)
Fenestration U-value	1.8 to 6.42
Wall U-value	0.37 (Large curtain wall building) 0.35 – 1.21 (Large concrete panel building) 0.55 – 1.21 (Small building)
Roof U-value	0.47 – 0.74 (Large curtain wall building) 0.47 – 1.41 (Large concrete panel building) 0.47 – 1.36 (Small building)
Infiltration rate (ach)	1.0 to 0.1
Heating efficiency	75% to 95%
Cooling cop	1.7 to 5.2
Blinds?	Yes / No
Turndown ratio	Yes / No
Daylighting?	Yes / No
Heat recovery efficiency	0% to 60%
Gas pre-heat w/economizer?	Yes / No

In order to properly capture the effect that changing individual and multiple variables has on the energy consumption of a building, a method for simulating each variable change was developed. This simulation strategy centres on how the archetype scheme was developed. Since three main vintage points were chosen as representative stages in building construction practices, the variables associated with these three time periods were first defined and set as a starting point for variable alteration. In general the simulations were divided into a separate but repeated scheme for each archetype level. First the "Base Level" model was simulated for its energy consumption. Then, for each of the variables listed in Table 3.8, the "Base Level" variables were adjusted, individually, to reflect a jump in the archetype vintage. For example, for a building of the Pre-1950's era, the base lighting load was set to 26 W/m^2, then the lighting load was updated to 17.8 W/m^2 to reflect the difference between Pre-1950's levels and 1950-1975 levels. This process was repeated for each of the variables and for each of the archetype periods, including a "Retrofit" vintage which contained additional upgraded levels. After each of the individual simulations was completed, the effect on energy consumption was determined by dividing the updated consumption by the base level consumption.

In addition to the individual variable change simulations, several multiple interaction simulations were also performed. These additional simulations were limited to the variables for which the associated effect on energy consumption exceeded 10% and were limited to 3 level interactions. The simulation scheme can be summarized in Figure 3.5. The simulations performed using EnergyPlus were repeated for three cities representing different climatic regions, namely, Edmonton, Ottawa and Vancouver.

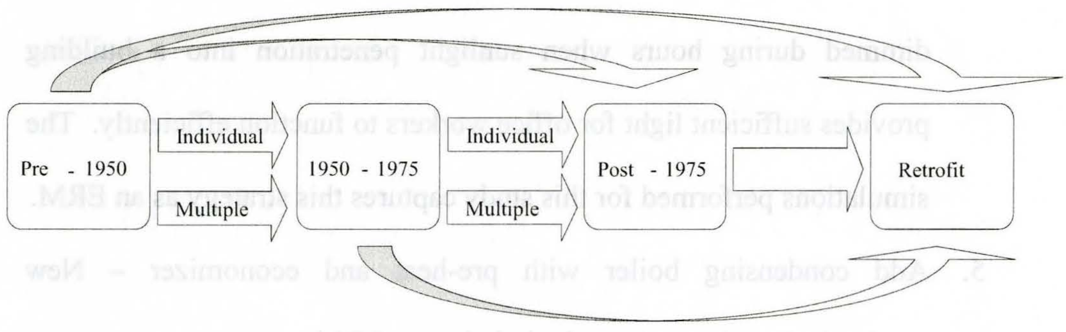

Figure 3.5: Representation of the simulation scheme

3.4 Energy Retrofit Measures

A total of six energy retrofit measures were chosen for this study which comply with the progress made in the construction and HVAC industry to reduce energy consumption. They include:

1. Reduce the lighting load to a value of 10 W/m^2 – This retrofit was chosen to aid in the representation of the impact of changing the majority of the lighting fixtures within a building to high efficiency fluorescent units.
2. Improve the Fenestration U-value – Improved U-values of windows were included to represent advances made through the years.

3. Improve the external Walls and Roof U-value – The U-value of the external walls and roofing has been improved with the introduction of new insulating materials and construction practices. The impact of this retrofit on the energy consumption is studied.
4. Add Perimeter Daylighting with light dimming – The lighting can be dimmed during hours when sunlight penetration into a building provides sufficient light for office workers to function efficiently. The simulations performed for this study captures this strategy as an ERM.
5. Add condensing boiler with pre-heat and economizer – New mechanical equipment was included as an ERM.
6. Add 60% air to air heat recovery – New HVAC technologies are included as ERMs.

In addition to the energy retrofits described, there were additional measures that were considered in order to comply with the new usage of the office buildings. These include an increase in the occupancy of the building and additions to the equipment and appliance loads. The former represents an increase in the number of people per square meter while the latter represents the introduction of computers and other office equipment.

3.5 Representative Building Modelling Results: Base Case

Figure 3.6 to Figure 3.14 present the energy consumption results for the base level for each of the building types and archetype vintages. Using EnergyPlus it was possible to break down the energy consumption into its various components. Breaking down the energy consumption in this manner allows for a better understanding of how the retrofit options affect consumption levels.

The results for the base cases of the representative building allows for an examination to be made on the differences that exist between buildings of similar construction characteristics situated in various climatic regions within Canada.

By first observing the breakdown in percentage of the use of energy for each of the components of the buildings, several key observations can be made.

1. The consumption of energy to supply the systems of lighting and appliances (process and computer loads) are consistent and unaffected by weather characteristics. This is an expected result and is useful in ensuring that the base models have been developed correctly.
2. The percentage of total electricity used for chiller operation was found to be the highest for buildings located in Vancouver followed by Ottawa and Edmonton. This trend was found to be consistent over all building types.

3. The percentage of energy used for heating a building is higher in Edmonton then in the other locations, with Vancouver requiring the least percentage for heating.

In determining the affects of location on the base case results for the representative buildings, it is also useful to calculate the difference in consumption between the cities modelled. By normalizing the results with the consumptions found in Ottawa, it was possible to examine the increased or decreased energy consumption requirements. It is observed from Table 3.9 that Edmonton buildings consume the most energy for heating where as buildings located in Ottawa and Vancouver consume the lowest. Ottawa is the highest consumer of energy for cooling and overall Vancouver buildings consume the least amount of energy.

Table 3.9: Base case consumption normalized to Ottawa

Building Type R1			
	Ottawa	Edmonton	Vancouver
Pumps	100%	84%	79%
Fans	100%	91%	76%
Chiller	100%	82%	83%
Boiler	100%	138%	70%
Building Type R2			
	Ottawa	Edmonton	Vancouver
Pumps	100%	90%	80%
Fans	100%	100%	84%
Chiller	100%	89%	88%
Boiler	100%	106%	47%
Building Type R3			
	Ottawa	Edmonton	Vancouver
Pumps	100%	81%	80%
Fans	100%	80%	67%
Chiller	100%	76%	79%
Boiler	100%	109%	62%

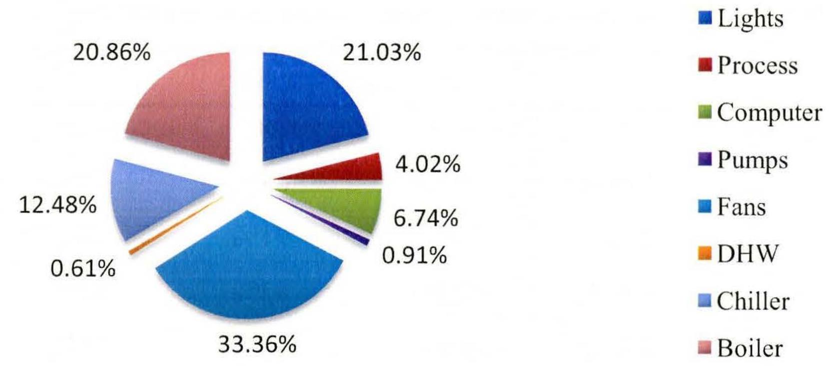

Figure 3.6: Energy consumption breakdown for building type R1 in Vancouver, Pre - 1950

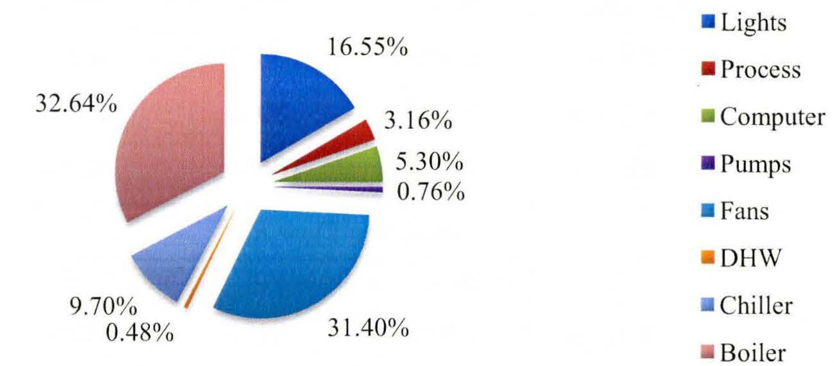

Figure 3.7: Energy consumption breakdown for building type R1 in Edmonton, Pre - 1950

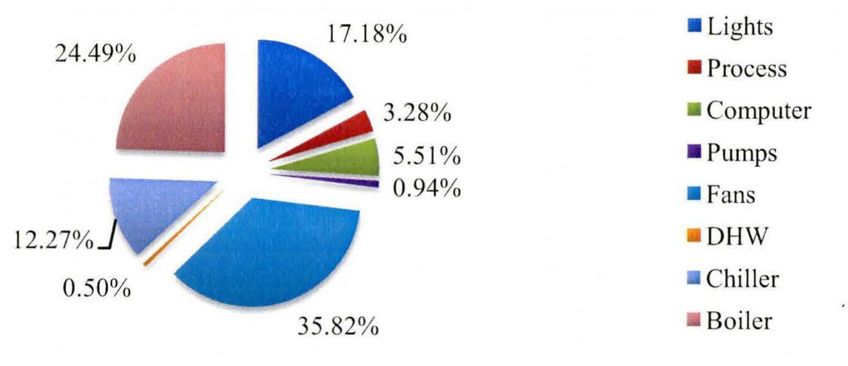

Figure 3.8: Energy consumption breakdown for building type R1 in Ottawa, Pre - 1950

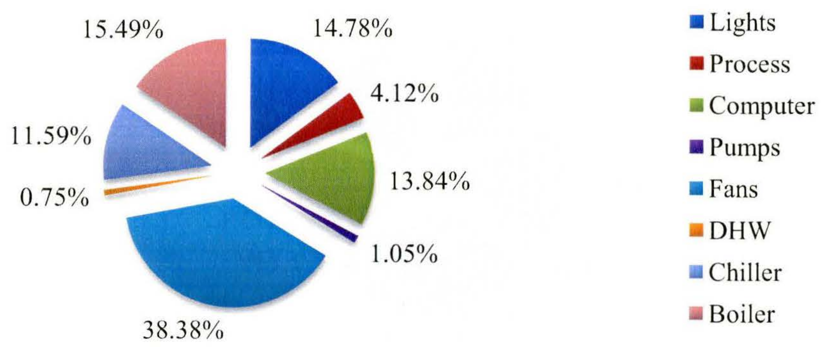

Figure 3.9: Energy consumption breakdown for building type R2 in Vancouver, Pre - 1950

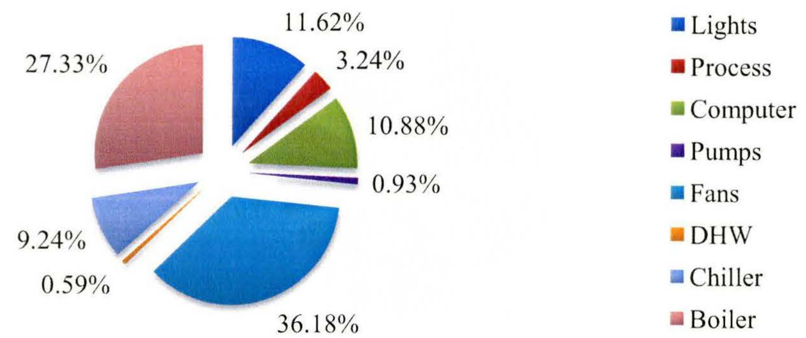

Figure 3.10: Energy consumption breakdown for building type R2 in Edmonton, Pre - 1950

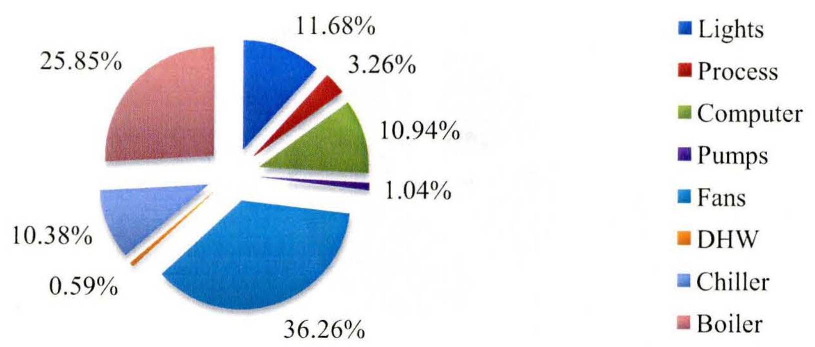

Figure 3.11: Energy consumption breakdown for building type R2 in Ottawa, Pre - 1950

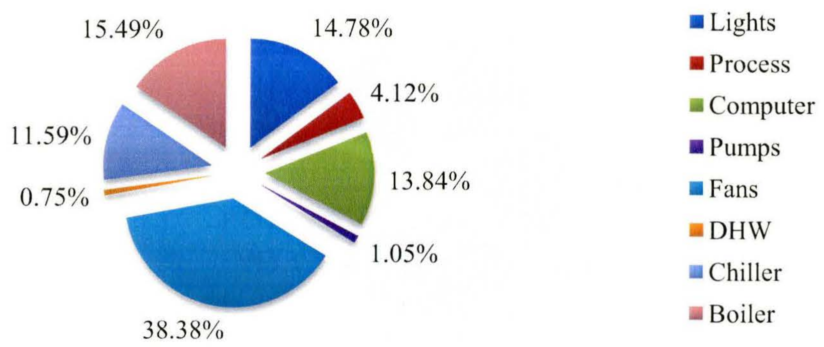

Figure 3.9: Energy consumption breakdown for building type R2 in Vancouver, Pre - 1950

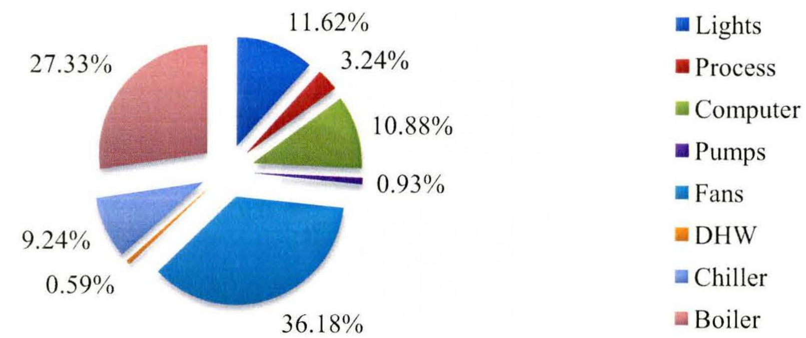

Figure 3.10: Energy consumption breakdown for building type R2 in Edmonton, Pre - 1950

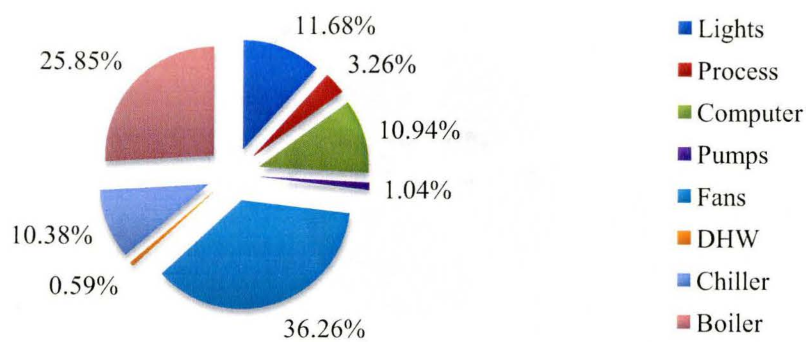

Figure 3.11: Energy consumption breakdown for building type R2 in Ottawa, Pre - 1950

3.6 Effects of Retrofit Implementation

Based on the tables for the three building types presented in Section 3.2 one can see that the movement between archetype levels results in an incremental change of various aspects of the building's design. Each of these incremental changes are presented in Table 3.10 to Table 3.14 for each of the building types. Reference numbers were used to aid in the graphical representation of the results that follow. These retrofits were applied both individually and in combination. The combined effect of a retrofit measure is of interest since it is not clearly known what effect two or more retrofit measures have when applied simultaneously. For example, two individual retrofits may reduce consumption by 15%, but together their additive effect could be less than 20%. Knowing the value of the combined effects, one can develop appropriate strategies for determining cost effective retrofits that consider single and multiple ERM applications.

Table 3.10: Building type R1 – Large concrete wall retrofit list

Ref. #	*Retrofit Description*	*Associated Vintage*
1	Base model	Pre - 1950
2	*Ret.* Medium reflectivity blinds	Pre - 1950
3	*Increase in appliance load 10 to 20*	Pre - 1950
4	*Ret.* Cooling COP 1.8 to 2.5	Pre - 1950
5	*Ret.* Infiltration 1 to 0.75	Pre - 1950
6	*Ret.* Lighting load 26 to 17.8	Pre - 1950
7	*Occupancy change 30 to 25* m^2*/person*	Pre - 1950
8	*Ret.* Percent fenestration 30 to 40	Pre - 1950
9	*Ret.* Roof to U-value 0.74	Pre - 1950
10	*Ret.* Windows to U-value 4.50	Pre - 1950
11	*Ret.* Chiller COP 1.8 to 5.2	Pre - 1950
12	*Increase in appliance load 10 to 30*	Pre - 1950
13	*Ret.* HVAC CAV to VAV (0.3)	Pre - 1950
14	*Ret.* Infiltration 1.0 to 0.5	Pre - 1950
15	*Ret.* Lighting 26 to 10	Pre - 1950
16	*Ret.* Medium reflectivity blinds	Pre - 1950
17	*Occupancy change 30 to 20*	Pre - 1950
18	*Ret.* Percent windows 30 to 50	Pre - 1950
19	*Ret.* Roof U-value 1.41 to 0.64	Pre - 1950
20	*Ret.* Wall U-value 1.21 to 1.16	Pre - 1950
21	*Ret.* Windows U-value 6.42 to 3.40	Pre - 1950
22	*Ret.* 60% heat recovery	Pre - 1950
23	*Ret.* Daylighting	Pre - 1950
24	*Occupancy change 30 to 18*	Pre - 1950
25	*Ret.* Roof U-value 1.41 to 0.47	Pre - 1950
26	*Ret.* Wall U-value 1.21 to 0.55	Pre - 1950
27	*Ret.* Window U-value 6.42 to 1.8	Pre - 1950

Table 3.11: Building Type R1 – Large concrete wall retrofit list (cont'd)

Ref. #	*Retrofit Description*	*Associated Vintage*
28	Base model	1950 - 1975
29	*Increase in appliance load 20 to 30*	1950 - 1975
30	*Ret.* Chiller COP 2.5 to 5.2	1950 - 1975
31	*Ret.* HVAC CAV to VAV (0.3)	1950 - 1975
32	*Ret.* Infiltration 0.75 to 0.5	1950 - 1975
33	*Occupancy change 25 to 20* m^2*/person*	1950 - 1975
34	*Ret.* Roof 0.74 to 0.64	1950 - 1975
35	*Ret.* Wall 1.21 to 1.16	1950 - 1975
36	*Ret.* Windows 40 to 50 percent	1950 - 1975
37	*Ret.* Windows from 4.50 to 3.4	1950 - 1975
38	*Ret.* 60% heat recovery	1950 - 1975
39	*Ret.* Add preheat econ and 0.95 efficiency	1950 - 1975
40	*Ret.* Daylighting	1950 - 1975
41	*Ret.* Lighting load 17.8 to 10	1950 - 1975
42	*Occupancy change 25 to 18*	1950 - 1975
43	*Ret.* Roof U-value 0.74 to 047	1950 - 1975
44	*Ret.* Wall U-value 1.21 to 0.55	1950 - 1975
45	*Ret.* Window U-value 4.50 to 1.8	1950 - 1975
46	Base model	Post - 1975
47	*Ret.* 60% heat recovery	Post - 1975
48	*Ret.* Heating efficiency to 0.95 + eco-preheat	Post - 1975
49	*Ret.* Improved walls U-value 1.16 to 0.55	Post - 1975
50	*Ret.* Lighting 17.8 to 10	Post - 1975
51	*Ret.* Lighting linear light dimming	Post - 1975
52	*Ret.* Occupancy 20 to 18	Post - 1975
53	*Ret.* Roof U-value 0.64 to 0.47	Post - 1975
54	*Ret.* Windows U-value 3.4 to 1.8	Post - 1975

Table 3.12: Building Type R2 – Large curtain wall retrofit list

Ref #	*Retrofit Description*	*Ref #*
1	Base model	1950 - 1975
2	*Increase appliance load 20 to 30*	1950 – 1975
3	*Ret.* Chiller COP 2.5 to 5.2	1950 – 1975
4	*Ret.* HVAC CAV to VAV (proportional at 0.3)	1950 – 1975
5	*Ret.* Infiltration 0.75 to 0.5	1950 - 1975
6	*Occupancy change 25 to 20*	1950 – 1975
7	*Ret.* Roof U-value 0.74 to 0.64	1950 – 1975
8	*Ret.* Windows percent 85 to 100	1950 – 1975
9	*Ret.* Windows U-value 4.5 to 3.4	1950 - 1975
10	*Ret.* 60 heat recovery	1950 - 1975
11	*Ret.* Daylighting	1950 - 1975
12	*Ret.* Heating eff. 0.95 + econ + preheat	1950 - 1975
13	*Ret.* Lighting load 17.8 to 10	1950 - 1975
14	*Ret.* Occupancy 25 to 18	1950 - 1975
15	*Ret.* Roof U-value 0.74 to 0.47	1950 - 1975
16	*Ret.* Windows U-value 4.50 to 1.8	1950 - 1975
17	Base model	Post 1950
18	*Ret.* Added air to air heat recovery	Post 1950
19	*Ret.* Boiler eff. 0.95 adding economizer and preheat	Post 1950
20	*Ret.* Lighting 17.8 to 10	Post 1950
21	*Ret.* Daylighting	Post 1950
22	*Occupancy change 20 to 18*	Post 1950
23	*Ret.* Roof U-value 0.64 to 0.47	Post 1950
24	*Ret.* Window U-value from 3.4 to 1.8	Post 1950

Table 3.13: Building Type R3 – Small building retrofit list

Ref #	*Retrofit Description*	*Ref #*
1	Base model	Pre - 1950
2	*Ret.* Add medium reflectivity blinds	Pre - 1950
3	*Ret.* Change lighting 26 to 17.8	Pre - 1950
4	*Increase Appliance load 10 to 20*	Pre - 1950
5	*Ret.* Infiltration 1 to 0.75	Pre - 1950
6	*Occupancy change 30 to 25*	Pre - 1950
7	*Ret.* Percent fenestration 30 to 40	Pre - 1950
8	*Ret.* Roof 1.36 to 0.74	Pre - 1950
9	*Ret.* Windows from 6.42 to 4.50	Pre - 1950
10	*Ret.* Add medium reflectivity blinds	Pre - 1950
11	*Ret.* Change lighting 26 to 17.8	Pre - 1950
12	*Ret.* Cooling COP 1.8 to 2.6	Pre - 1950
13	*Increase Appliance load 10 to 30*	Pre - 1950
14	*Ret.* HVAC CAV to VAV(0.3)	Pre - 1950
15	*Ret.* Infiltration 1 to 0.5	Pre - 1950
16	*Occupancy change 30 to 20*	Pre - 1950
17	*Ret.* Percent windows 30 to 50	Pre - 1950
18	*Ret.* Roof U-value 1.36 to 0.47	Pre - 1950
19	*Ret.* Wall U-value to 1.16	Pre - 1950
20	*Ret.* Windows U-value to 3.40	Pre - 1950
21	*Ret.* Air to air heat recovery	Pre - 1950
22	*Ret.* Boiler eff. 0.95 + econ + preheat	Pre - 1950
23	*Ret.* Daylighting	Pre - 1950
24	*Ret.* Lighting load 26 to 10	Pre - 1950
25	*Occupancy change 30 to 18*	Pre - 1950
26	*Ret.* Roof U-value 1.36 to 0.64	Pre - 1950
27	*Ret.* Wall U-value 1.21 to 0.55	Pre - 1950
28	*Ret.* Windows U-value to 6.42 to 1.8	Pre - 1950

Table 3.14: Building Type R3 – Small building retrofit list (cont'd)

Ref #	***Retrofit Description***	***Ref #***
29	Base model	1950 - 1975
30	*Ret.* HVAC CAV to VAV (0.3)	1950 - 1975
31	*Increase in appliance loads 20 to 30*	1950 - 1975
32	*Ret.* Infiltration 0.75 to 0.5	1950 - 1975
33	*Occupancy change 25 to 20*	1950 - 1975
34	*Ret.* Percent fenestration 40 to 50	1950 - 1975
35	*Ret.* Roof U-value 0.74 to 0.64	1950 - 1975
36	*Ret.* Wall U-value 1.21 to 1.16	1950 - 1975
37	*Ret.* Windows U-value 4.50 to 3.4	1950 - 1975
38	*Ret.* Air to air heat recovery	1950 - 1975
39	*Ret.* Boiler eff. 0.95 + econ + preheat	1950 - 1975
40	*Ret.* Daylighting	1950 - 1975
41	*Ret.* Lighting load 17.8 to 10	1950 - 1975
42	*Occupancy change 25 to 18*	1950 - 1975
43	*Ret.* Roof U-value 0.74 to 0.47	1950 - 1975
44	*Ret.* Walls U-value 1.21 to 0.55	1950 - 1975
45	*Ret.* Windows U-value 4.50 to 1.8	1950 - 1975
46	Base model	Post - 1975
47	*Ret.* Added air to air heat recovery	Post - 1975
48	*Ret.* Added lighting dimming	Post - 1975
49	*Ret.* Heating to 0.95+econo+preheat	Post - 1975
50	*Ret.* Lighting 17.8 to 10	Post - 1975
51	*Occupancy change 20 to 18*	Post - 1975
52	*Ret.* Roof U-value 0.64 to 0.47	Post - 1975
53	*Ret.* Wall U-value 1.16 to 0.55	Post - 1975
54	*Ret.* Windows U-value 3.4 to 1.8	Post - 1975

3.6.1 Modelling Results: Individual ERM Application

The modelling results are presented through the use of bar plots for each city and for each building type in Figure 3.15 to Figure 3.38. These plots will help to highlight the retrofits that have the largest impact on the energy consumption of each building. The data obtained for each of these plots was calculated using the base case consumption data for each archetype as a criterion for normalization. As such, the simulation results for each retrofit implementation were divided by the energy consumption of the base case model.

When analyzing the effects of retrofit opportunities it is important to first note that when normalizing the data in which the improvements to the building described in section 3.4 were included, attention was paid to not include the effects of non-ERM building changes. As a result, the effect of an increase in occupancy or change in appliance load was not reflected in the effects calculated for the remaining ERMs.

From the results, the retrofits which have the highest and lowest impact on energy consumption were different for each building archetype.

The retrofit which caused the largest reduction in energy consumption for building R1 over all archetype years was the reduction of the infiltration rate of the building. Reducing the infiltration rate can be accomplished by improving the overall tightness of the building envelope. The savings in natural gas experienced varied between 41% in Ottawa, 44% in Edmonton and 30% in Vancouver from the original consumption levels. A similar trend was found for buildings R2 and R3 where the maximum savings in natural gas overshadowed the other ERMs. The electrical consumption savings that result from an improvement in the tightness of a building are negligible in comparison.

Wall and window U-values were next in line for largest reducers in energy consumption with the greatest benefits observed in building R2. This is likely due to the large percentage of windows possessed by this building type. Values between 70% and 75% of base model consumptions were noted.

When changes to a building's characteristics occurred that were not the direct result of the application of an ERM, benefits to the energy consumption levels were still present. When appliance loads or occupancy levels were increased, the demands on the heating systems were consistently reduced due to the excess heat gains that result. In contrast, these excess heat gains have a negative effect on the cooling requirements of a building resulting in increased electricity needs.

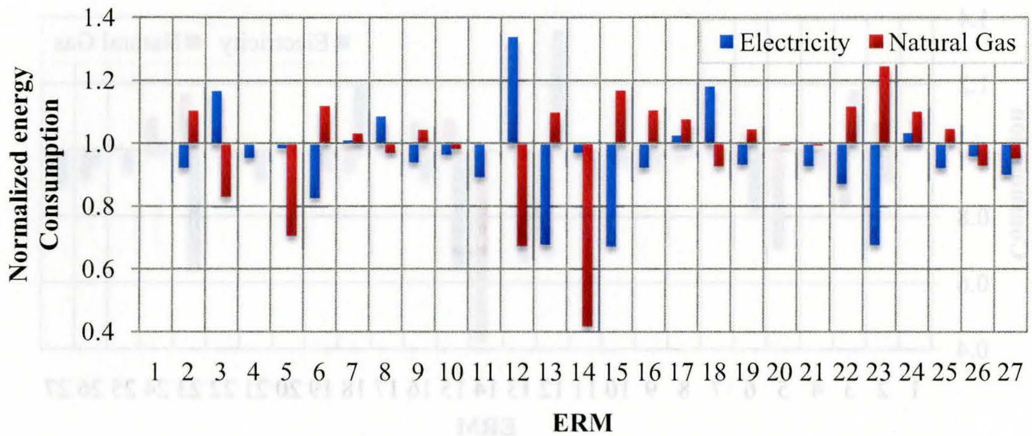

Figure 3.15: Consumption change for pre – 1950 building R1 in Ottawa

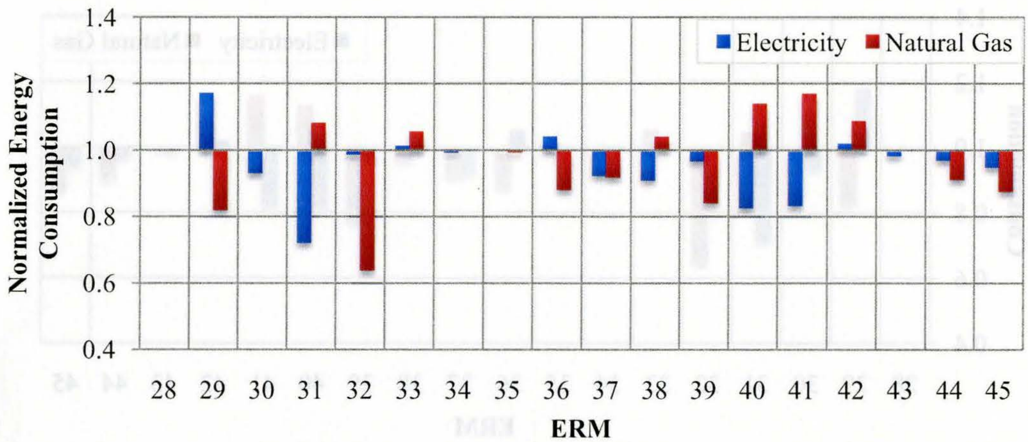

Figure 3.16: Consumption change for 1950 – 1975 building R1 in Ottawa

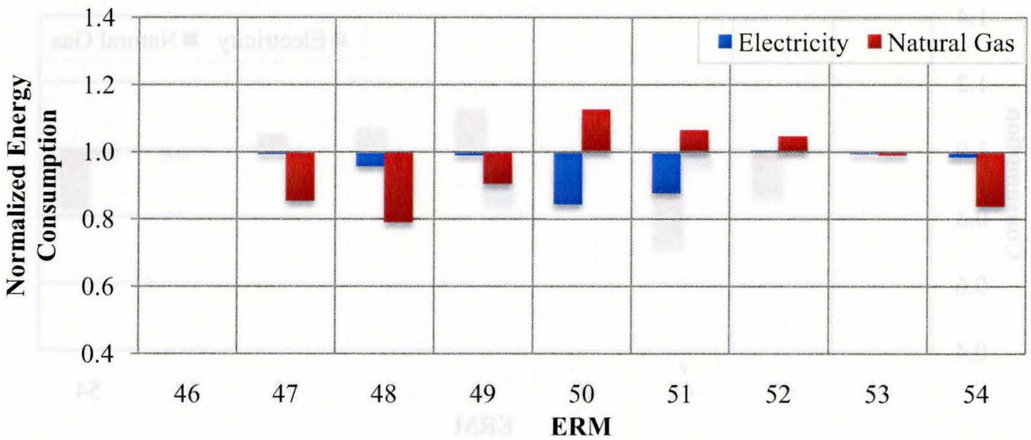

Figure 3.17: Consumption change for post – 1975 building R1 in Ottawa

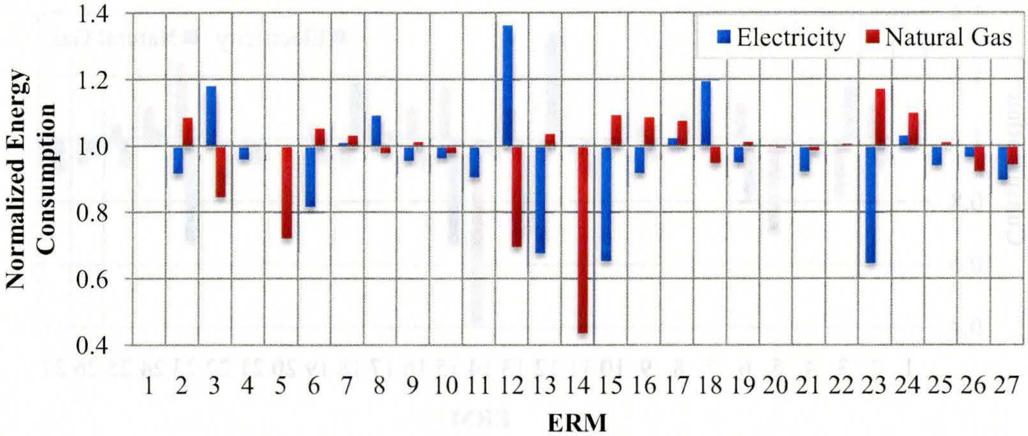

Figure 3.18: Consumption change for pre – 1950 building R1 in Edmonton

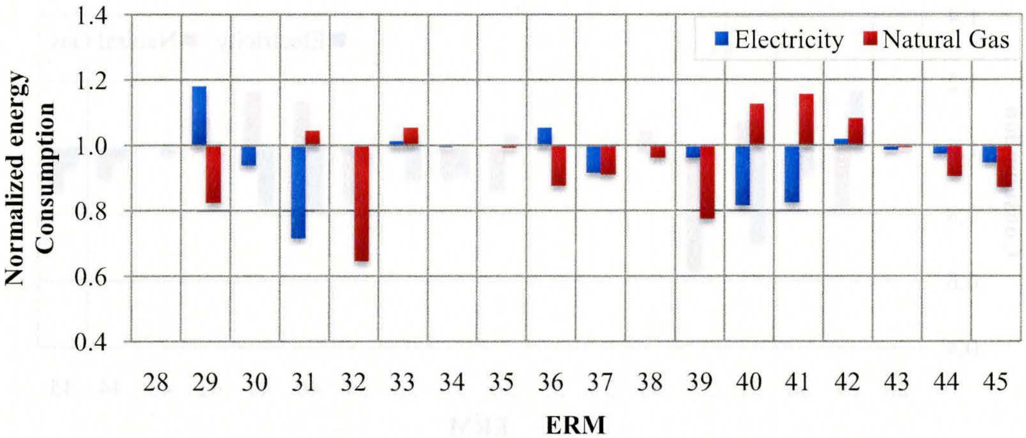

Figure 3.19: Consumption change for 1950 – 1975 building R1 in Edmonton

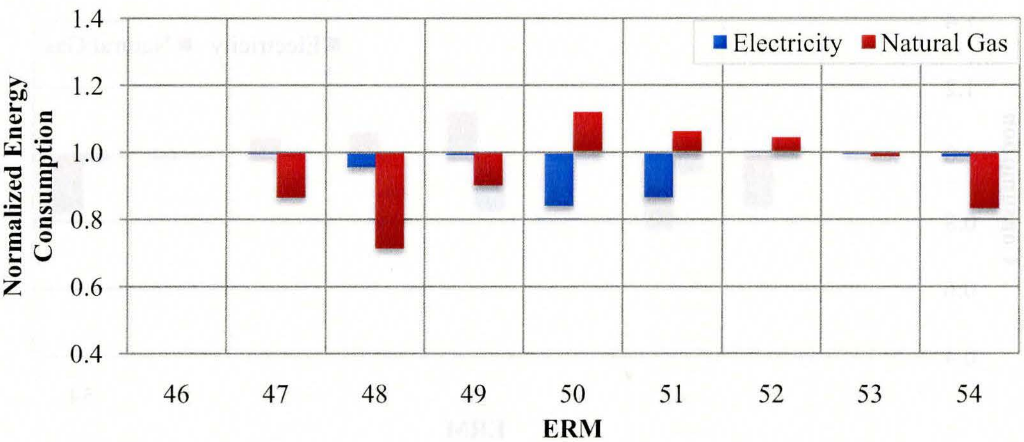

Figure 3.20: Consumption change for post – 1975 building R1 in Edmonton

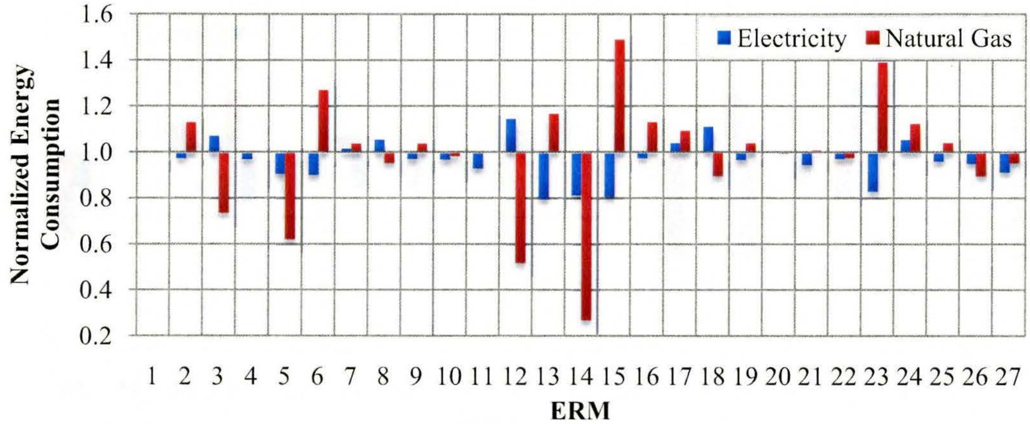

Figure 3.21: Consumption change for pre – 1950 building R1 in Vancouver

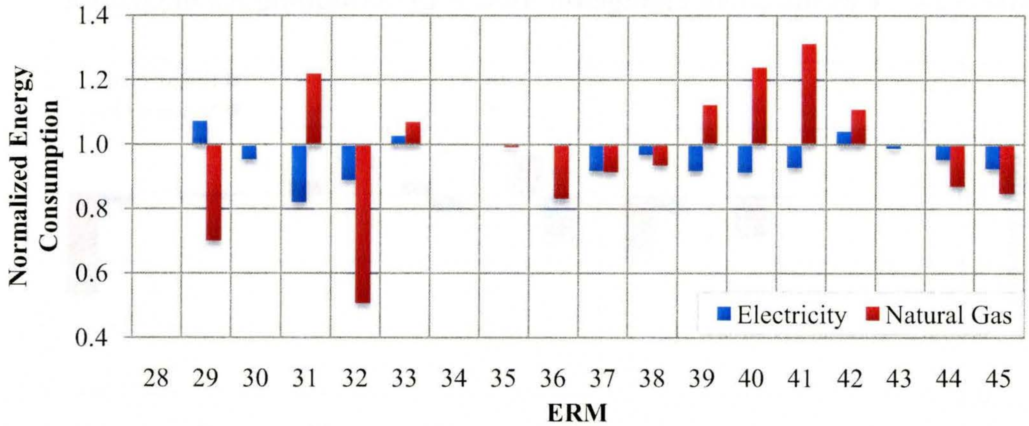

Figure 3.22: Consumption change for 1950 – 1975 building R1 in Vancouver

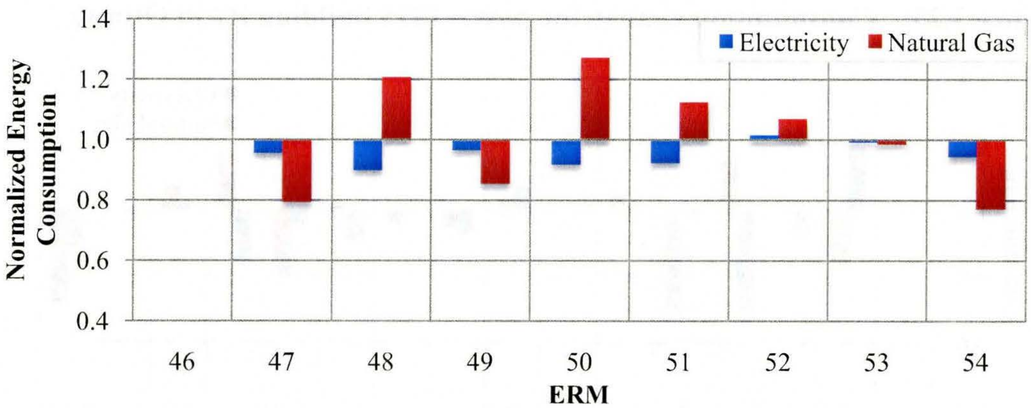

Figure 3.23: Consumption change for post – 1975 building R1 in Vancouver

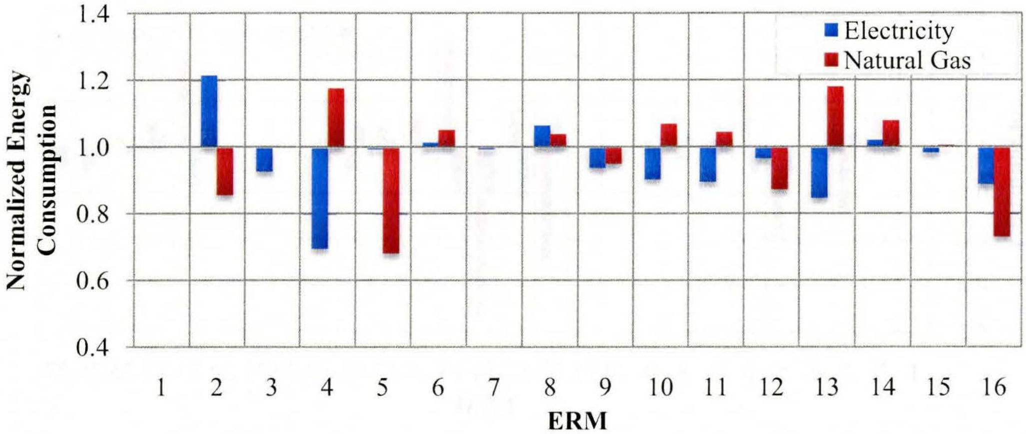

Figure 3.24: Consumption change for 1950 – 1975 building R2 in Ottawa

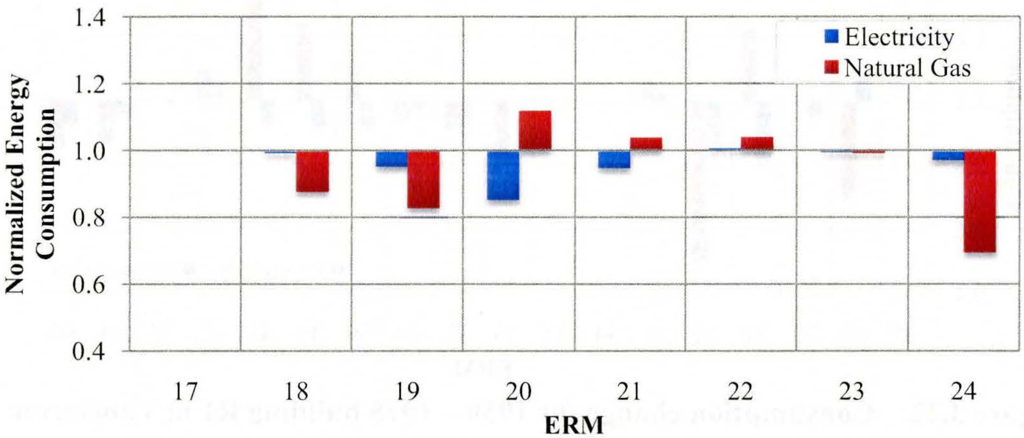

Figure 3.25: Consumption change for post – 1975 building R2 in Ottawa

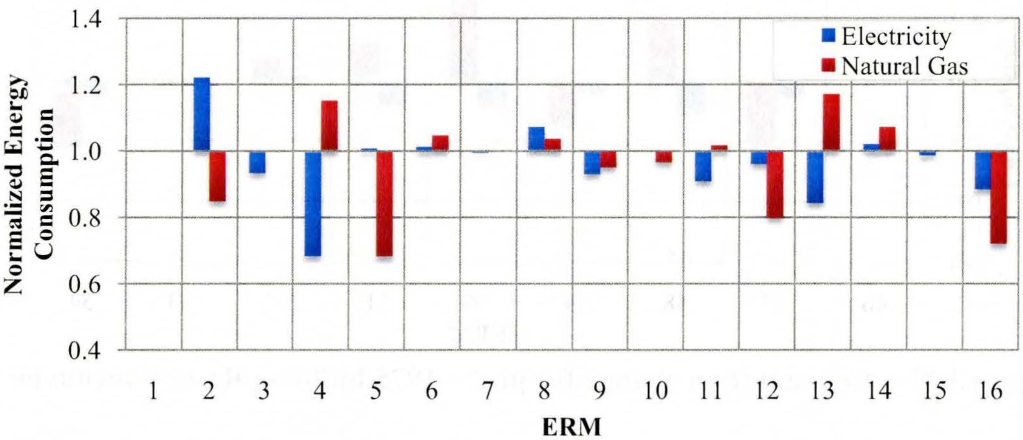

Figure 3.26: Consumption change for 1950 – 1975 building R2 in Edmonton

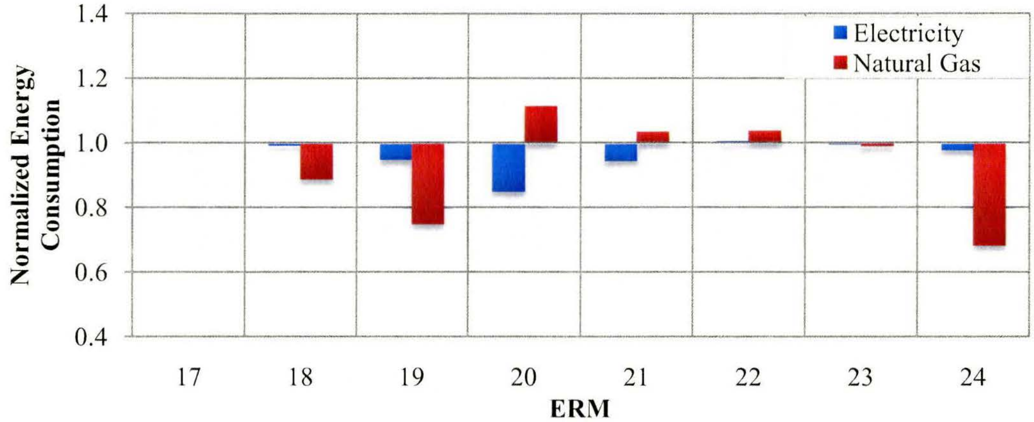

Figure 3.27: Consumption change for post – 1975 building R2 in Edmonton

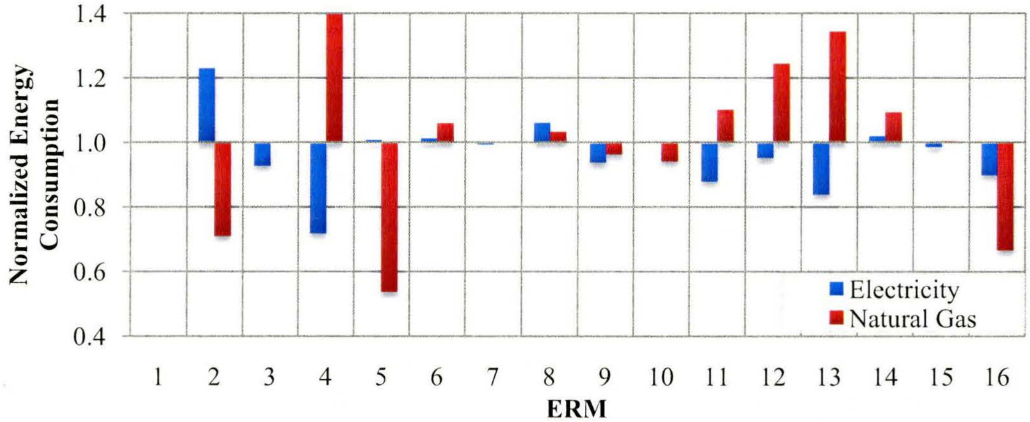

Figure 3.28: Consumption change for 1950 – 1975 building R2 in Vancouver

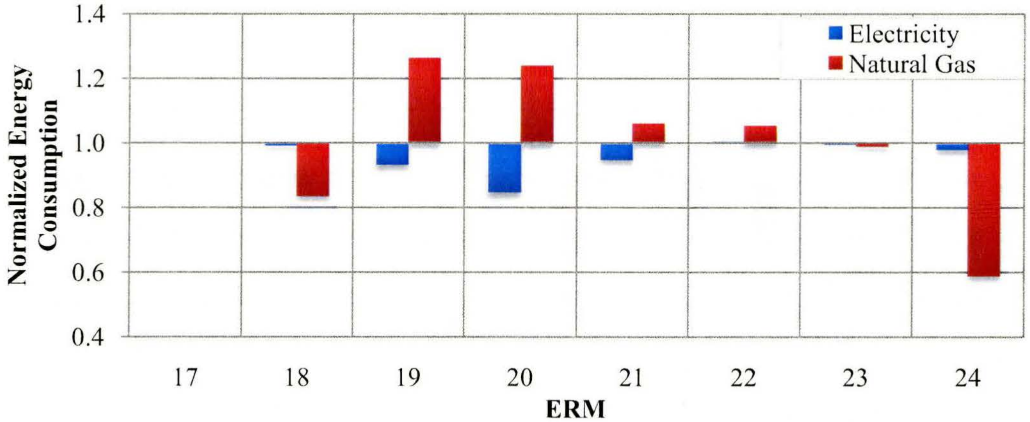

Figure 3.29: Consumption change for post – 1975 building R2 in Vancouver

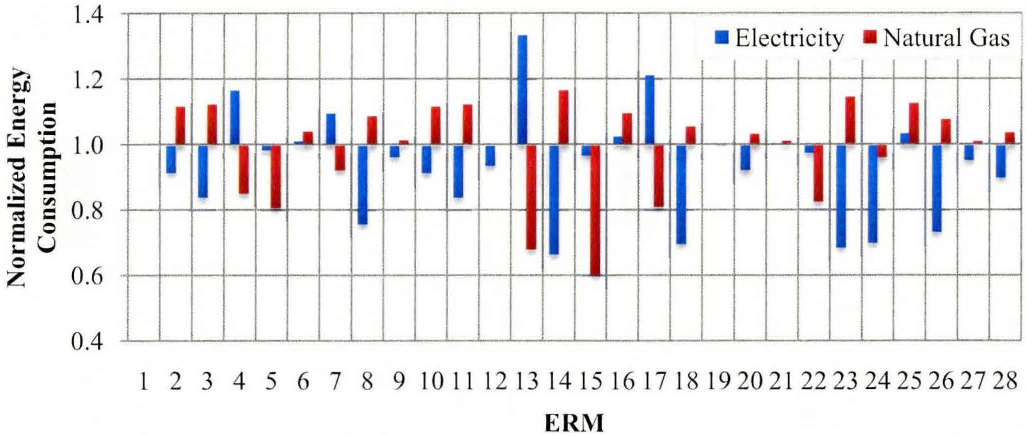

Figure 3.30: Consumption change for pre – 1950 building R3 in Ottawa

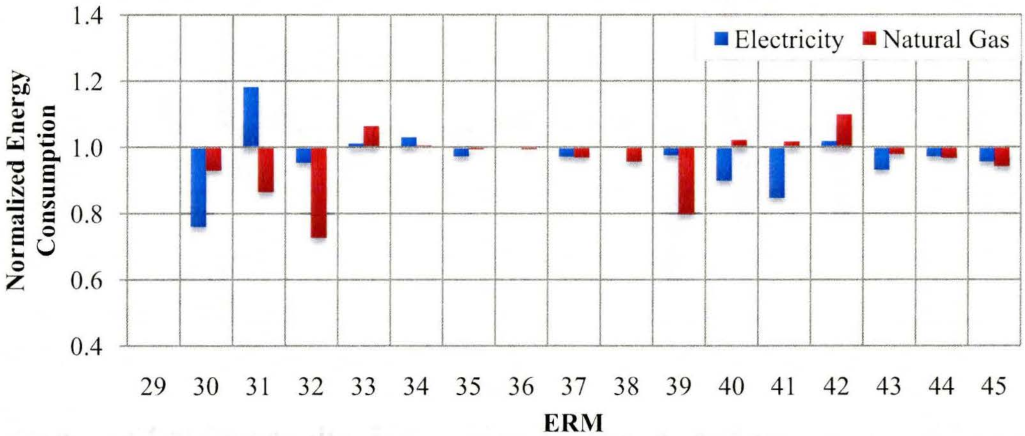

Figure 3.31: Consumption change for 1950 – 1975 building R3 in Ottawa

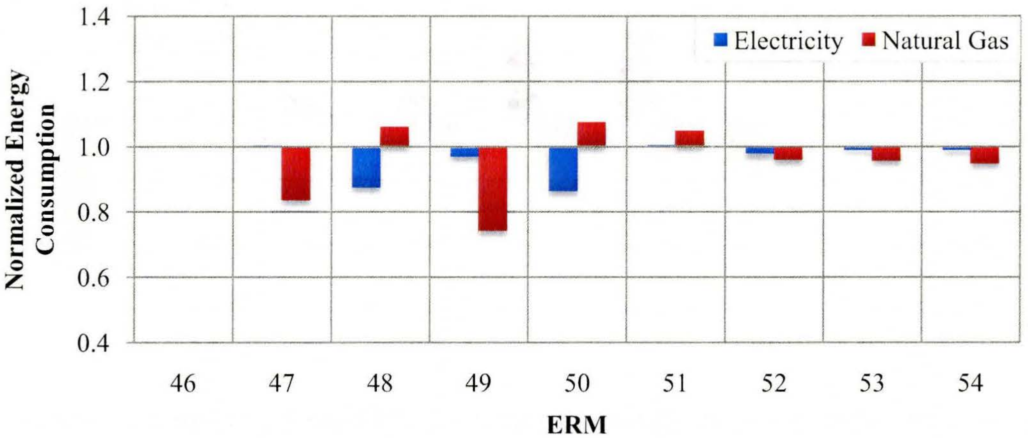

Figure 3.32: Consumption change for post – 1975 building R3 in Ottawa

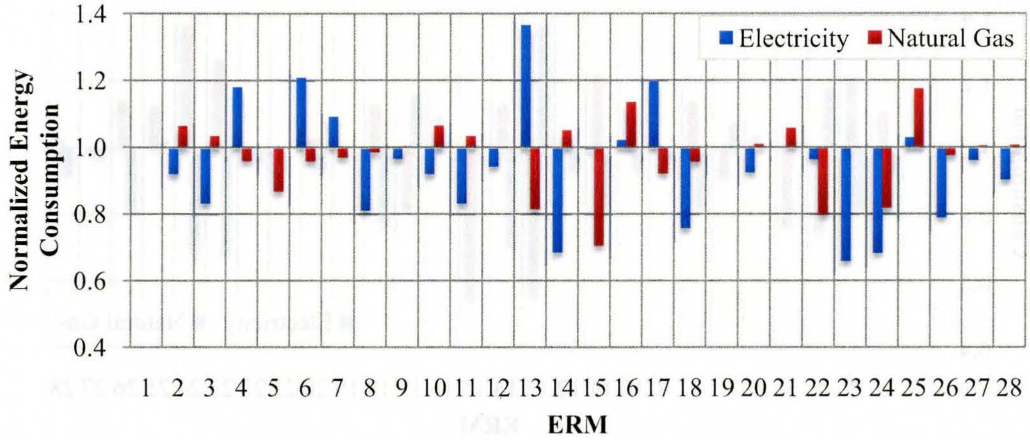

Figure 3.33: Consumption change for pre – 1950 building R3 in Edmonton

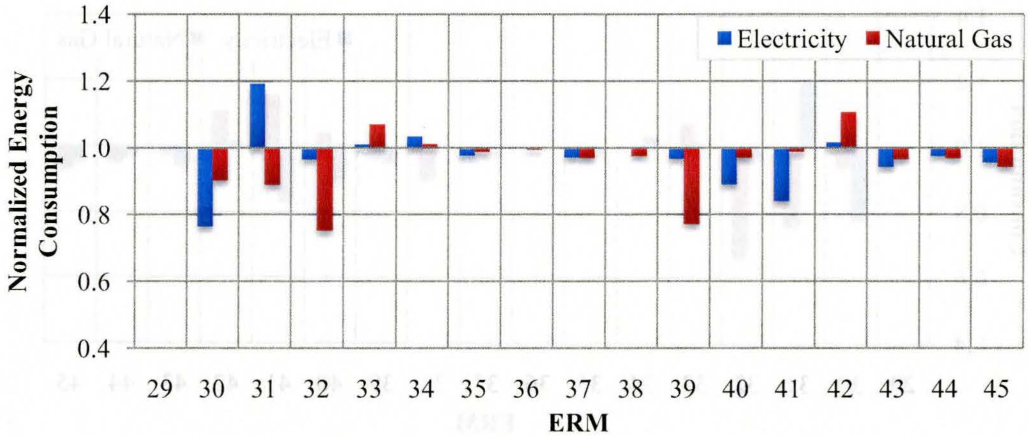

Figure 3.34: Consumption change for 1950 – 1975 building R3 in Edmonton

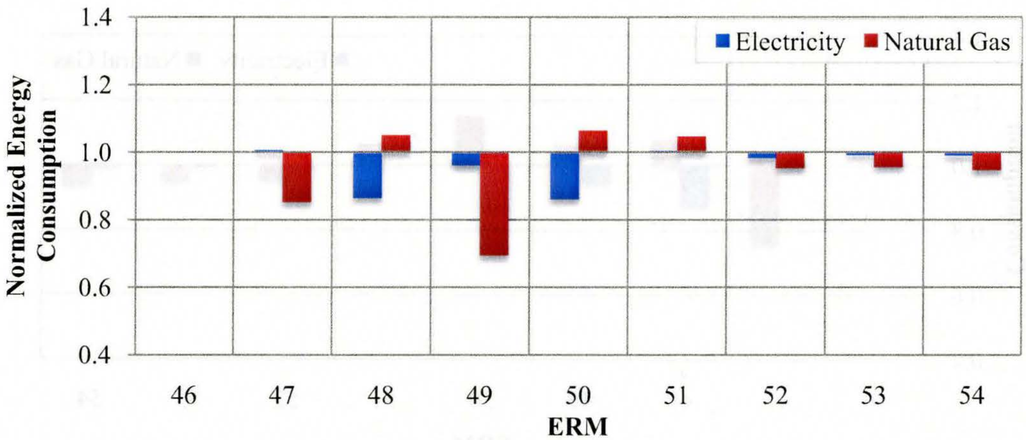

Figure 3.35: Consumption change for post– 1975 building R3 in Edmonton

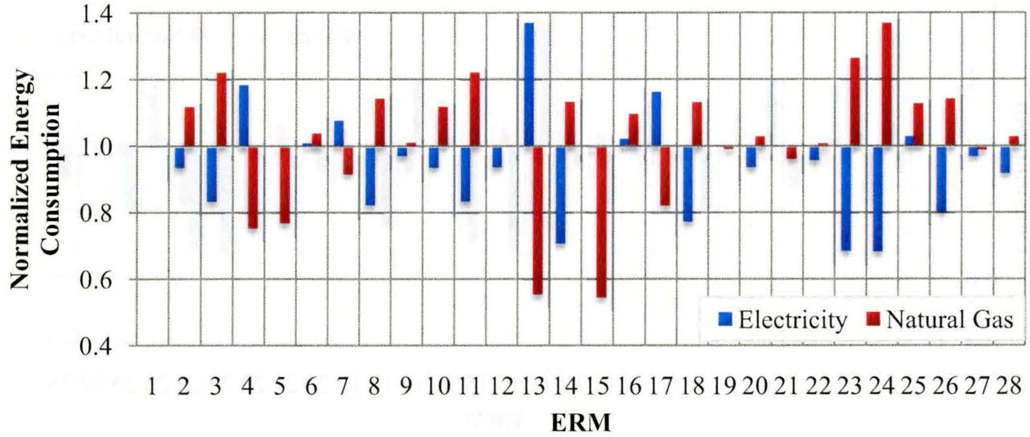

Figure 3.36: Consumption change for pre – 1950 building R3 in Vancouver

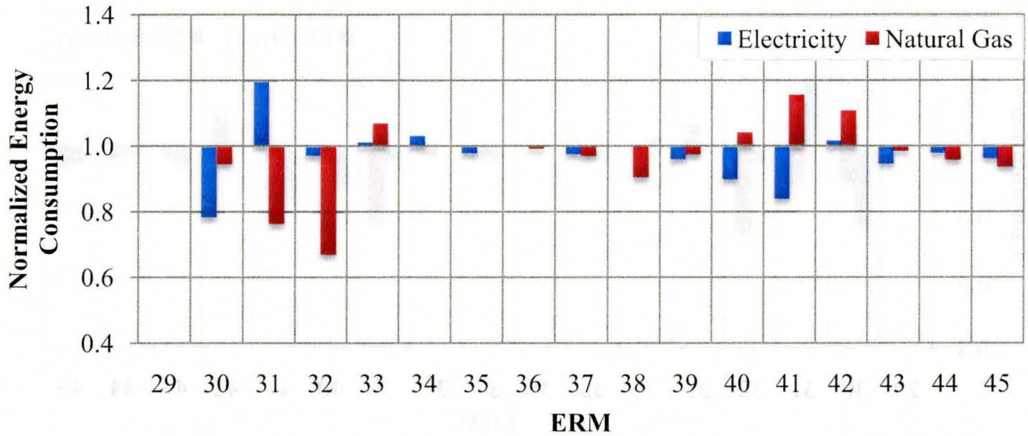

Figure 3.37: Consumption change for 1950 –1975 building R3 in Vancouver

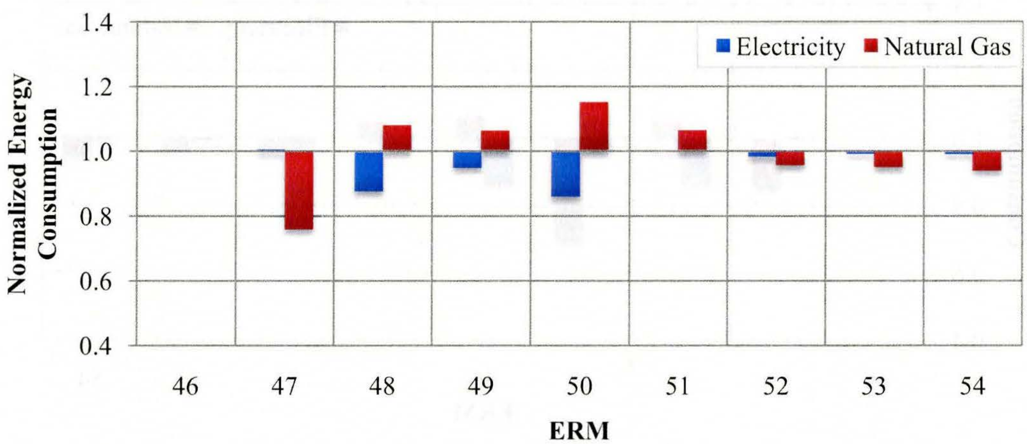

Figure 3.38: Consumption change for post – 1975 building R3 in Vancouver

3.6.2 Modelling Results: Multiple ERMs Application

The effects of the application of individual energy retrofit measures make it possible to observe which ERMs are most suited to the different building types. However, when examining the effects these single ERMs have on consumption, it is important to discover the differences in influence the addition of multiple ERMs may have. The data presented in Table 3.15 to Table 3.23 display the effects of multiple retrofits. In the tables, the column labelled "Single" represents the linear addition of the benefit received from combining multiple retrofit options and the column labelled "Multi" is the actual benefit received as determined by EnergyPlus modelling. Looking at the data, it is observed that the inclusion of multiple ERMs can be both synergistic and destructively additive, hence the combined ERM effects can be greater or less than the sum of the benefits expected. For example, the addition of light dimming features with more efficient lighting fixtures is not as beneficial to consumption as the linear estimation indicates, as well, the implementation of building envelope improvements combined with a boiler efficiency upgrade provides a greater than expected reduction in energy consumption.

Table 3.15: Comparison of single and multiple ERMs on building R1 in Ottawa

ERM (#)	*Vintage*	*Electricity*		*Natural Gas*	
		Single	Multi	Single	Multi
5 + 6 + 2	Pre-1950	73.7%	75.0%	92.9%	96.5%
5 + 6	Pre-1950	81.3%	81.4%	82.5%	86.8%
5 + 2	Pre-1950	90.9%	91.1%	81.1%	81.3%
6 + 2	Pre-1950	75.1%	76.1%	122.2%	118.6%
31 + 32	1950 - 1975	70.9%	72.5%	72.0%	80.9%
48 +49 + 50	Post - 1975	79.1%	80.0%	82.0%	78.6%
48 +49 + 51	Post - 1975	82.5%	82.8%	75.9%	76.2%
48 +49 + 54	Post - 1975	93.3%	93.2%	53.3%	57.5%
48 +49	Post - 1975	94.8%	94.6%	69.5%	71.1%
48 + 50 + 51	Post - 1975	67.8%	75.6%	97.9%	88.4%
48 + 50 + 54	Post - 1975	78.7%	79.6%	75.3%	73.4%
48 + 50	Post - 1975	80.1%	81.1%	91.6%	86.3%
48 + 51 + 54	Post - 1975	82.0%	83.4%	69.2%	71.2%
48 + 51	Post - 1975	83.5%	84.3%	85.5%	84.0%
48 + 54	Post - 1975	95.7%	94.2%	79.1%	65.7%
49 + 50 + 51	Post - 1975	71.1%	77.7%	109.4%	106.6%
49 + 50 + 54	Post - 1975	81.9%	82.2%	86.8%	87.5%
49 + 51 + 54	Post - 1975	85.3%	85.7%	80.7%	83.9%
49 + 51	Post - 1975	86.7%	86.4%	96.9%	99.4%
49 + 54	Post - 1975	97.6%	97.7%	74.3%	74.0%
50 + 51 + 54	Post - 1975	70.6%	77.4%	102.7%	100.8%
50 + 51	Post - 1975	72.1%	78.7%	118.9%	115.5%
50 + 54	Post - 1975	82.9%	83.0%	96.3%	97.0%
51 + 54	Post - 1975	86.3%	87.0%	90.2%	93.1%

Note: For the ERM reference number definition see Table 3.10 to Table 3.14.

Table 3.16: Comparison of single and multiple ERMs on building R1 in Edmonton

ERM (#)	*Vintage*	*Electricity*		*Natural Gas*	
		Single	Multi	Single	Multi
5 + 6 + 2	Pre-1950	73.7%	74.8%	85.9%	94.4%
5 + 6	Pre-1950	81.9%	81.9%	77.4%	85.6%
5 + 2	Pre-1950	92.0%	92.1%	80.8%	81.9%
6 + 2	Pre-1950	73.6%	74.6%	113.7%	112.1%
31 + 32	1950 - 1975	71.9%	72.8%	69.0%	79.3%
48 +49 + 50	Post - 1975	78.9%	79.7%	73.4%	71.5%
48 +49 + 51	Post - 1975	81.5%	82.0%	67.7%	68.9%
48 +49 + 54	Post - 1975	93.6%	93.4%	44.8%	49.9%
48 +49	Post - 1975	94.9%	94.7%	61.5%	63.4%
48 + 50 + 51	Post - 1975	66.2%	74.7%	89.5%	81.1%
48 + 50 + 54	Post - 1975	78.4%	79.3%	66.6%	66.4%
48 + 50	Post - 1975	79.6%	80.6%	83.3%	79.1%
48 + 51 + 54	Post - 1975	81.0%	82.4%	60.9%	63.9%
48 + 51	Post - 1975	82.2%	83.0%	77.6%	76.5%
48 + 54	Post - 1975	95.6%	94.3%	71.4%	58.1%
49 + 50 + 51	Post - 1975	69.9%	77.0%	108.2%	105.7%
49 + 50 + 54	Post - 1975	82.0%	82.2%	85.3%	86.3%
49 + 51 + 54	Post - 1975	84.6%	85.4%	79.6%	82.8%
49 + 51	Post - 1975	85.9%	85.7%	96.3%	99.0%
49 + 54	Post - 1975	98.0%	98.1%	73.4%	73.0%
50 + 51 + 54	Post - 1975	69.4%	76.7%	101.4%	99.8%
50 + 51	Post - 1975	70.6%	77.8%	118.1%	114.8%
50 + 54	Post - 1975	82.8%	82.8%	95.2%	96.0%
51 + 54	Post - 1975	85.4%	86.1%	89.5%	92.6%

Note: For the ERM reference number definition see Table 3.10 to Table 3.14.

Table 3.17: Comparison of single and multiple ERMs on building R1 in Vancouver

ERM (#)	*Vintage*	*Electricity*		*Natural Gas*	
		Single	Multi	Single	Multi
5 + 6 + 2	Pre-1950	78.5%	81.2%	102.2%	100.8%
5 + 6	Pre-1950	81.1%	83.0%	89.3%	89.1%
5 + 2	Pre-1950	88.2%	88.5%	75.2%	75.3%
6 + 2	Pre-1950	87.8%	87.7%	140.0%	137.6%
31 + 32	1950 - 1975	71.1%	74.9%	72.5%	84.6%
48 +49 + 50	Post - 1975	78.6%	78.5%	133.4%	121.7%
48 +49 + 51	Post - 1975	79.2%	79.7%	118.6%	114.2%
48 +49 + 54	Post - 1975	81.2%	82.4%	83.4%	89.2%
48 +49	Post - 1975	86.7%	87.1%	106.2%	108.6%
48 + 50 + 51	Post - 1975	74.4%	77.8%	160.2%	135.7%
48 + 50 + 54	Post - 1975	76.4%	76.8%	125.1%	114.8%
48 + 50	Post - 1975	81.9%	81.3%	147.8%	133.4%
48 + 51 + 54	Post - 1975	77.0%	78.7%	110.3%	107.2%
48 + 51	Post - 1975	82.5%	82.7%	133.1%	125.7%
48 + 54	Post - 1975	90.0%	85.3%	120.7%	101.5%
49 + 50 + 51	Post - 1975	81.0%	85.2%	125.1%	119.9%
49 + 50 + 54	Post - 1975	83.1%	83.5%	90.0%	90.8%
49 + 51 + 54	Post - 1975	83.6%	84.9%	75.2%	78.5%
49 + 51	Post - 1975	89.1%	89.7%	98.0%	101.4%
49 + 54	Post - 1975	91.2%	91.2%	62.8%	62.5%
50 + 51 + 54	Post - 1975	78.8%	83.4%	116.8%	112.3%
50 + 51	Post - 1975	84.3%	88.4%	139.6%	133.0%
50 + 54	Post - 1975	86.4%	86.7%	104.4%	105.3%
51 + 54	Post - 1975	86.9%	88.3%	89.6%	92.9%

Note: For the ERM reference number definition see Table 3.10 to Table 3.14.

Table 3.18: Comparison of single and multiple ERMs on building R2 in Ottawa

ERM (#)	*Vintage*	*Electricity*		*Natural Gas*	
		Single	Multi	Single	Multi
4 + 5	1950 - 1975	68.9%	69.9%	85.6%	89.5%
18 + 19 + 20	Post - 1975	79.7%	85.1%	82.1%	74.5%
18 + 19 + 24	Post - 1975	91.5%	96.9%	39.7%	42.2%
18 + 19	Post - 1975	94.4%	99.9%	70.3%	65.8%
18 + 20 + 24	Post - 1975	81.6%	81.8%	68.8%	68.9%
18 + 20	Post - 1975	84.5%	84.6%	99.4%	98.7%
18 + 24	Post - 1975	97.1%	96.3%	69.4%	57.5%
19 + 20 + 24	Post - 1975	77.4%	78.2%	63.8%	64.6%
19 + 20	Post - 1975	80.4%	81.3%	94.5%	89.4%
19 + 24	Post - 1975	92.2%	91.9%	52.1%	57.6%
20 + 24	Post - 1975	82.3%	82.4%	81.1%	81.9%

Note: For the ERM reference number definition see Table 3.10 to Table 3.14.

Table 3.19: Comparison of single and multiple ERMs on building R2 in Edmonton

ERM (#)	*Vintage*	*Electricity*		*Natural Gas*	
		Single	Multi	Single	Multi
4 + 5	1950 - 1975	69.1%	69.7%	83.4%	88.7%
18 + 19 + 20	Post - 1975	79.2%	85.0%	74.9%	73.9%
18 + 19 + 24	Post - 1975	91.9%	97.7%	31.9%	41.2%
18 + 19	Post - 1975	94.2%	99.9%	63.6%	65.6%
18 + 20 + 24	Post - 1975	82.0%	82.1%	68.3%	68.8%
18 + 20	Post - 1975	84.3%	84.4%	100.1%	99.6%
18 + 24	Post - 1975	97.7%	97.0%	68.3%	57.4%
19 + 20 + 24	Post - 1975	77.7%	78.1%	54.5%	57.3%
19 + 20	Post - 1975	79.9%	80.8%	86.2%	82.0%
19 + 24	Post - 1975	92.7%	92.1%	43.1%	49.8%
20 + 24	Post - 1975	82.7%	82.6%	79.6%	80.6%

Note: For the ERM reference number definition see Table 3.10 to Table 3.14.

Table 3.20: Comparison of single and multiple ERMs on building R2 in Vancouver

ERM (#)	*Vintage*	*Electricity*		*Natural Gas*	
		Single	Multi	Single	Multi
4 + 5	1950 - 1975	72.7%	73.4%	93.5%	99.2%
18 + 19 + 20	Post - 1975	77.2%	84.7%	133.6%	88.3%
18 + 19 + 24	Post - 1975	90.4%	97.9%	68.6%	38.8%
18 + 19	Post - 1975	92.5%	100.0%	109.7%	70.2%
18 + 20 + 24	Post - 1975	81.9%	82.3%	66.3%	64.4%
18 + 20	Post - 1975	84.0%	84.2%	107.4%	103.1%
18 + 24	Post - 1975	97.9%	97.4%	58.9%	44.8%
19 + 20 + 24	Post - 1975	76.0%	77.0%	109.0%	102.2%
19 + 20	Post - 1975	78.0%	79.3%	150.1%	137.0%
19 + 24	Post - 1975	91.2%	90.9%	85.1%	91.6%
20 + 24	Post - 1975	82.7%	82.7%	82.8%	83.0%

Note: For the ERM reference number definition see Table 3.10 to Table 3.14.

Table 3.21: Comparison of single and multiple ERMs on building R3 in Ottawa

ERM (#)	*Vintage*	*Electricity*		*Natural Gas*	
		Single	Multi	Single	Multi
3+ 5	Pre - 1950	73.7%	75.9%	104.3%	103.4%
3+ 8	Pre - 1950	51.1%	60.0%	132.2%	109.7%
2 + 3	Pre - 1950	75.4%	76.9%	123.7%	119.4%
2 + 5 + 8	Pre - 1950	65.5%	70.6%	100.7%	98.4%
2 + 5	Pre - 1950	89.8%	90.0%	92.1%	93.0%
2 + 8	Pre - 1950	67.2%	71.6%	120.1%	111.8%
3 + 5 + 8	Pre - 1950	58.0%	62.4%	101.4%	98.9%
3 + 5	Pre - 1950	82.3%	82.4%	92.8%	95.8%
3 + 8	Pre - 1950	59.7%	63.4%	120.7%	109.9%
5 + 8	Pre - 1950	74.1%	74.6%	89.2%	94.0%
30 + 32	1950 - 1975	71.4%	75.6%	65.9%	77.9%
47 + 48 + 49	Post - 1975	84.9%	87.5%	63.8%	66.2%
47 + 48 + 49 + 50	Post - 1975	71.2%	80.0%	71.1%	69.5%
47 + 48	Post - 1975	87.8%	87.8%	89.6%	89.2%
47 + 49 + 50	Post - 1975	83.8%	86.4%	65.2%	67.3%
47 + 49	Post - 1975	97.4%	100.0%	57.8%	61.4%
47 + 50	Post - 1975	86.7%	86.8%	91.0%	90.6%
48 + 49 + 50	Post - 1975	70.9%	77.7%	87.6%	80.3%
48 + 49	Post - 1975	97.4%	84.9%	57.8%	77.8%
48 + 50	Post - 1975	73.9%	80.0%	113.3%	110.1%

Note: For the ERM reference number definition see Table 3.10 to Table 3.14.

Table 3.22: Comparison of single and multiple ERMs on building R3 in Edmonton

ERM (#)	*Vintage*	*Electricity*		*Natural Gas*	
		Single	Multi	Single	Multi
3+ 5	Pre - 1950	75.0%	76.8%	96.5%	96.7%
3+ 8	Pre - 1950	56.4%	63.4%	108.3%	96.9%
2 + 3	Pre - 1950	75.3%	76.7%	109.7%	107.7%
2 + 5 + 8	Pre - 1950	72.8%	76.3%	91.8%	91.6%
2 + 5	Pre - 1950	91.7%	91.8%	93.2%	94.4%
2 + 8	Pre - 1950	73.2%	76.4%	105.0%	101.0%
3 + 5 + 8	Pre - 1950	64.0%	66.9%	88.7%	90.5%
3 + 5	Pre - 1950	82.9%	82.9%	90.1%	93.7%
3 + 8	Pre - 1950	64.3%	67.0%	101.9%	97.5%
5 + 8	Pre - 1950	80.8%	81.0%	85.4%	88.1%
30 + 32	1950 - 1975	73.1%	76.8%	65.7%	77.5%
47 + 48 + 49	Post - 1975	83.0%	86.5%	59.4%	65.0%
47 + 48 + 49 + 50	Post - 1975	69.0%	79.2%	65.6%	67.9%
47 + 48	Post - 1975	87.0%	87.0%	90.0%	89.8%
47 + 49 + 50	Post - 1975	82.6%	86.1%	60.8%	66.1%
47 + 49	Post - 1975	96.6%	100.1%	54.5%	61.0%
47 + 50	Post - 1975	86.6%	86.6%	91.4%	91.4%
48 + 49 + 50	Post - 1975	68.4%	76.1%	80.5%	74.7%
48 + 49	Post - 1975	96.6%	83.1%	54.5%	72.3%
48 + 50	Post - 1975	72.4%	79.1%	111.1%	108.4%

Note: For the ERM reference number definition see Table 3.10 to Table 3.14.

Table 3.23: Comparison of single and multiple ERMs on building R3 in Vancouver

ERM (#)	*Vintage*	*Electricity*		*Natural Gas*	
		Single	Multi	Single	Multi
3+ 5	Pre - 1950	76.7%	78.1%	110.8%	109.3%
3+ 8	Pre - 1950	59.4%	65.0%	148.1%	127.3%
2 + 3	Pre - 1950	77.0%	78.0%	133.9%	130.2%
2 + 5 + 8	Pre - 1950	75.7%	78.5%	103.0%	97.6%
2 + 5	Pre - 1950	93.3%	93.4%	88.7%	88.9%
2 + 8	Pre - 1950	76.0%	78.5%	126.1%	118.8%
3 + 5 + 8	Pre - 1950	65.5%	68.0%	113.2%	108.2%
3 + 5	Pre - 1950	83.1%	83.1%	98.9%	99.8%
3 + 8	Pre - 1950	65.8%	68.1%	136.3%	126.7%
5 + 8	Pre - 1950	82.1%	82.3%	91.1%	91.4%
30 + 32	1950 - 1975	75.7%	78.8%	61.6%	78.0%
47 + 48 + 49	Post - 1975	83.2%	87.8%	90.2%	73.1%
47 + 48 + 49 + 50	Post - 1975	69.2%	79.7%	105.3%	81.4%
47 + 48	Post - 1975	88.3%	88.3%	83.9%	80.3%
47 + 49 + 50	Post - 1975	81.4%	86.0%	97.3%	78.9%
47 + 49	Post - 1975	95.4%	100.0%	82.2%	67.0%
47 + 50	Post - 1975	86.5%	86.6%	91.1%	87.3%
48 + 49 + 50	Post - 1975	68.6%	75.8%	129.3%	113.2%
48 + 49	Post - 1975	95.4%	83.5%	82.2%	107.8%
48 + 50	Post - 1975	73.7%	79.7%	123.0%	118.3%

Note: For the ERM reference number definition see Table 3.10 to Table 3.14.

3.7 Summary

Using historical data, a set of representative building models were established to capture the majority of office building types. With a manageable set of representative models it was possible to establish a database of energy consumption using the energy modelling software tool EnergyPlus. This database can then be used to make approximations of the most suitable ERMs to apply to a specific building. By reviewing the results from the database of energy consumption it was observed that the effect of single ERM application does not accurately predict the effect multiple ERMs have.

Chapter 4: Regression Analysis and Results

4.1 Introduction

By examining the EnergyPlus simulation results, it was possible to observe that the application of different retrofit measures (both single and multiple) have varying degrees of effect on energy consumption. In order to provide a mathematical representation of the data, a multi-variable statistical regression analysis was adopted. Equations where developed through the use of the least squares regression approach and subsequently used to estimate energy consumption based on the limited set of variables described.

4.2 Procedure for Developing the Regression Equations

The formation of optimally defined regression equations is an iterative process and involves the continual re-evaluation of the adequacy of each function. The procedure employed for determining the equations was divided into the following steps.

1. Develop an initial equation using least squares regression assuming a linear interaction between the variables and responses.
2. Examine the results of the regression performed in Step 1 by exploring the normality of the residuals as well as plots of the residuals versus: fitted values, observation number and variables.

3. From the examination of the residual plots determine the necessity for including higher order terms in the regression equation.
4. Re-develop the equation using the results from Step 3 and re-analyze the normality of the residuals and plotted responses.
5. Repeat until an optimal regression equation is achieved.

This procedure uses the initial assumption that the interaction of each variable in the model is linear. The inclusion of higher order terms in the model do not change the overall shape of the linear equation, instead replacement variables used to represent the higher order variables, e.g. $x_8 = x_4^2$, are incorporated into the equation.

By examining the plots of the residuals of the equation versus the variables included in the model, the need for higher order terms can be determined by observing the trends associated with the interaction. Figure 4.1 is an example of the need for examining the inclusion of higher order variables. The response function under analysis is the chiller load for building R1 located in the city of Ottawa. The trend of the effect of the lighting load on the errors in the regression is noticeably larger in the positive direction when the value for lighting load is at the high and low ends. By adding higher order terms, this pattern is eliminated and the interaction between the variables and the residuals becomes more linear, as is shown in Figure 4.2.

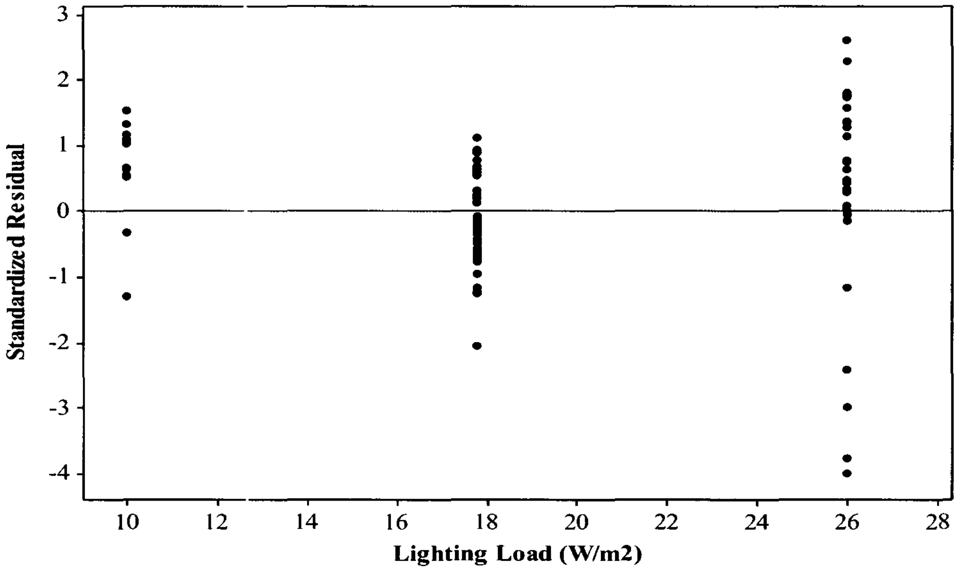

Figure 4.1: Response Chiller: Residual vs. Lighting Load Linear

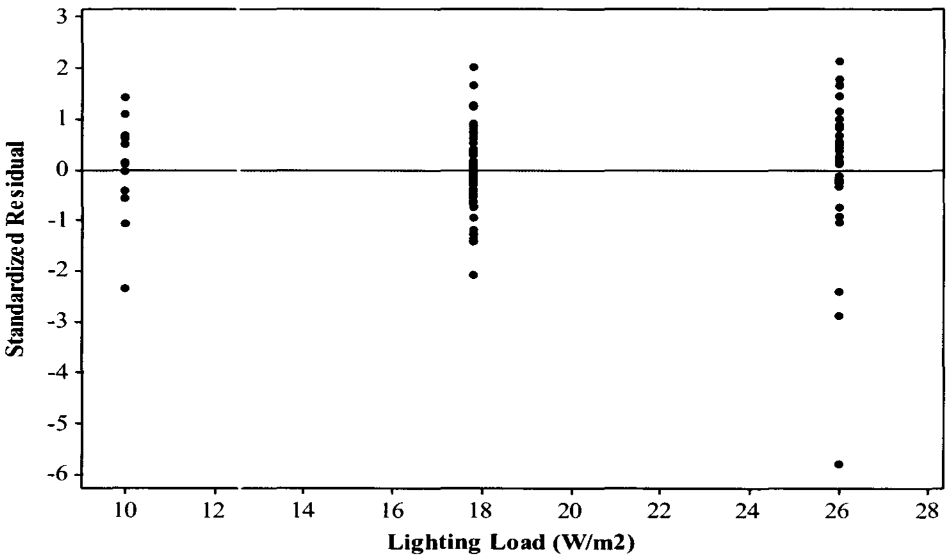

Figure 4.2: Response Chiller: Residual vs. Lighting Load Higher Order

The inclusion or removal of higher order terms in the regression model can be verified using many other tools for establishing the adequacy of a model. Along with the residual vs. variable plots it is necessary to examine the normality of the residuals, the R-Squared values, the Mean Square Error (MSE), and the confidence intervals associated with the coefficients of the equation.

The normal probability plot, shown in Figure 4.3, was taken from the equation for the response of natural gas for Building type R1 in Ottawa. Included in this equation are only the linear variable terms. By examining the normal probability plot it can be seen that the distribution of the residuals in this equation have a high level of normality. This is indicated by the fact that the points on the plot follow a straight line and the P-Value for the Anderson-Darling (A.D.) statistic is greater than 0.05 (Montgomery & Runger, 2003).

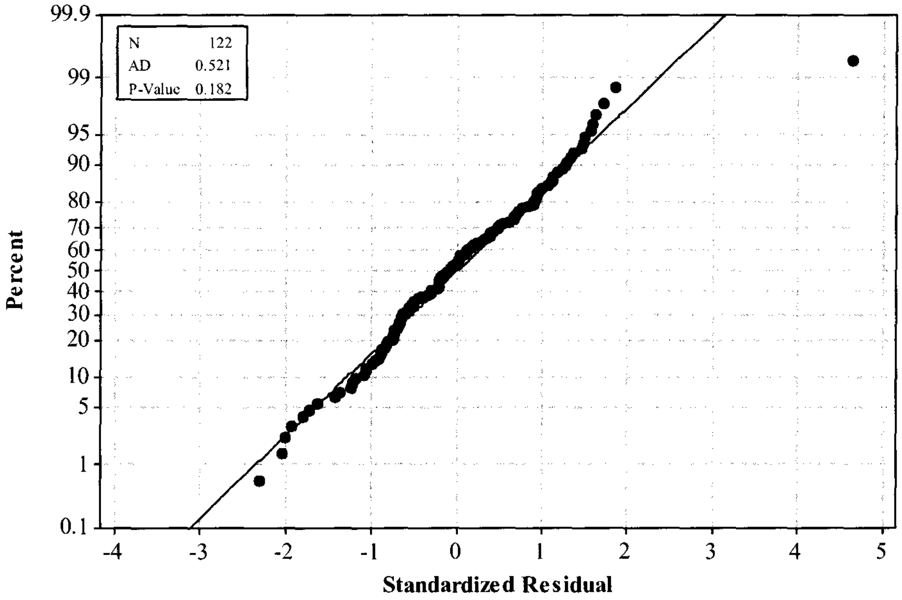

Figure 4.3: Response: Natural Gas, Norm Probability Plot

Correlation among the variables included in the models is also a deciding factor on whether or not to incorporate a given variable. When developing the regression equations, it is possible to determine if correlation between variables is negatively affecting the estimation of the regression coefficients. The variance influence factor (VIF) defined in Equation 4.1 is useful in determining the level of correlation between variables. When the VIF is greater than 10 there is a strong indication that multicollinearity is a problem (Montgomery & Runger, 2003, p. 460).

$$\mathbf{VIF}\left(\beta_j\right)=\frac{1}{\left(1-R_j^2\right)} \quad j=1,2,\ldots,k \tag{4.1}$$

The variable *R*, in Equation 4.1, is the coefficient of multiple determination of the regression of each variable in relation to others. It can be seen that the higher the coefficient of multiple determination, the greater the influence of the variance of the variable. Co-linearity between variables negatively affects the model since it implies that there exists a linear relationship between variable values and this linear interaction can cause the coefficients of the regression equation to be improperly estimated.

4.3 Variable Selection

In Table 3.2 to Table 3.13 several variables relating to the energy consumption and physical properties of the representative building sets are listed. Since it was from these variable definitions that the EnergyPlus simulations were established, it was from these same variables that the regression analysis was developed. Table 4.1 lists the variables used in the analysis and the range of values associated with each. This table contains the same information as Table 3.8, differing only in the addition of the x variable assignment. The variables that remain constant for each of the building types are omitted since they have no beneficial effect on the equations developed. However, it is important to note that factors such as volume, number of floors and scheduling do have considerable influence on the overall energy consumption of a building.

In addition to the variables listed in Table 3.2 to Table 3.13, other factors including, Daylighting, Heat Recovery efficiency, Gas Pre-Heat with Economizer and Turndown Ratio have been included in the regressor variable list. These factors account for the additional retrofits that were simulated and their parameters take on binary properties, as they possess one of two values, simplified by an on or off (1 or 0) status. The values obtained from the simulation of these variables are limited to the details involved in the way they were simulated. Additional simulations would be required if further expansion of the variable base is needed.

Table 4.1: Regression Variables

Variables		*Range*
x_1	Lighting load (W/m^2)	10 to 26 W/m^2
x_2	Equipment load (W/m^2)	15 to 30 W/m^2
x_3	Occupancy density (m^2/per)	18 to 30 m^2/person
x_4	Fenestration	85% - 100% (Large curtain wall building) 30% - 50% (Large concrete panel building) 30% - 50% (Small building)
x_5	Fenestration U-value	1.8 to 6.42
x_6	Wall U-value	0.37 (Large curtain wall building) 0.55 – 1.21 (Large concrete panel building) 0.55 – 1.21 (Small building)
x_7	Roof U-value	0.47 – 0.74 (Large curtain wall building) 0.47 – 1.41 (Large concrete panel building) 0.47 – 1.36 (Small building)
x_8	Infiltration rate (ACH)	1.0 to 0.1
x_9	Heating efficiency	75% - 95%
x_{10}	Cooling COP	1.7 to 5.2
x_{11}	Blinds?	Yes / No
x_{12}	Turndown ratio	1 to 0.3
x_{13}	Daylighting?	Yes / No
x_{14}	Heat recovery efficiency	0% to 60%
x_{15}	Gas pre-heat w/economizer?	Yes / No

4.4 Regression Equations

The equations for estimating energy consumption for the individual building types were developed to correspond to the following energy consumption parameters: Lighting, Equipment, Pumps, Fan, Demand Hot Water (DHW), Chiller, and Boiler Loads. The total secondary fuel consumption is determined by the value given by the Boiler load, and the total Electrical consumption is calculated by combining the results from the remaining components of the energy parameters. Separating the overall energy consumption into individual components provides a clear definition/benefit of an ERM. A reduction in the lighting load, for example, had a direct influence on the energy required for lighting. However, it also has an effect on the heating and cooling system requirements due to a reduction in internal heat gains, and this in turn reduces the energy demands on the pumps and fans. It can then be seen how knowledge of the interactive influences of implementing an ERM on each energy component is useful for gaining a full understanding of the resulting changes in consumption.

The regression equations were developed according to the modelling tools presented in Section 4.2. They were individually examined for normality, correlation and the need to add higher order terms. The software application Minitab (Minitab Inc., 2007) was used for the regression analyses. The developed regression equations are presented in Appendix A. The equations themselves do not shed much light on how well they fit the simulated values so plots of the residuals versus the fitted values and the percent error versus observation number have been included in Appendix B. For each building type, the statistical results for each of the regression equations developed are presented in Table 4.2 to Table 4.4. The R-Squared value shows that the general fit of each of the models is very high (R > 0.90). However, it is important to take note of the mean square error value (MSE). When the MSE value is high compared to the response variables there is a strong indication that the model is fitting the data poorly. The R-Squared (coefficient of determination) is simply an indicator of the amount of variability in the model that is explained by the regression equation (Montgomery & Runger, 2003). It does not give an indication of how significant the errors in the predictions of the model are. Variability in the model can be perfectly captured by an equation but the individual errors in the model may still be large. For this reason the MSE value was looked at in combination with R^2.

By examining the results in Table 4.2 to Table 4.4, several observations can be made regarding accuracy of each of the equations developed. The Lighting load regression equations provide a high level of fit for all building types with the lapses in accuracy stemming only from the inclusion of the daylighting retrofit option, as illustrated in Figure B.2, Figure B.16 and Figure B.30, where the errors associated with the residuals are the largest and in the range of 20%.

For all building types and for all three locations, the equations for estimating the Equipment and DHW loads were determined with a high level of accuracy as indicated by the 1.0 coefficient of determination (R^2) and a MSE value approaching zero. These optimal fits are not unexpected since the equipment load of each building is directly related to the archetype vintage in which it belongs and the DHW load is linked only to the occupancy level of the building. This implies that the regression equations are not affected by variations in other building parameters including climatic effects.

Pump loads were estimated well for all building types over each of the locations modelled, with the maximum errors associated with the regression equation remaining below 10%. When comparing the two large building types R1 and R2, it is observed that the fit of the equations are better approximated for building R1 as noted by the higher R^2 value and lower MSE also, the fit with respect to building type R3 was further improved. This gives an indication that the size of the building may be linked to the level of accuracy of the regression equations.

The analysis of fit of the Fan load equations reveal possible links to internal gains and the errors associated with the regression model. When large alterations to the internal gains of each building type, i.e. lighting, and equipment loads, were present, the errors in the calculated fan consumption were the greatest. This gives an indication that additional simulation points focusing on multiple variations of the internal gains of a building may be useful for improving the accuracy of the models. The errors associated with these scenarios are reasonable and are below 20% for all buildings.

The regression equations for the chiller loads are the least representative of each building type indicated by the high contrast between the high R^2 value and the large associated MSE. The buildings that were coupled with these higher error values were again found to be connected with the simulated models for which the internal gains experience large changes, thus further indicating the necessity for future exploration into the effects that large changes to the equipment and lighting loads will have on these components of consumption.

The boiler consumption values were estimated well for all locations and for each building type. The relatively large MSE values do give an indication that the model may not completely fit the consumption results. However, the associated errors are consistently below 10%.

Table 4.2: Building Type R1: Statistics of Regression

	R-squared	*F-Value*	*P-Value*	*MSE*
Ottawa				
Lights	0.994	6094	0	1.0E+09
Equipment	1.000	7.7E+29	0	0.0E+00
Pumps	0.953	114	0	4.2E+06
Fans	0.985	352	0	2.2E+10
DHW	1.000	4.2E+06	0	1.3E+03
Chiller	0.991	570	0	2.0E+09
Electrical	0.988	365	0	3.5E+10
Boiler	0.982	331	0	1.4E+10
Edmonton				
Lights	0.994	6003	0	1.1E+09
Equipment	1.000	7.7E+29	0	0.0E+00
Pumps	0.956	121	0	3.8E+06
Fans	0.985	344	0	1.9E+10
DHW	1.000	4.2E+06	0	1.3E+03
Chiller	0.992	600	0	1.4E+09
Electrical	0.987	353	0	3.0E+10
Boiler	0.982	324	0	1.7E+10
Vancouver				
Lights	0.995	7479	0	8.0E+08
Equipment	1.000	7.7E+29	0	0.0E+00
Pumps	0.939	86	0	4.5E+06
Fans	0.985	353	0	1.3E+10
DHW	1.000	4.2E+06	0	1.3E+03
Chiller	0.992	639	0	1.3E+09
Electrical	0.988	363	0	2.2E+10
Boiler	0.972	212	0	8.8E+09

Table 4.3: Building Type R2: Statistics of Regression

	R-squared	*F-Value*	*P-Value*	*MSE*
Ottawa				
Lights	0.931	237	0	4.9E+09
Equipment	1.000	7.8E+29	0	0.0E+00
Pumps	0.914	33	0	7.6E+06
Fans	0.989	170	0	2.1E+10
DHW	1.000	5.6E+06	0	2.8E+03
Chiller	0.980	101	0	3.7E+09
Electrical	0.983	120	0	4.5E+10
Boiler	0.967	62	0	2.0E+10
Edmonton				
Lights	0.932	241	0	4.8E+09
Equipment	1.000	7.8E+29	0	0.0E+00
Pumps	0.919	35	0	6.4E+06
Fans	0.996	492	0	7.7E+09
DHW	1.000	5.6E+06	0	2.8E+03
Chiller	0.974	77	0	4.2E+09
Electrical	0.989	193	0	2.8E+10
Boiler	0.978	94	0	1.6E+10
Vancouver				
Lights	0.940	276	0	4.1E+09
Equipment	1.000	7.8E+29	0	0.0E+00
Pumps	0.935	44	0	4.9E+06
Fans	0.996	479	0	5.2E+09
DHW	1.000	5.6E+06	0	2.8E+03
Chiller	0.964	56	0	5.5E+09
Electrical	0.986	150	0	2.6E+10
Boiler	0.924	25	0	1.6E+10

Table 4.4: Building Type R3: Statistics of Regression

	R-squared	*F-Value*	*P-Value*	*MSE*
Ottawa				
Lights	0.995	5156	0	3.1E+07
Equipment	1.000	4.5E+29	0	0.0E+00
Pumps	0.977	194	0	1.1E+05
Fans	0.982	228	0	1.3E+09
DHW	1.000	1.3E+28	0	0.0E+00
Chiller	0.990	373	0	1.2E+08
Electrical	0.986	269	0	2.0E+09
Boiler	0.936	72	0	5.8E+08
Edmonton				
Lights	0.994	4807	0	3.4E+07
Equipment	1.000	4.5E+29	0	0.0E+00
Pumps	0.911	46	0	3.7E+05
Fans	0.974	158	0	1.2E+09
DHW	1.000	1.3E+28	0	0.0E+00
Chiller	0.983	230	0	1.2E+08
Electrical	0.973	141	0	2.3E+09
Boiler	0.936	72	0	6.0E+08
Vancouver				
Lights	0.996	6530	0	2.4E+07
Equipment	1.000	4.5E+29	0	0.0E+00
Pumps	0.971	152	0	9.6E+04
Fans	0.985	280	0	4.4E+08
DHW	1.000	1.3E+28	0	0.0E+00
Chiller	0.986	270	0	9.9E+07
Electrical	0.988	318	0	8.0E+08
Boiler	0.967	145	0	1.7E+08

Chapter 5: Screening Methodology

5.1 Introduction

The methodology for screening office buildings for their optimal set of energy retrofit opportunities is based on the proposed concept that office buildings can be grouped into representative buildings and that the energy consumption calculated using EnergyPlus can be mathematically represented by functions developed on the basis of a multivariate statistical regression analysis. Furthermore, the determination of the cost effectiveness of ERMs is derived from a present value analysis using payback period as a criterion.

5.2 The Screening Process

When a building is examined for its current level of energy efficiency and its potential for retrofit application, it must first be categorized using the archetype scheme established in Chapter 3. This is done by first ascertaining the age of the building, based on the date of construction, and then determining the appropriate sizing category. Large buildings can be defined primarily on the number of floors they possess; generally 6 or more floors are necessary to be considered in this grouping. Wall type and fenestration coverage are necessary when determining the appropriate large building type.

Classifying buildings under one of the archetype schemes is necessary for two reasons. When building information is collected occasionally the values associated with all variables are not obtainable, for example the U-value of the walls may not be known. Using the information stored in the archetype strategy, estimations of the values of these unknown parameters can be made. Secondly, the classification of the archetype category defines the set of regression equations that will be used to estimate the energy consumption of the building.

By examining the values for each building characteristic with respect to the representative archetype, the current status of various building components can be quantitatively analyzed. The various properties that define a building, such as envelope material properties, heating and cooling system efficiencies and electrical equipment type, can be compared to that of the representative case. If certain traits are superior or inferior to the representative case, an understanding of the current level of energy efficiency can be made.

Estimating the current consumption rates of a building is the next step. The base level energy consumption of the building is estimated using the regression formulas developed. This acts as a starting point for all future retrofit estimation calculations. Retrofits are then added one at a time and in multiple combinations, and the effects on the energy consumption are recorded.

Finally, a cost component is used in combination with the estimated changes in energy consumption to develop a list of payback periods for each individual or multiple set of retrofit opportunities. Figure 5.1 summarizes the methodology and the sequence of steps involved. This chapter presents the cost functions and calculation procedure in order to compare the costs effectiveness of different ERMs.

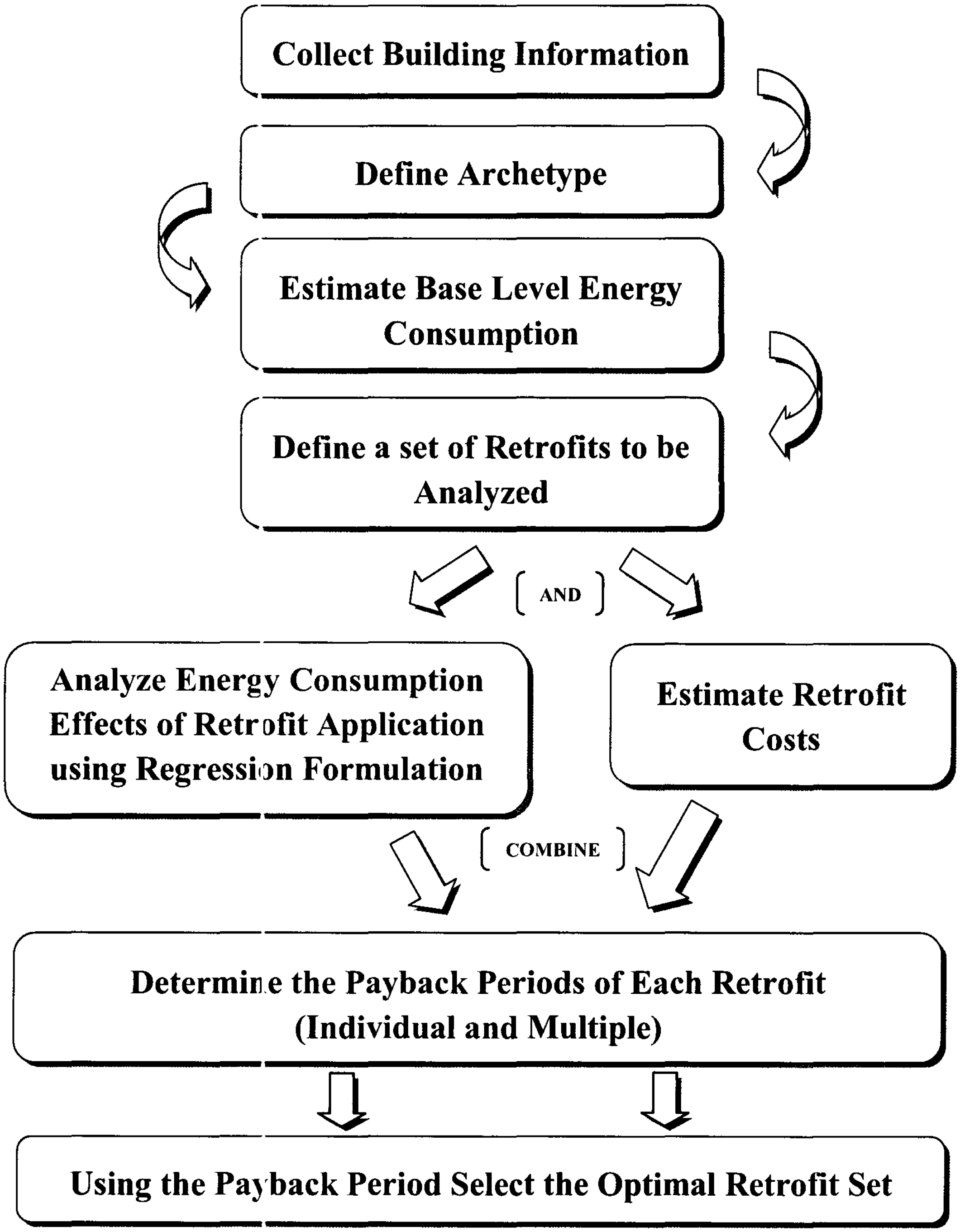

Figure 5.1: Summary of screening methodology

5.3 Cost Estimation

Installation and material costs are obtainable, with some degree of confidence, from numerous sources such as the RSMeans database (Reed Business Information, 2007). RSMeans can provide cost data for a wide variety of retrofit projects, ranging from a simple electrical system upgrade to a more complex building envelope improvement. Costs within the RSMeans database are broken down into several useful components, including crew size, labour hours involved, material and equipment costs. Additionally, overhead and profit costs can also be incorporated into the calculations. A useful program for extracting cost data from the RSMeans database is the "Cost Works" tool, available from Reed Business Information. This tool allows a user to enter project specific requirements and estimate the total cost involved.

5.3.1 Retrofit Cost Estimations Using RSMeans

As an example of the cost estimation capabilities of the RSMeans database, several retrofit options were chosen to evaluate the screening methodology. These retrofits include electrical, HVAC system and building envelope upgrades. It must be stated that the estimates contained within the next section had the following mark-ups applied to them, in compliance with current construction practices: 10% for general contractor's mark-up on subs, 8% for general conditions and 10% for general contractor's overhead & profit.

5.3.1.1 Lighting Load Improvement

Improving the lighting load within a building is generally accomplished by converting the inefficient main lighting source used to a more efficient one. This typically involves the upgrade of a fluorescent lighting system to replace T-12 with T-8 lamps. An upgrade of this type involves the removal or replacement of the existing lamps and ballast equipment and the installation of upgraded components. From the RSMeans estimator, cost for the replacement of fluorescent lamps with a T-8 lighting system can be established by first calculating the number of fixtures that require replacement and then multiplying this value by the per unit cost of the retrofit. This calculation involves multiplying the lighting load per meter squared by the floor area affected.

5.3.1.2 Boiler Replacement

Improving the efficiency of the main heating system in a building typically involves the replacement of the older inefficient boiler with a newer unit with a higher efficiency rating. When examining both the large and small representative buildings it can be observed that the main boiler is fed by natural gas. The typical efficiency range for a natural gas boiler is between 75% and 95% (American Society of Heating Refrigeration and Air-Conditioning Engineers Inc., 1977). Replacing the boiler in the large and small office building involves calculating the capacity required to supply the heating demands of the building. Heating capacity is generally based on a winter design-day calculation with an included safety factor. This calculation can be performed using EnergyPlus. For the representative small building there is a single boiler that feeds the needs of the building. For the large building there is a higher heating requirement due to its volume and envelope differences. As a result four natural gas boilers must be installed to meet the building's capacity needs. The type of boiler used in the replacement estimation are natural gas, however the RSMeans database limits the amount of information provided and an exact estimate of the energy efficiency rating is not included. The estimated cost was then based on maintaining the required heating design capacity for each building. For the small building this involved the installation of a single cast iron 3570 MBH steam boiler and for the large building 4 x 3060 MBH cast iron boilers.

5.3.1.3 Roofing insulation

Improving the insulation of the roof can reduce energy consumption as was seen in the simulation results of the representative buildings. Adding insulation can be accomplished in several ways. If space exists in the interior of the roof then additional insulation can be added using rigid insulating boards. If space is limited however, it is also possible to add roofing tiles to provide additional insulation. Rigid insulation was chosen for this retrofit application and involved the addition of ½ inch thick Roof Deck Insulation which would provide an additional R-Value of 1.39 $m^2 \cdot {}^\circ C/W$.

5.3.1.4 Exterior Insulation Finish System (EIFS)

Improving the U-value of the exterior wall of a building is possible by adding a layer of external insulation which is affixed to the exterior. Expanded polystyrene is typically used in this type of application. For the purpose of estimating the costs involved in EIFS application, it was assumed that a one inch thick layer would be utilized. Based on this thickness it would provide an additional R-Value of 0.805 $m^2 \cdot °C/W$.

Table 5.1 outlines each of the retrofits described. The "Line Number" can be used to refer to the RSMeans cost data source used to gather the information. The quantities displayed were calculated for each building type. The lighting load upgrade was assumed to be applied to the Pre – 1950 archetype. The boiler and building envelope upgrade costs are not dependant on the archetype age of the building as the costs are not affected by the existing building technologies.

Table 5.1: Description of retrofit estimations (RSMeans)

Building	*Ref. #*	*Quantity*	*Line Number*	*Description*
Building R1 & Building R2	1	2704	265113500960	Fluorescent fixture, interior, acryl lens, grid recess ceiling mounted, 4-32 W, 2' W x 4' L, incl. lamps, mounting hardware and connections
	2	4	235223202380	Boiler, gas fired, natural or propane, cast iron, steam, gross output, 3060 MBH, includes standard controls and insulated jacket
	3	21797	072216100080	Roof Deck Insulation, ceiling sound board, 1/2" thick, R1.39
Building R1	4.1	50180	072413100095	Exterior Insulation Finish System, field applied, 1" EPS insulation
	4.2	42986		
	4.3	35794		
Building R3	5	467	265113500960	Fluorescent fixture, interior, acryl lens, grid recess ceiling mounted, 4-32 W, 2' W x 4' L, incl. lamps, mounting hardware and connections
	6	1	235223202400	Boiler, gas fired, natural or propane, cast iron, steam, gross output, 3570 MBH, includes standard controls and insulated jacket
	7	22604	072216100080	Roof Deck Insulation, ceiling sound board, 1/2" thick, R1.39
	8.1	13164	072413100095	Exterior Insulation Finish System, field applied, 1" EPS insulation
	8.2	8783		
	8.3	7320		

Table 5.2: Summary of costs associated with retrofit upgrades

Ref. #	*Labour Hours*	*Unit*	*Material*	*Labour*	*Equipment*
1	1.702	Ea.	$98.75	$73.16	$0.00
2	172	Ea.	$17,318.40	$6,933.80	$0.00
3	0.008	S.F.	$0.26	$0.23	$0.00
4.1	0.136	S.F.	$2.31	$3.89	$0.40
4.2	0.136	S.F.	$2.31	$3.89	$0.40
4.3	0.136	S.F.	$2.31	$3.89	$0.40
5	1.702	Ea.	$98.75	$73.16	$0.00
6	181	Ea.	$19,302.80	$7,332.03	$0.00
7	0.008	S.F.	$0.26	$0.23	$0.00
8.1	0.136	S.F.	$2.31	$3.89	$0.40
8.2	0.136	S.F.	$2.31	$3.89	$0.40
8.3	0.136	S.F.	$2.31	$3.89	$0.40

Table 5.3: Summary of total base costs per component (to nearest $100)

Ref. #	*Ext. Mat.*	*Ext. Labour*	*Ext. Equip.*	*Ext. Total*
1	$267,000	$198,000	$0	$465,000
2	$69,300	$27,700	$0	$97,000
3	$5,700	$5,000	$0	$10,700
4.1	$116,000	$195,000	$20,100	$331,000
4.2	$99,300	$167,000	$17,200	$284,000
4.3	$82,700	$139,000	$14,300	$236,000
5	$46,100	$34,200	$0	$80,300
6	$19,300	$7,300	$0	$26,600
7	$5,900	$5,200	$0	$11,100
8.1	$30,400	$51,200	$5,270	$86,900
8.2	$20,300	$34,200	$3,500	$58,000
8.3	$16,900	$28,500	$2,900	$48,300

Table 5.4: Overhead and profit costs per unit

Ref. #	*Mat. O&P*	*Labour O&P*	*Equip. O&P*	*Total O&P*
1	$108.82	$112.93	$0.00	$221.75
2	$19,032.20	$10,775.50	$0.00	$29,807.70
3	$0.28	$0.42	$0.00	$0.70
4.1	$2.53	$6.26	$0.43	$9.22
4.2	$2.53	$6.26	$0.43	$9.22
4.3	$2.53	$6.26	$0.43	$9.22
5	$108.82	$112.93	$0.00	$221.75
6	$21,287.20	$11,431.40	$0.00	$32,718.60
7	$0.28	$0.42	$0.00	$0.70
8.1	$2.53	$6.26	$0.43	$9.22
8.2	$2.53	$6.26	$0.43	$9.22
8.3	$2.53	$6.26	$0.43	$9.22

Table 5.5: Total costs including overhead and profit (to nearest $100)

Ref. #	*Ext. Mat. O&P*	*Ext. Labour O&P*	*Ext. Equip. O&P*	*Ext. Total O&P*
1	$294,200	$305,400	$0	$599,600
2	$76,100	$43,100	$0	$119,200
3	$6,100	$9,200	$0	$15,300
4.1	$127,000	$314,100	$21,600	$462,700
4.2	$108,800	$269,100	$18,500	$396,300
4.3	$90,600	$224,100	$15,400	$330,000
5	$50,800	$52,700	$0	$103,600
6	$21,300	$11,400	$0	$32,700
7	$6,300	$9,500	$0	$15,800
8.1	$33,300	$82,400	$5,700	$121,400
8.2	$22,200	$55,000	$3,800	$81,000
8.3	$18,500	$45,800	$3,100	$67,500

5.4 Calculation of Payback Period

To calculate the payback period while incorporating the effects of inflation and interest rates into the calculation, it was necessary to first develop a set of equations that will perform the required calculations. These cost equations function by taking all the cost-related information about the implementation of an energy efficient retrofit and comparing them to expected energy prices over the following years to determine the present worth. The payback period is the year in which these values become equal.

As stated in Section 5.3, retrofit implementation costs are composed of several factors beyond the simple cost of labour and materials associated with the installation. Depending on the type of retrofit being performed, secondary costs may also be incurred, due to set-backs in the operation of the building and changes to annual maintenance costs. Operation set-back costs are determined solely by the building operators as these costs are determined on a per case basis. Maintenance costs are also assumed, as actual costs are determined by building operations managers. Fuel costs vary from year to year and there are sources available which forecast escalation rates for fuel, based on location and fuel type. Natural Resources Canada (1997) contains data tables which summarize expected changes to fuel rates between 1996 and 2020.

5.5 Formulation

The general format for determining payback period involves equating the Present Value of savings $PV_{Savings}$ with the present value of the costs PV_{Costs} associated with a retrofit option (Fraser et. al. 2006).

$PV_{Savings}$ can be calculated using known interest and inflation rates. The interest rate will be applied to the cost of implementing the retrofit option if funds are borrowed to pay for the installation. The components of Equation 5.1 were extracted from Fraser et. al. (2006).

$$\begin{aligned} PV_{Savings} = \; & (AMD) *(P/A, i_f, N) \\ & + AFC_e *S_E*(P/A, i_{fe}^{\circ}, N)*(1/(1+g_e)) \\ & + AFC_s *S_S*(P/A, i_{fg}^{\circ}, N)*(1/(1+g_s)) \end{aligned} \quad (5.1)$$

Where:

$(P/A, i, N)$ = Series Present Worth Factor: $[(1 + i)^N - 1]/[i(1 + i)^N]$

AMD = Difference in the annual maintenance costs (Assumed Constant) ($)

AFC_e = Annual electrical fuel costs for year one ($/kWh)

AFC_s = Annual secondary fuel costs for year one ($/kWh)

S_e = Calculated annual electrical savings (kWh)

S_s = Calculated annual secondary fuel savings (kWh)

g_e, g_s = Growth rate expected on fuel costs, electrical and secondary fuel source

i_f = Inflation adjusted interest determined using the (f) inflation rate obtained from the Bank of Canada and the Minimum Acceptable Rate of Return on investment (MARR).

i_{fe}° = Growth adjusted interest rate for Electricity based on inflation and MARR

i_{fg}° = Growth adjusted interest rate for Natural Gas based on inflation and MARR

N = Number of years (to be calculated)

The present value of the cost associated with the implementation of a retrofit option is a function of the initial borrowing value and the number of payments agreed upon for payback. Equation 5.2 shows the calculation process where the original loan is first broken down into the equal annuity payments that must be made. This is based both on the interest rate attached to the loan and the accepted rate of inflation. After converting the initial loan into annuities it can then be returned to the present value amount which includes all the penalties associated with borrowing funds. The components of Equation 5.2 were extracted from Fraser et. al. (2006).

$$PV\,(costs) = LOP + L*(A/P,\, i,\, N_L)*\,(P/A,\, f,\, N_L) \qquad (5.2)$$

Where:

$(A/P, i, N)$ = Capital Recovery Factor: $i\,(1 + i)^N/[(1 + i)^N - 1]$

$(P/A, i, N)$ = Series Present Worth Factor: $[(1 + i)^N - 1]/\,i(1 + i)^N$

LOP = Loss of production

L = Load Amount (known)

N_L = Agreed upon number of payments to payback loan

i = Interest rate associated with the loan (Estimated: Bank of Canada)

f = Inflation rate (Estimated: Bank of Canada)

Setting the present value of the cost to equal the present value of the savings, the payback period can then be calculated by solving for the variable N. This value can then be used to determine if the retrofit, or combinations of retrofit options, are accepted or rejected.

5.5.1 Demonstration of Payback Calculations

From the retrofit cost estimates presented in Section 5.3.1 for the four types of energy conservation measures discussed, an example of the payback period calculations can be made.

For these calculations several assumptions need to be defined.

1. The cost of the implementation of each retrofit opportunity will be paid for using a loan for the value of the installation costs under the assumption that the number of months to be used for the re-payment of the loan will be constant at 48 months.
2. The loss of production cost will be neglected

3. Maintenance cost will also be neglected due to lack of information and high degree of error in the estimations.
4. A Minimum Acceptable Rate of Return (MARR) of 10% will be used as a rate of return that will make the project acceptable.
5. Interest and inflation rates will be taken as 4.5% and 2.2% respectively, and have been extracted from the Bank of Canada website (Bank of Canada)
6. The growth rates for Electricity and Natural Gas were taken as 2.13% and 2.05% respectively. These values were taken as the average of the escalation rate from 1997 to 2020 (Natural Resoures Canada, 1997)
7. Cost of each retrofit will include the total associated overhead and profits.
8. The initial cost of energy will be taken as $0.07/kWh for Electricity and $0.04/kWh for Natural Gas (Public Works and Government Services Canada, 2007)

The effective changes in consumption due to the implementation of each retrofit option were estimated using the regression formulation developed in Chapter 4. The results are summarized in Table 5.6 to Table 5.9.

Table 5.6: Summary of retrofit implementation costs

Building	*Ref. #*	*Archetype*	*Description of Change*	*Total Implementation Cost*
Building R1 & Building R2	1	Pre – 1950 to Post 1975	Reduces the Lighting load to 14.24 W/m2	$599,600.00
	2	Pre – 1950 to Post 1975	Improves Boiler Efficiency to 95%	$119,200.00
	3	Pre – 1950 to Post 1975	Changes Roof U-value to 0.476	$15,300.00
Building R1	4.1	Pre – 1950	Changes Wall U-value to 0.61	$462,700.00
	4.2	1950 – 1975		$396,300.00
	4.3	Post – 1975		$330,000.00
Building R3	5	Pre – 1950 to Post 1975	Reduces the Lighting load to 14.24 W/m2	$103,600.00
	6	Pre – 1950 to Post 1975	Improves Boiler Efficiency to 95%	$32,700.00
	7	Pre – 1950 to Post 1975	Changes Roof U-value to 0.471	$15,800.00
	8.1	Pre – 1950	Changes Wall U-value to 0.61	$121,400.00
	8.2	1950 – 1975		$81,000.00
	8.3	Post – 1975		$67,500.00

Table 5.7: Payback period (years) for retrofit application on building R1

Retrofit	*Building R1*			
	Location	Pre - 1950	1950 - 1975	Post - 1975
Lighting Load Improvement	Ottawa	6.48	Not Applicable	
	Edmonton	6.46		
	Vancouver	7.32		
Boiler Replacement	Ottawa	3.86	3.86	3.86
	Edmonton	3.62	3.62	3.62
	Vancouver	9.12	9.12	9.12
Roofing insulation	Ottawa	0.34	Retrofit exceeds parameter range	
	Edmonton	0.44		
	Vancouver	0.50		
Exterior Insulation Finish System (EIFS)	Ottawa	Infeasible		
	Edmonton			
	Vancouver			

Table 5.8: Payback period (years) for retrofit application on building R2

Retrofit	*Building R2*		
	Location	1950 - 1975	Post - 1975
Lighting Load Improvement	Ottawa	Not Applicable	
	Edmonton		
	Vancouver		
Boiler Replacement	Ottawa	4.93	4.93
	Edmonton	3.78	3.78
	Vancouver	16.06	16.06
Roofing insulation	Ottawa	Retrofit exceeds parameter range	
	Edmonton		
	Vancouver		
Exterior Insulation Finish System (EIFS)	Ottawa	Not Applicable	
	Edmonton		
	Vancouver		

Table 5.9: Payback period (years) for retrofit application on building R3

Retrofit	*Building R3*			
	Location	Pre - 1950	1950 - 1975	Post - 1975
Lighting Load Improvement	Ottawa	5.82	Not Applicable	
	Edmonton	5.83		
	Vancouver	7.53		
Boiler Replacement	Ottawa	8.76	8.76	8.76
	Edmonton	6.75	6.75	6.75
	Vancouver	24.46	24.46	24.46
Roofing insulation	Ottawa	0.50	Retrofit exceeds parameter range	
	Edmonton	0.68		
	Vancouver	0.86		
Exterior Insulation Finish System (EIFS)	Ottawa	Infeasible		
	Edmonton			
	Vancouver			

From the payback calculation given in Table 5.7 to Table 5.9 the following observations were made.

1. Retrofitting the lighting fixtures is found to be slightly more beneficial to the buildings located in Edmonton and Ottawa in comparison to those in Vancouver.
2. Retrofitting the boiler system is found to be more beneficial for larger buildings and for buildings located in colder climates. A factor of approximately three in the payback period is observed between buildings located in colder climates (Ottawa and Edmonton) and moderate climate (Vancouver). Focusing on building R1 and R2 it can

be observed that longer payback periods occur for the curtain walled structure.

3. Payback period for upgrading the roofing insulation is found to be influenced by the size of the building and the climate region.
4. An upgrade to the exterior walls using EIFS is found to be cost ineffective for all three types of buildings as well as for all three climate regions.

5.6 Summary

The calculation of the costs involved in the application of an energy conservation measure relies highly on the ability of the user to determine the many aspects related to the retrofit. It is for this reason that building operators must be closely involved in the estimation process. Loss of production and changes in maintenance cost are the most difficult values to determine and the validity of each can have a large effect on the number of payback years for a project. Using the MARR to calculate the number of payback years allows for a better understanding of how the funds are being invested. As a result the calculated payback period is the longest time between investment in a project and the expected return.

Chapter 6: Conclusions and Future Work

6.1 Conclusions

The goal of this research project was to develop a methodology for screening office buildings for energy efficiency and retrofit potential. As described within this report, it was determined that:

1. There have been numerous studies performed on the subject of analyzing the implication of ERMs. However, due to the lack of wide spread applicability and the inability to rapidly estimate energy consumption on a per case basis while incorporating payback periods, this new methodology was developed.
2. There is a large array of modelling tools available to estimate the energy consumption of a building and each has its advantages and disadvantages.
3. The energy modelling tool EnergyPlus is a more versatile and accurate program for the analysis of the energy consumption when compared to FEDS. This was determined using both annual and monthly energy consumption data.
4. The properties of buildings including the materials and construction practices used varied widely from pre-1950, 1950–1975 and post 1975.

5. From energy consumption data it was found that the application of ERMs to different building types produced varying results and the applications of some ERMs were found to be more beneficial than others.
6. The additive benefit of applying multiple ERMs is not linear since the benefits received from applying a single ERM can negate the benefit of others.
7. Using a non-linear regression analysis, a set of equations can be established that adequately predict energy consumption based on a limited number of variables.
8. Establishing the effects that single and multiple retrofit opportunities have on energy consumption is possible using the formulations developed to allow for estimations of energy consumption to be made.
9. Current levels of energy efficiency can be determined through a comparison between a building's current set of variable values to the representative building's established set of variables.
10. By applying a set of cost equations, in combination with an approach for estimating the cost of retrofit implementation and expected payback period, an acceptable rate of return on investment can be determined.

6.2 Future Work

Up to this point, the screening methodology was limited to the modelling of a set of representative buildings, using simulated energy consumption, to develop a set of regression equations. These equations were then used to estimate energy consumption and in turn predict the results of retrofit opportunities. There is however a limit to how applicable these regression equations are to real-world applications. Because these are based on historical commonalities and standardized practices, the range of variables used in the modelling of the representative buildings does not capture all possible values. For example, if an actual building possesses unusual material properties or has a higher than average equipment load, using the regression equations to estimate energy consumption would not be an adequate solution since no simulations have been included in the development of the regression equations that lie outside the ranges given in Table 4.1.

The inclusion, not only of a wider range to the current set of building variables, but also of new additional variables, is necessary for expanding the applicability of the regression equations. Currently, the application of the regression equations is limited to the size and number of floors they were based on. The original assumption during the development of the simulation scheme was that the interaction between the number of floors and the size of the building was linear. If true, it allows for simplistic scaling of the determined energy consumptions based on the ratios relating to volume and number of floors. However, it was later discovered that the relationship between these two variables was non-linear. The solution to this problem is to include an additional set of building variable simulations. Using the base model buildings defined in Section 3.2, additional model sets possessing varying volumes and number of floors need to be added to the simulation scheme.

The focus of future work related to this project must be to first, expand the simulation database as suggested, re-assess the regression equations and then apply the updated equations to existing buildings, allowing for a final validation of the screening process presented. Once completed, the application of this methodology for screening office buildings for energy efficiency and retrofit potential will allow for the rapid estimation of the optimal set of energy efficient retrofit measures to apply. This will facilitate the potential for future office building enhancement by providing accurate cost reduction scenarios for managing these buildings, while at the same time lowering greenhouse gas emissions going into the atmosphere.

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Appendix A: Regression Equations

Equation A.1: General format of the regression equations

$$Energy\ Consumption = b_0 + b_1 * x_1 + b_2 * x_2 + b_3 * x_3 + b_4 * x_4 + b_5 * x_5 + b_6 * x_6 + b_7 * x_7 + b_8 * x_8 + b_9 * x_9 + b_{10} * x_{10} + b_{11} * x_{11} + b_{12} * x_{12} + b_{13} * x_{13} + b_{14} * x_{14} + b_{15} * x_{15} + b_{16} * x_{16} + b_{17} * x_{17} + b_{18} * x_{18} + b_{19} * x_{19} + b_{20} * x_{20} + b_{21} * x_{21} + b_{22} * x_{22} + b_{23} * x_{23} + b_{24} * x_{24} + b_{25} * x_{25} + b_{26} * x_{26} + b_{27} * x_{27} + b_{28} * x_{28} + b_{29} * x_{29} + b_{30} * x_{30} + b_{31} * x_{31} + b_{32} * x_{32} + b_{33} * x_{33} + b_{34} * x_{34} + b_{35} * x_{35}$$

Where:

b = coefficient

x = variable

Note: *The regression equation coefficients under the heading 'Electrical' can be used to directly calculate the* <u>*total electrical*</u> *consumption of the building if the parameters 'Lights', 'Equipment', 'Pumps', 'Fans', 'DHW' and 'Chiller' are electrically supplied. Otherwise, the total electrical consumption must be determined by summing the components that contribute to the electrical demand*

Table A.1: Variables corresponding to regression

Variables			
Lighting Load (W/m2)	x_1	% Fenestration ^{2}	x_{19}
Equipment Load (W/m2)	x_2	Fenestration U-value ^{2}	x_{20}
Occupancy Density (m2/Person)	x_3	Wall U-value ^{2}	x_{21}
% Fenestration	x_4	Roof U-value ^{2}	x_{22}
Fenestration U-value	x_5	Infiltration Rate (ACH) ^{2}	x_{23}
Wall U-value	x_6	Heating Efficiency (%) ^{2}	x_{24}
Roof U-value	x_7	Cooling COP ^{2}	x_{25}
Infiltration Rate (ACH)	x_8	Lighting Load (W/m2) ^{3}	x_{26}
Heating Efficiency (%)	x_9	Equipment Load (W/m2) ^{3}	x_{27}
Cooling COP	x_{10}	Occupancy Density (m2/Person) ^{3}	x_{28}
Blinds?	x_{11}	% Fenestration ^{3}	x_{29}
Turndown Ratio	x_{12}	Fenestration U-value ^{3}	x_{30}
Daylighting?	x_{13}	Wall U-value ^{3}	x_{31}
Heat Recovery Efficiency	x_{14}	Roof U-value ^{3}	x_{32}
Gas Pre-Heat w/Economizer?	x_{15}	Infiltration Rate (ACH) ^{3}	x_{33}
Lighting Load (W/m2) ^{2}	x_{16}	Heating Efficiency (%) ^{3}	x_{34}
Equipment Load (W/m2) ^{2}	x_{17}	Cooling COP ^{3}	x_{35}
Occupancy Density (m2/Person) ^{2}	x_{18}		

Table A.2: Building R1 - Ottawa: Regression coefficients equations

Coef.	*'Lights'*	*'Equipment'*	*'Pumps'*	*'Fans'*
b_0	206082.3	372382.8	43458.72	-4172427
b_1	54084.65	0	75.04661	53314.04
b_2	0	62451	853.4076	45439.05
b_3	0	0	0	37772.44
b_4	0	0	48245.1	3948816
b_5	0	0	1942.622	0
b_6	0	0	3992.226	159844.6
b_7	0	0	2798.227	606952.9
b_8	0	0	29550.69	337159.4
b_9	0	0	-4403.463	121189.7
b_{10}	0	0	39.3837	-1268.893
b_{11}	0	0	-1468.39	-583272.1
b_{12}	0	0	-7282.464	2845471
b_{13}	-419023.9	0	-8043.207	-153828.8
b_{14}	0	0	-20007.4	-1406085
b_{15}	0	0	-1641.654	-87513.58
b_{16}	497.3195	0	30.19309	0
b_{17}	0	0	0	0
b_{18}	0	0	-26.29002	-1041.122
b_{19}	0	0	0	0
b_{20}	0	0	0	15234.16
b_{21}	0	0	0	0
b_{22}	0	0	0	0
b_{23}	0	0	0	0
b_{24}	0	0	0	0
b_{25}	0	0	0	0
b_{26}	0	0	0	0
b_{27}	0	0	0	0
b_{28}	0	0	0	0
b_{29}	0	0	0	0
b_{30}	0	0	0	159.0707
b_{31}	0	0	0	0
b_{32}	0	0	0	0
b_{33}	0	0	0	0
b_{34}	0	0	0	0
b_{35}	0	0	0	0

Table A.3: Building R1 - Ottawa: Regression coefficients equations (cont'd)

Coef.	*'DHW'*	*'Chiller'*	*Electrical*	*Boiler*
b_0	273324.6	638982.3	-4506079	6297869
b_1	0	-18135.79	-25823.38	-42973.7
b_2	0	19417.16	129798.9	-47571.8
b_3	-16429.1	108307.6	-18472.39	-33424.85
b_4	0	865557.1	10984822	-539245.4
b_5	0	20431.38	154065.8	81562.96
b_6	0	12159.68	196975.9	259803.3
b_7	0	70479.8	869872.2	-206167.2
b_8	0	-58436.65	7277551	3853382
b_9	0	-1521.957	147366.2	-4950890
b_{10}	0	-745895.1	-198557.1	-1235.582
b_{11}	0	-72460.4	-620507.3	369518.8
b_{12}	0	431196.6	3227799	-720488.8
b_{13}	0	-58470.09	-635483.5	189987.8
b_{14}	0	0	-1837890	701917.3
b_{15}	0	-152040	-260111.1	551742.1
b_{16}	0	980.999	4866.991	0
b_{17}	0	0	0	0
b_{18}	436.7173	-4601.335	0	0
b_{19}	0	0	-7957279	0
b_{20}	0	0	0	0
b_{21}	0	0	0	0
b_{22}	0	0	0	0
b_{23}	0	0	-10804713	0
b_{24}	0	0	0	0
b_{25}	0	0	0	0
b_{26}	0	0	0	0
b_{27}	0	0	0	0
b_{28}	-4.336236	60.49	0	0
b_{29}	0	0	0	0
b_{30}	0	0	0	0
b_{31}	0	0	0	0
b_{32}	0	0	0	0
b_{33}	0	0	5222319	0
b_{34}	0	0	0	0
b_{35}	0	12287.01	0	0

Table A.4: Building R1 - Edmonton: Regression coefficients equations

Coef.	*'Lights'*	*'Equipment'*	*'Pumps'*	*'Fans'*
b_0	212358.4	372382.8	38804.98	-4217686
b_1	53449.48	0	90.39378	52905.27
b_2	0	62451	868.201	45351.15
b_3	0	0	0	60753.43
b_4	0	0	49556.01	4023613
b_5	0	0	1808.388	0
b_6	0	0	3248.835	142588.8
b_7	0	0	1706.284	431398.8
b_8	0	0	16231.04	10999.15
b_9	0	0	-3998.801	186441.9
b_{10}	0	0	49.9354	-8090.4
b_{11}	0	0	-1734.102	-580258.9
b_{12}	0	0	-5891.953	2785727
b_{13}	-435390.8	0	-8752.312	-178903.2
b_{14}	0	0	12730.29	3730.12
b_{15}	0	0	-3106.608	-100866.7
b_{16}	512.4649	0	29.2337	0
b_{17}	0	0	0	0
b_{18}	0	0	-23.27036	-1468.684
b_{19}	0	0	0	0
b_{20}	0	0	0	17028.65
b_{21}	0	0	0	0
b_{22}	0	0	0	0
b_{23}	0	0	0	0
b_{24}	0	0	0	0
b_{25}	0	0	0	0
b_{26}	0	0	0	0
b_{27}	0	0	0	0
b_{28}	0	0	0	0
b_{29}	0	0	0	0
b_{30}	0	0	0	-106.8943
b_{31}	0	0	0	0
b_{32}	0	0	0	0
b_{33}	0	0	0	0
b_{34}	0	0	0	0
b_{35}	0	0	0	0

Table A.5: Building R1-Edmonton: Regression coefficients equations (cont'd)

Coef.	*'DHW'*	*'Chiller'*	*Electrical*	*Boiler*
b_0	273324.6	-271122.5	-3942815	6376438
b_1	0	-18188.43	-18449.81	-38284.02
b_2	0	18992.18	129678.2	-46745.7
b_3	-16429.1	166355.4	-13895.86	-37461.76
b_4	0	885666.7	11758362	-391762
b_5	0	21236.63	153124.1	87975.62
b_6	0	10768.73	176810	277341.5
b_7	0	53562.03	644384.7	-102646
b_8	0	-175630.4	3083396	3989883
b_9	0	39771.58	220481.5	-5354950
b_{10}	0	-599152.2	-173050.6	1474.241
b_{11}	0	-79408.54	-623633.3	366854.5
b_{12}	0	448180.9	3177250	-603965.3
b_{13}	0	-60698.12	-679375.2	199047
b_{14}	0	0	1515.472	110179.4
b_{15}	0	-174827.1	-292015.1	456755.1
b_{16}	0	985.2337	4627.91	0
b_{17}	0	0	0	0
b_{18}	436.7173	-6926.813	0	0
b_{19}	0	0	-8643920	0
b_{20}	0	0	0	0
b_{21}	0	0	0	0
b_{22}	0	0	0	0
b_{23}	0	0	-5068027	0
b_{24}	0	0	0	0
b_{25}	0	0	0	0
b_{26}	0	0	0	0
b_{27}	0	0	0	0
b_{28}	-4.336236	92.50889	0	0
b_{29}	0	0	0	0
b_{30}	0	0	0	0
b_{31}	0	0	0	0
b_{32}	0	0	0	0
b_{33}	0	0	2466500	0
b_{34}	0	0	0	0
b_{35}	0	9730.532	0	0

Table A.6: Building R1 - Vancouver: Regression coefficients equations

Coef.	*'Lights'*	*'Equipment'*	*'Pumps'*	*'Fans'*
b_0	181148.4	372382.8	32724.31	-3424068
b_1	56608.08	0	465.1663	46404.53
b_2	0	62451	645.3893	40619.74
b_3	0	0	0	50720.5
b_4	0	0	44030.4	3069555
b_5	0	0	1743.862	0
b_6	0	0	2757.785	104209.2
b_7	0	0	2587.367	371154.7
b_8	0	0	23722.9	-45753.76
b_9	0	0	-4928.984	161655.3
b_{10}	0	0	270.9484	-7771.289
b_{11}	0	0	-1749.178	-444593.1
b_{12}	0	0	-11024.8	2328989
b_{13}	-369456.7	0	-6703.509	-168759.4
b_{14}	0	0	5532.978	5181.169
b_{15}	0	0	-1525.028	-111291.6
b_{16}	437.1488	0	12.56736	0
b_{17}	0	0	0	0
b_{18}	0	0	-19.62278	-1230.946
b_{19}	0	0	0	0
b_{20}	0	0	0	12919.12
b_{21}	0	0	0	0
b_{22}	0	0	0	0
b_{23}	0	0	0	0
b_{24}	0	0	0	0
b_{25}	0	0	0	0
b_{26}	0	0	0	0
b_{27}	0	0	0	0
b_{28}	0	0	0	0
b_{29}	0	0	0	0
b_{30}	0	0	0	-28.13433
b_{31}	0	0	0	0
b_{32}	0	0	0	0
b_{33}	0	0	0	0
b_{34}	0	0	0	0
b_{35}	0	0	0	0

Table A.7: Building R1 – Vancouver: Regression coefficients equations (cont'd)

Coef.	*'DHW'*	*'Chiller'*	*Electrical*	*Boiler*
b_0	273324.6	221557.6	-2601786	3882015
b_1	0	-17362.7	-4154.665	-45789.68
b_2	0	18465.38	123724.2	-42555.91
b_3	-16429.1	119985.4	-13392.82	-21246.18
b_4	0	776178.2	7673141	-472782.5
b_5	0	19729.68	122851	51522.75
b_6	0	10568.16	133709.4	187827.6
b_7	0	51912.9	558559.3	-69960.21
b_8	0	-139337	2924747	2625680
b_9	0	33054.43	183578.6	-2589166
b_{10}	0	-601296.5	-180889	3718.926
b_{11}	0	-64246.47	-477677.3	225910.1
b_{12}	0	376573.8	2657232	-700773.3
b_{13}	0	-60516.3	-601617.1	147056.4
b_{14}	0	0	9982.605	-82230.89
b_{15}	0	-212819.5	-335228.7	693655.1
b_{16}	0	945.8073	4018.038	0
b_{17}	0	0	0	0
b_{18}	436.7173	-5053.131	0	0
b_{19}	0	0	-4941903	0
b_{20}	0	0	0	0
b_{21}	0	0	0	0
b_{22}	0	0	0	0
b_{23}	0	0	-4824626	0
b_{24}	0	0	0	0
b_{25}	0	0	0	0
b_{26}	0	0	0	0
b_{27}	0	0	0	0
b_{28}	-4.336236	67.54482	0	0
b_{29}	0	0	0	0
b_{30}	0	0	0	0
b_{31}	0	0	0	0
b_{32}	0	0	0	0
b_{33}	0	0	2343763	0
b_{34}	0	0	0	0
b_{35}	0	9639.315	0	0

Table A.8: Building R2 - Ottawa: Regression coefficients equations

Coef.	*'Lights'*	*'Equipment'*	*'Pumps'*	*'Fans'*
b_0	-1.7E-10	372382.8	35469.28	-3696229
b_1	74941.2	0	967.2159	41333.32
b_2	0	62451	685.7841	41840.31
b_3	0	0	0	-15472.8
b_4	0	0	43474.54	2884431
b_5	0	0	5873.009	0
b_6	0	0	0	0
b_7	0	0	0	367096.6
b_8	0	0	28127.34	6642.62
b_9	0	0	0	-121434
b_{10}	0	0	0	-7349.46
b_{11}	0	0	0	0
b_{12}	0	0	-11367.5	3336671
b_{13}	-453476	0	-6775.51	-67552.6
b_{14}	0	0	-7429.81	-172432
b_{15}	0	0	0	0
b_{16}	0	0	0	0
b_{17}	0	0	0	0
b_{18}	0	0	-35.7689	0
b_{19}	0	0	0	0
b_{20}	0	0	0	-52301
b_{21}	0	0	0	0
b_{22}	0	0	0	0
b_{23}	0	0	0	0
b_{24}	0	0	0	0
b_{25}	0	0	0	0
b_{26}	0	0	0	0
b_{27}	0	0	0	0
b_{28}	0	0	0	0
b_{29}	0	0	0	0
b_{30}	0	0	0	18755.55
b_{31}	0	0	0	0
b_{32}	0	0	0	0
b_{33}	0	0	0	0
b_{34}	0	0	0	0
b_{35}	0	0	0	0

Table A.9: Building R2 -Ottawa: Regression coefficients equations (cont'd)

Coef.	*'DHW'*	*'Chiller'*	*Electrical*	*Boiler*
b_0	236953	131960.6	-2129247	2602496
b_1	0	10613.91	130242.5	-36567.3
b_2	0	16315.38	121517.3	-46822
b_3	-10987.5	76252.48	-23157.3	-36239.4
b_4	0	551007.8	3033962	1262877
b_5	0	23984.92	238533.3	349228.7
b_6	0	0	0	0
b_7	0	10771.95	500520.4	-129354
b_8	0	-164028	-138251	3790812
b_9	0	-666237	-893440	-2207654
b_{10}	0	-228792	-260936	30005.33
b_{11}	0	0	0	0
b_{12}	0	393595.8	3715688	-922705
b_{13}	0	-82187.4	-639029	139575.8
b_{14}	0	0	-146456	-396784
b_{15}	0	0	0	0
b_{16}	0	0	0	0
b_{17}	0	0	0	0
b_{18}	168.8434	-1905.83	0	0
b_{19}	0	0	0	0
b_{20}	0	0	0	0
b_{21}	0	0	0	0
b_{22}	0	0	0	0
b_{23}	0	0	0	0
b_{24}	0	0	0	0
b_{25}	0	0	0	0
b_{26}	0	0	0	0
b_{27}	0	0	0	0
b_{28}	0	0	0	0
b_{29}	0	0	0	0
b_{30}	0	0	0	0
b_{31}	0	0	0	0
b_{32}	0	0	0	0
b_{33}	0	0	0	0
b_{34}	0	0	0	0
b_{35}	0	0	0	0

Table A.10: Building R2 - Edmonton: Regression coefficients equations

Coef.	*'Lights'*	*'Equipment'*	*'Pumps'*	*'Fans'*
b_0	-1.7E-10	372382.8	29861.88	-3961050
b_1	74941.2	0	983.9404	44297.32
b_2	0	62451	634.98	42465.4
b_3	0	0	0	-11996.6
b_4	0	0	41495.86	3171537
b_5	0	0	5631.522	0
b_6	0	0	0	0
b_7	0	0	0	362608.2
b_8	0	0	18488.24	-207688
b_9	0	0	0	-144630
b_{10}	0	0	0	-10256.6
b_{11}	0	0	0	0
b_{12}	0	0	-10319	3457044
b_{13}	-447930	0	-6051.58	-29916.5
b_{14}	0	0	-1234.84	30659.18
b_{15}	0	0	0	0
b_{16}	0	0	0	0
b_{17}	0	0	0	0
b_{18}	0	0	-28.8566	0
b_{19}	0	0	0	0
b_{20}	0	0	0	-78898.9
b_{21}	0	0	0	0
b_{22}	0	0	0	0
b_{23}	0	0	0	0
b_{24}	0	0	0	0
b_{25}	0	0	0	0
b_{26}	0	0	0	0
b_{27}	0	0	0	0
b_{28}	0	0	0	0
b_{29}	0	0	0	0
b_{30}	0	0	0	24764.92
b_{31}	0	0	0	0
b_{32}	0	0	0	0
b_{33}	0	0	0	0
b_{34}	0	0	0	0
b_{35}	0	0	0	0

Table A.11: Building R2 – Edmonton: Regression coefficients equations (cont'd)

Coef.	*'DHW'*	*'Chiller'*	*Electrical*	*Boiler*
b_0	236953	-347858	-2481169	3212000
b_1	0	10865.03	133603.5	-37485.5
b_2	0	15634.73	121256.6	-48186.6
b_3	-10987.5	107681.3	-15504.5	-39704.1
b_4	0	594367.9	3197125	1352972
b_5	0	21399.88	243843	376926.6
b_6	0	0	0	0
b_7	0	34864.23	532211.1	-167272
b_8	0	-246273	-438291	3893545
b_9	0	-763223	-1026636	-2982511
b_{10}	0	-203639	-248088	33671.86
b_{11}	0	0	0	0
b_{12}	0	426823.9	3872542	-935624
b_{13}	0	-83471.6	-594245	117612.5
b_{14}	0	0	129912.5	-390524
b_{15}	0	0	0	0
b_{16}	0	0	0	0
b_{17}	0	0	0	0
b_{18}	168.8434	-2568.75	0	0
b_{19}	0	0	0	0
b_{20}	0	0	0	0
b_{21}	0	0	0	0
b_{22}	0	0	0	0
b_{23}	0	0	0	0
b_{24}	0	0	0	0
b_{25}	0	0	0	0
b_{26}	0	0	0	0
b_{27}	0	0	0	0
b_{28}	0	0	0	0
b_{29}	0	0	0	0
b_{30}	0	0	0	0
b_{31}	0	0	0	0
b_{32}	0	0	0	0
b_{33}	0	0	0	0
b_{34}	0	0	0	0
b_{35}	0	0	0	0

Table A.12: Building R2 - Vancouver: Regression coefficients equations

Coef.	*'Lights'*	*'Equipment'*	*'Pumps'*	*'Fans'*
b_0	-1.7E-10	372382.8	21116.29	-2980995
b_1	74941.2	0	820.1914	40524.06
b_2	0	62451	430.3307	38194.04
b_3	0	0	0	-9920.8
b_4	0	0	44329.77	2371086
b_5	0	0	5549.069	0
b_6	0	0	0	0
b_7	0	0	0	327317.6
b_8	0	0	25544.51	-229590
b_9	0	0	0	-259165
b_{10}	0	0	0	-10014
b_{11}	0	0	0	0
b_{12}	0	0	-15060.6	2822188
b_{13}	-409146	0	-5185.61	-122476
b_{14}	0	0	-4650.95	41206.11
b_{15}	0	0	0	0
b_{16}	0	0	0	0
b_{17}	0	0	0	0
b_{18}	0	0	-26.0757	0
b_{19}	0	0	0	0
b_{20}	0	0	0	-56239
b_{21}	0	0	0	0
b_{22}	0	0	0	0
b_{23}	0	0	0	0
b_{24}	0	0	0	0
b_{25}	0	0	0	0
b_{26}	0	0	0	0
b_{27}	0	0	0	0
b_{28}	0	0	0	0
b_{29}	0	0	0	0
b_{30}	0	0	0	18280.53
b_{31}	0	0	0	0
b_{32}	0	0	0	0
b_{33}	0	0	0	0
b_{34}	0	0	0	0
b_{35}	0	0	0	0

Table A.13: Building R2 - Vancouver: Regression coefficients equations (cont'd)

Coef.	*'DHW'*	*'Chiller'*	*Electrical*	*Boiler*
b_0	236953	-99792.9	-1264480	176345
b_1	0	10972.25	129585.5	-36207.4
b_2	0	15195.16	116498.6	-37793.6
b_3	-10987.5	106903.1	-14886.5	-20516.5
b_4	0	490430.9	2429171	786978.7
b_5	0	23316.33	201964.2	205569.7
b_6	0	0	0	0
b_7	0	51661.81	458883.5	-30866.6
b_8	0	-202049	-415217	2506828
b_9	0	-913513	-1268565	718062.1
b_{10}	0	-202699	-239048	27028.79
b_{11}	0	0	0	0
b_{12}	0	324469.9	3128340	-880074
b_{13}	0	-95706.2	-646625	105755.4
b_{14}	0	0	161375.8	-526602
b_{15}	0	0	0	0
b_{16}	0	0	0	0
b_{17}	0	0	0	0
b_{18}	168.8434	-2546.27	0	0
b_{19}	0	0	0	0
b_{20}	0	0	0	0
b_{21}	0	0	0	0
b_{22}	0	0	0	0
b_{23}	0	0	0	0
b_{24}	0	0	0	0
b_{25}	0	0	0	0
b_{26}	0	0	0	0
b_{27}	0	0	0	0
b_{28}	0	0	0	0
b_{29}	0	0	0	0
b_{30}	0	0	0	0
b_{31}	0	0	0	0
b_{32}	0	0	0	0
b_{33}	0	0	0	0
b_{34}	0	0	0	0
b_{35}	0	0	0	0

Table A.14: Building R3 - Ottawa: Regression coefficients equations

Coef.	*'Lights'*	*'Equipment'*	*'Pumps'*	*'Fans'*
b_0	40693.98	92461.01	4288.036	-1412753
b_1	8873.601	0	159.9182	10176.81
b_2	0	12949.72	220.9504	7470.69
b_3	0	0	0	16797.61
b_4	0	0	8372.392	1176700
b_5	0	0	308.5196	0
b_6	0	0	749.5447	66884.64
b_7	0	0	4599.654	474563
b_8	0	0	5192.185	86367.51
b_9	0	0	-3042.98	2842.192
b_{10}	0	0	349.731	-20962.9
b_{11}	0	0	-369.401	-98359.8
b_{12}	0	0	-106.942	409050.1
b_{13}	-80161.9	0	-1756.74	-19661.1
b_{14}	0	0	425.6672	-4479.72
b_{15}	0	0	0	0
b_{16}	96.57546	0	1.716691	0
b_{17}	0	0	0	0
b_{18}	0	0	-3.49278	-389.263
b_{19}	0	0	0	0
b_{20}	0	0	0	4242.378
b_{21}	0	0	0	0
b_{22}	0	0	0	0
b_{23}	0	0	0	0
b_{24}	0	0	0	0
b_{25}	0	0	0	0
b_{26}	0	0	0	0
b_{27}	0	0	0	0
b_{28}	0	0	0	0
b_{29}	0	0	0	0
b_{30}	0	0	0	-145.282
b_{31}	0	0	0	0
b_{32}	0	0	0	0
b_{33}	0	0	0	0
b_{34}	0	0	0	0
b_{35}	0	0	0	0

Table A.15: Building R3 - Ottawa: Regression coefficients equations (cont'd)

Coef.	*'DHW'*	*'Chiller'*	*Electrical*	*Boiler*
b_0	53229.12	871593.7	-1390621	868063.1
b_1	0	-1867.397	-1140.943	-2946.608
b_2	0	4930.021	25784.07	-5289.905
b_3	-2966.155	-102358.4	-4133.897	-5314.517
b_4	0	326474	5471780	-339906
b_5	0	7122.427	34253.13	-1783.583
b_6	0	13681.3	72899.39	4290.256
b_7	0	121546.4	596246.6	-54981.12
b_8	0	13008.02	-11878.24	337854.4
b_9	0	-111813.9	-112717.9	-443842.1
b_{10}	0	-131339.4	-182022.1	40864.82
b_{11}	0	-20084.23	-115146.3	47053.85
b_{12}	0	129784.7	536520.2	-7764.744
b_{13}	0	-17570.46	-118619.3	15393.33
b_{14}	0	15308.39	2672.138	-54001.43
b_{15}	0	0	0	0
b_{16}	0	167.5863	753.9979	0
b_{17}	0	0	0	0
b_{18}	71.93366	4526.372	0	0
b_{19}	0	0	-4935010	0
b_{20}	0	0	0	0
b_{21}	0	0	0	0
b_{22}	0	0	0	0
b_{23}	0	0	0	0
b_{24}	0	0	0	0
b_{25}	0	0	0	0
b_{26}	0	0	0	0
b_{27}	0	0	0	0
b_{28}	-0.638505	-66.00732	0	0
b_{29}	0	0	0	0
b_{30}	0	0	0	0
b_{31}	0	0	0	0
b_{32}	0	0	0	0
b_{33}	0	0	54892.74	0
b_{34}	0	0	0	0
b_{35}	0	0	0	0

Table A.16: Building R3 - Edmonton: Regression coefficients equations

Coef.	*'Lights'*	*'Equipment'*	*'Pumps'*	*'Fans'*
b_0	41690.61	92461.01	4613.678	-1880195
b_1	8773.774	0	116.3194	9028.919
b_2	0	12949.72	218.0076	6479.58
b_3	0	0	0	94621.49
b_4	0	0	8256.658	906502.9
b_5	0	0	351.2658	0
b_6	0	0	772.6138	57133.12
b_7	0	0	3716.488	332088.1
b_8	0	0	2571.261	49522.65
b_9	0	0	-3309.942	-463.4351
b_{10}	0	0	211.5151	-61349.47
b_{11}	0	0	-474.8341	-86782.03
b_{12}	0	0	109.0908	354400.3
b_{13}	-82546.51	0	-1951.049	-19003.66
b_{14}	0	0	378.1596	-4839.558
b_{15}	0	0	0	0
b_{16}	98.94067	0	2.941721	0
b_{17}	0	0	0	0
b_{18}	0	0	-4.075318	-2054.51
b_{19}	0	0	0	0
b_{20}	0	0	0	1368.884
b_{21}	0	0	0	0
b_{22}	0	0	0	0
b_{23}	0	0	0	0
b_{24}	0	0	0	0
b_{25}	0	0	0	0
b_{26}	0	0	0	0
b_{27}	0	0	0	0
b_{28}	0	0	0	0
b_{29}	0	0	0	0
b_{30}	0	0	0	237.2003
b_{31}	0	0	0	0
b_{32}	0	0	0	0
b_{33}	0	0	0	0
b_{34}	0	0	0	0
b_{35}	0	0	0	0

Table A.17: Building R3 - Edmonton: Regression coefficients equations (cont'd)

Coef.	*'DHW'*	*'Chiller'*	*Electrical*	*Boiler*
b_0	53229.12	1069761	-1029610	729680.5
b_1	0	-2326.74	10.95119	110.1985
b_2	0	4570.793	24342.91	-3117.134
b_3	-2966.155	-129249	-6129.997	-6169.701
b_4	0	269776	4771778	-192951.1
b_5	0	6962.861	31591.88	1689.668
b_6	0	11037.46	63477.38	12092.83
b_7	0	84388.1	415868	8042.118
b_8	0	-12582.76	-10766.35	284746.9
b_9	0	-139010.1	-149300.9	-529759
b_{10}	0	-118678.5	-143445.7	46365.79
b_{11}	0	-18671.16	-100449.4	35064.16
b_{12}	0	115427.6	478658.8	45083.55
b_{13}	0	-16796.9	-121125.4	8312.869
b_{14}	0	20966.65	5323.464	-36981.42
b_{15}	0	0	0	0
b_{16}	0	170.275	681.3713	0
b_{17}	0	0	0	0
b_{18}	71.93366	5989.552	0	0
b_{19}	0	0	-4517227	0
b_{20}	0	0	0	0
b_{21}	0	0	0	0
b_{22}	0	0	0	0
b_{23}	0	0	0	0
b_{24}	0	0	0	0
b_{25}	0	0	0	0
b_{26}	0	0	0	0
b_{27}	0	0	0	0
b_{28}	-0.638505	-90.65998	0	0
b_{29}	0	0	0	0
b_{30}	0	0	0	0
b_{31}	0	0	0	0
b_{32}	0	0	0	0
b_{33}	0	0	23029.95	0
b_{34}	0	0	0	0
b_{35}	0	0	0	0

Table A.18: Building R3 - Vancouver: Regression coefficients equations

Coef.	*'Lights'*	*'Equipment'*	*'Pumps'*	*'Fans'*
b_0	35825.48	92461.01	3748.783	-873228.8
b_1	9361.254	0	132.3493	7349.138
b_2	0	12949.72	196.1243	5890.819
b_3	0	0	0	10471.11
b_4	0	0	8237.727	688689.3
b_5	0	0	282.4626	0
b_6	0	0	551.4694	39040.69
b_7	0	0	3779.062	277020.3
b_8	0	0	3022.741	27307.81
b_9	0	0	-2627.291	1689.797
b_{10}	0	0	153.263	-11724.99
b_{11}	0	0	-422.8863	-60909.7
b_{12}	0	0	-428.2973	308096.1
b_{13}	-70319.32	0	-1717.774	-18173.9
b_{14}	0	0	52.84843	-3451.219
b_{15}	0	0	0	0
b_{16}	85.02149	0	1.552437	0
b_{17}	0	0	0	0
b_{18}	0	0	-2.499251	-240.1353
b_{19}	0	0	0	0
b_{20}	0	0	0	3379.588
b_{21}	0	0	0	0
b_{22}	0	0	0	0
b_{23}	0	0	0	0
b_{24}	0	0	0	0
b_{25}	0	0	0	0
b_{26}	0	0	0	0
b_{27}	0	0	0	0
b_{28}	0	0	0	0
b_{29}	0	0	0	0
b_{30}	0	0	0	-187.774
b_{31}	0	0	0	0
b_{32}	0	0	0	0
b_{33}	0	0	0	0
b_{34}	0	0	0	0
b_{35}	0	0	0	0

Table A.19: Building R3 - Vancouver: Regression coefficients equations (cont'd)

Coef.	*'DHW'*	*'Chiller'*	*Electrical*	*Boiler*
b_0	53229.12	971648.3	-751844.7	519926
b_1	0	-1766.006	2524.438	-5634.762
b_2	0	4589.95	23801.86	-5972.268
b_3	-2966.155	-105197	-2724.694	-3450.712
b_4	0	234706.3	3640247	-181135.1
b_5	0	5675.248	23124.05	-535.6959
b_6	0	7724.928	41132.94	5212.867
b_7	0	80788.91	358806.3	-46796.54
b_8	0	-10528.09	4054.815	252379.3
b_9	0	-167096.8	-166601.1	-34703.14
b_{10}	0	-106981.3	-139014.3	-894.4961
b_{11}	0	-13699.98	-73032.34	25948.73
b_{12}	0	114809.8	417751.9	-28128.57
b_{13}	0	-18113.51	-107626.7	10557.94
b_{14}	0	25690.14	15497.22	-69555
b_{15}	0	0	0	0
b_{16}	0	150.75	568.9726	0
b_{17}	0	0	0	0
b_{18}	71.93366	4565.723	0	0
b_{19}	0	0	-3371359	0
b_{20}	0	0	0	0
b_{21}	0	0	0	0
b_{22}	0	0	0	0
b_{23}	0	0	0	0
b_{24}	0	0	0	0
b_{25}	0	0	0	0
b_{26}	0	0	0	0
b_{27}	0	0	0	0
b_{28}	-0.638505	-65.1716	0	0
b_{29}	0	0	0	0
b_{30}	0	0	0	0
b_{31}	0	0	0	0
b_{32}	0	0	0	0
b_{33}	0	0	4443.681	0
b_{34}	0	0	0	0
b_{35}	0	0	0	0

Appendix B: Residual Plots

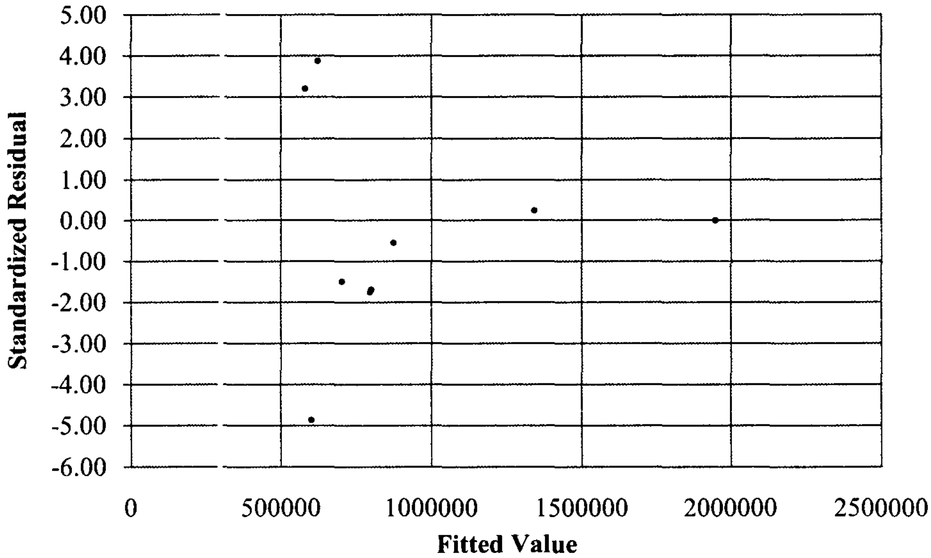

Figure B.1: Building Type R1 - Ottawa: Residuals vs. Fitted Values (Lighting Load)

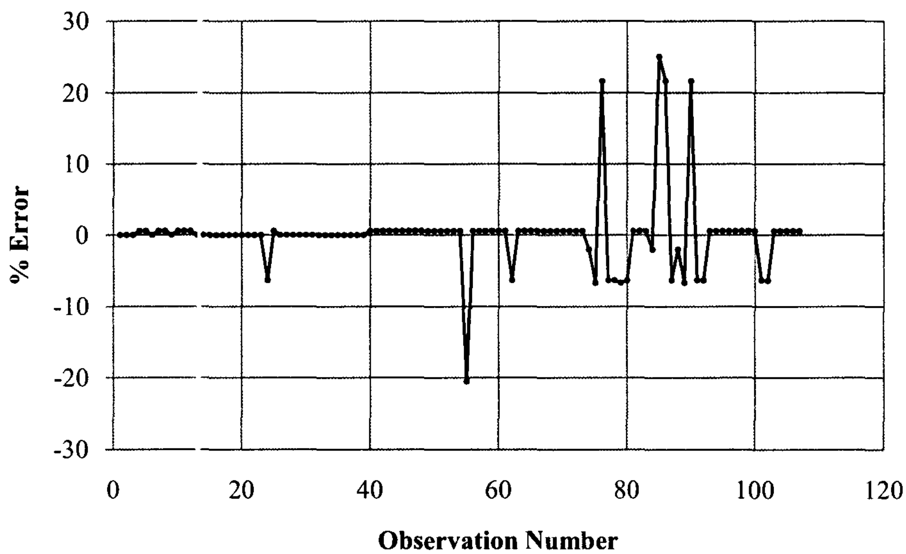

Figure B.2: Building Type R1 - Ottawa: % Error vs. Observation (Lighting Load)

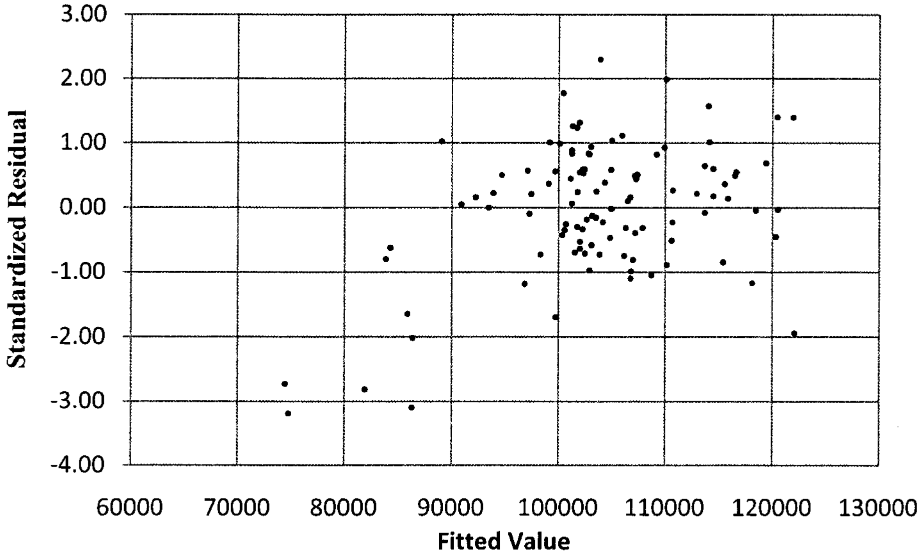

Figure B.3: Building Type R1 - Ottawa: Residuals vs. Fitted Values (Pump Load)

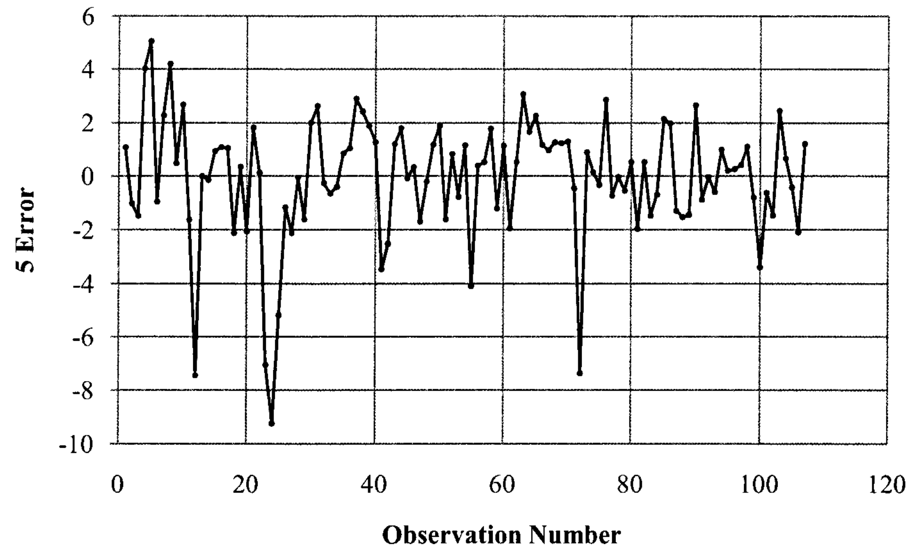

Figure B.4: Building Type R1 - Ottawa: % Error vs. Observation (Pump Load)

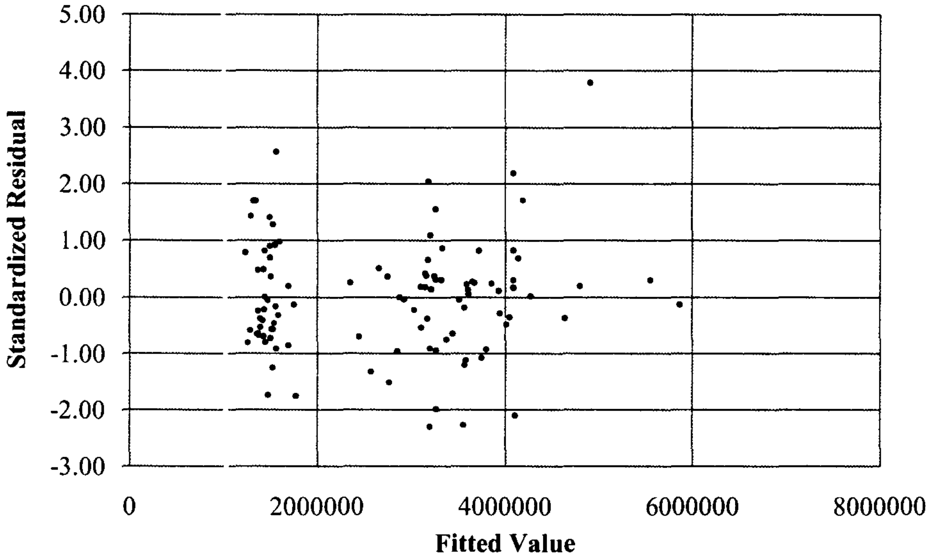

Figure B.5: Building Type R1 - Ottawa: Residuals vs. Fitted Values (Fan Load)

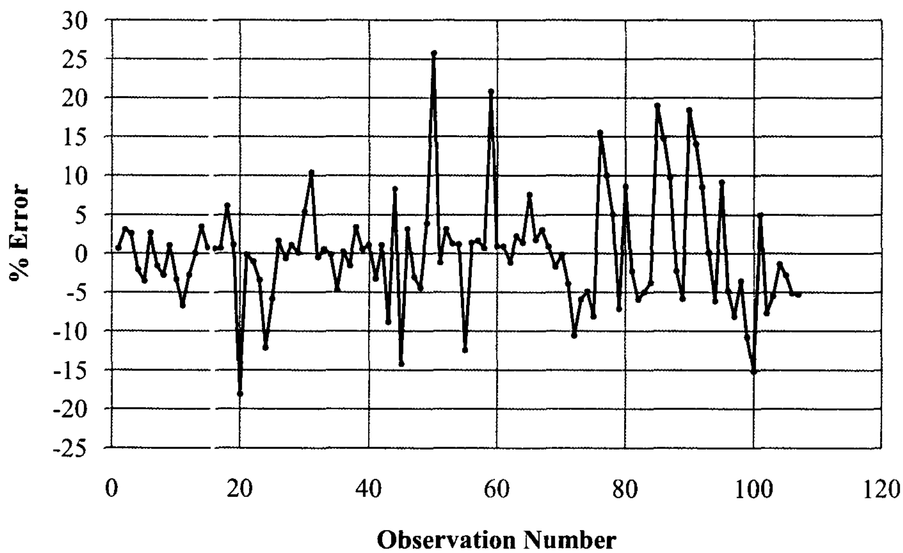

Figure B.6: Building Type R1 - Ottawa: % Error vs. Observation (Fan Load)

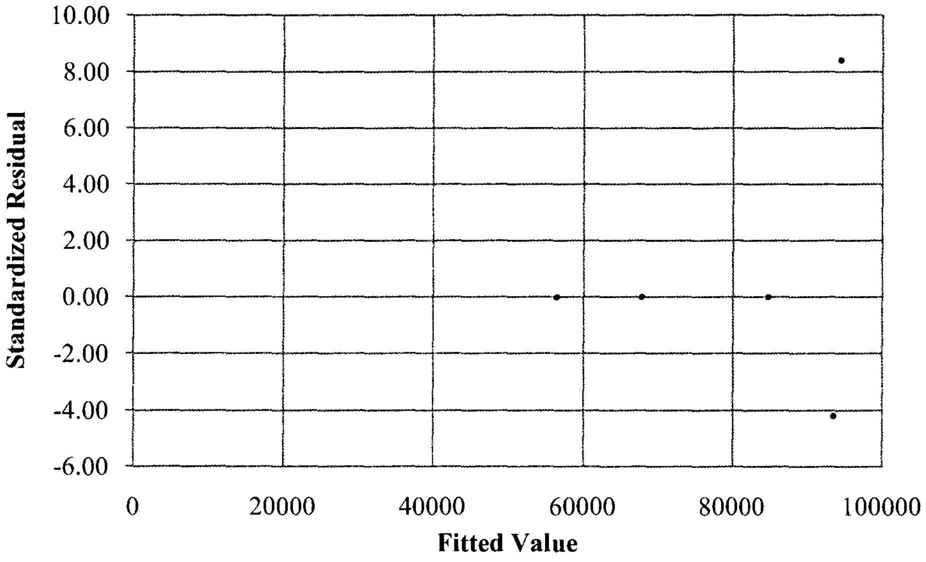

Figure B.7: Building Type R1 - Ottawa: Residuals vs. Fitted Values (DHW Loads)

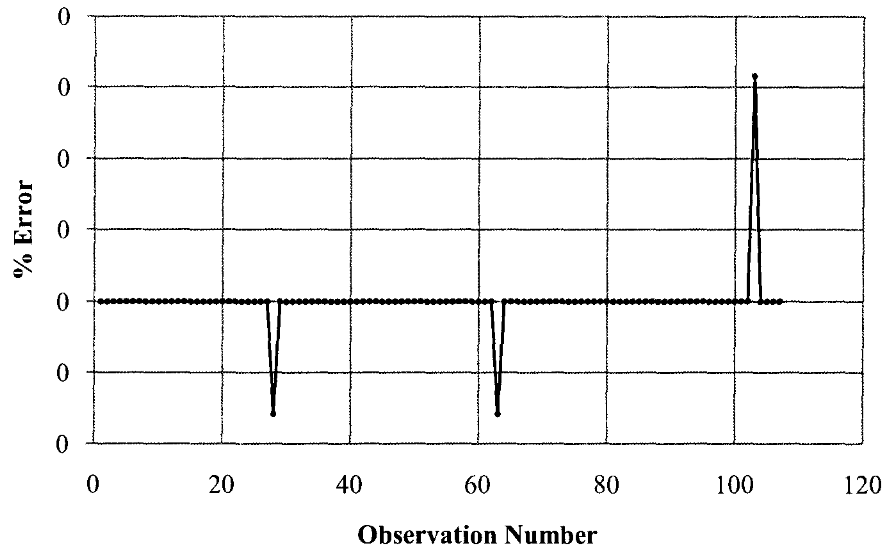

Figure B.8: Building Type R1 - Ottawa: % Error vs. Observation (DHW Load)

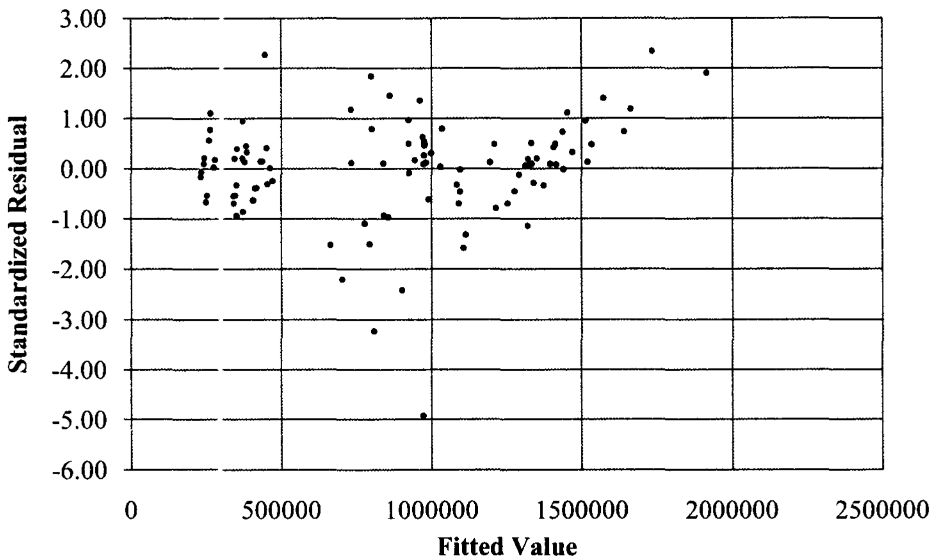

Figure B.9: Building Type R1 - Ottawa: Residuals vs. Fitted Values (Chiller Load)

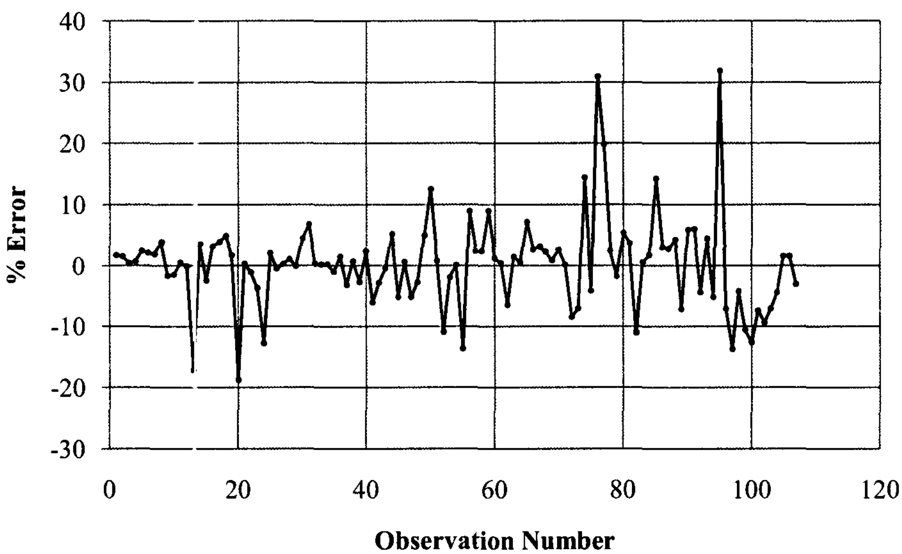

Figure B.10: Building Type R1 - Ottawa: % Error vs. Observation (Chiller Load)

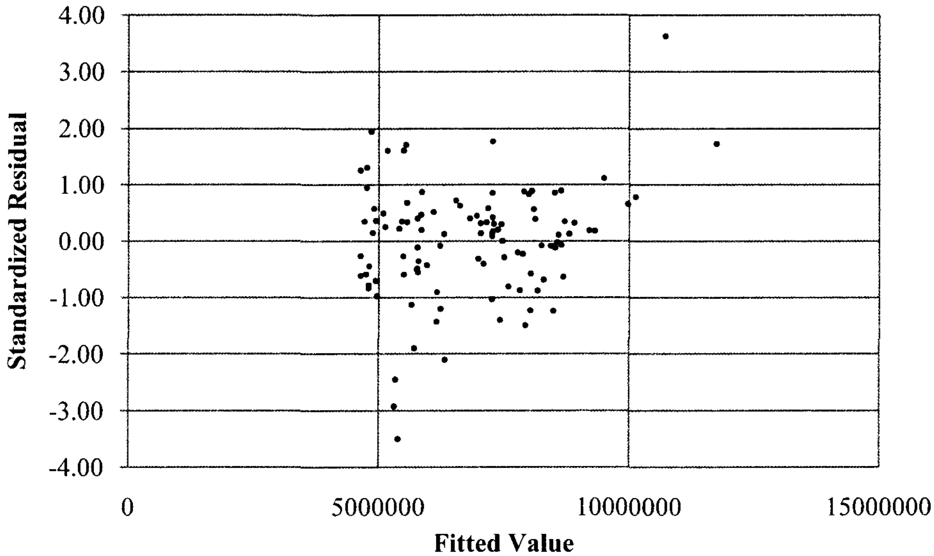

Figure B.11: Building Type R1 - Ottawa: Residuals vs. Fitted Values (Electrical Load)

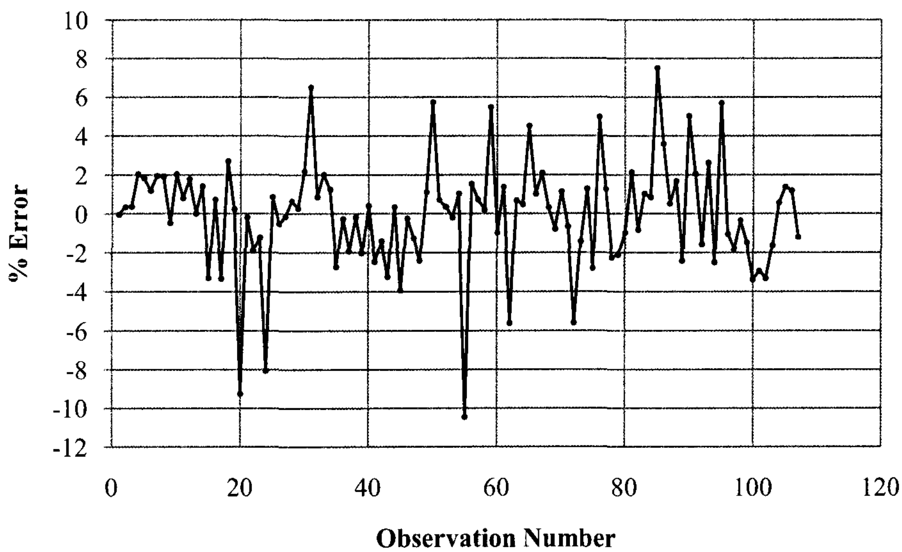

Figure B.12: Building Type R1 - Ottawa: % Error vs. Observation (Electrical Load)

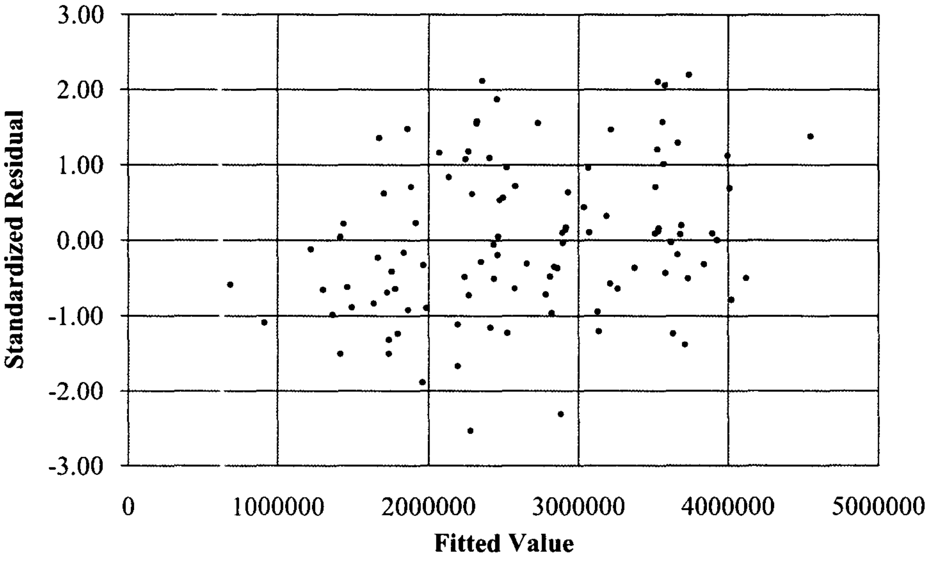

Figure B.13: Building Type R1 - Ottawa: Residuals vs. Fitted Values (Natural Gas Load)

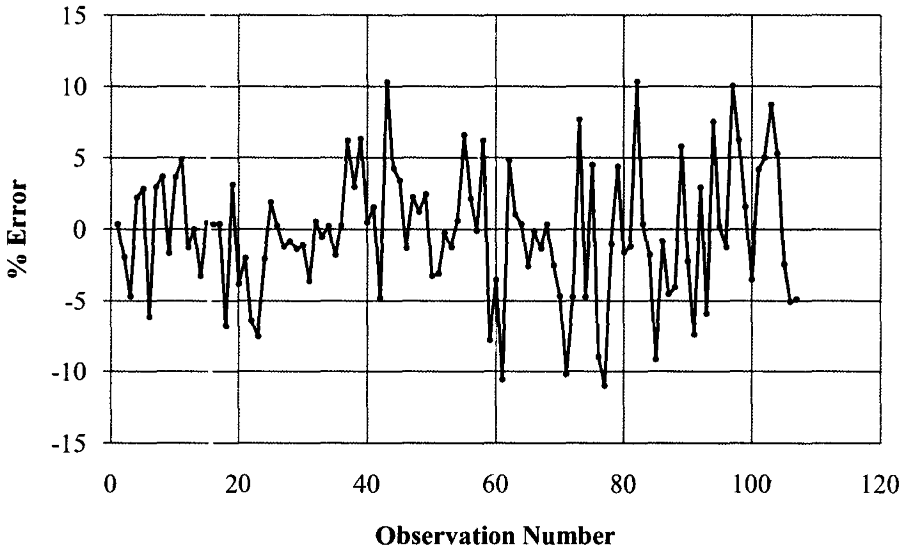

Figure B.14: Building Type R1 - Ottawa: % Error vs. Observation (Natural Gas Load)

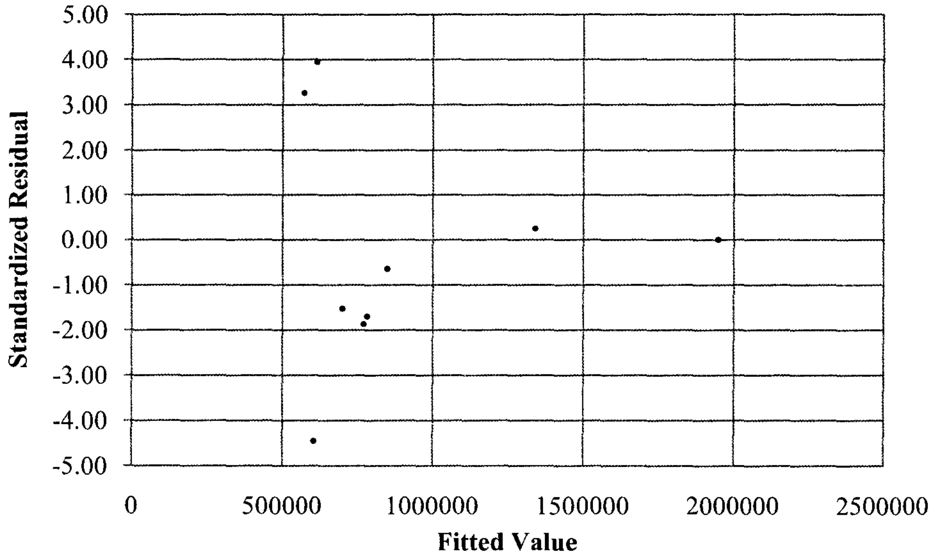

Figure B.15: Building Type R1 - Edmonton: Residuals vs. Fitted Values (Lighting Load)

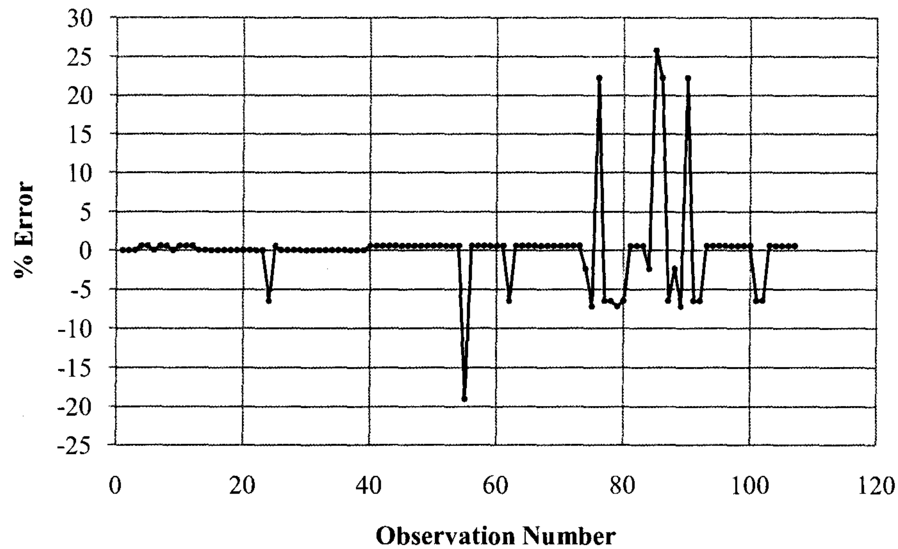

Figure B.16: Building Type R1 - Edmonton: % Error vs. Observation (Lighting Load)

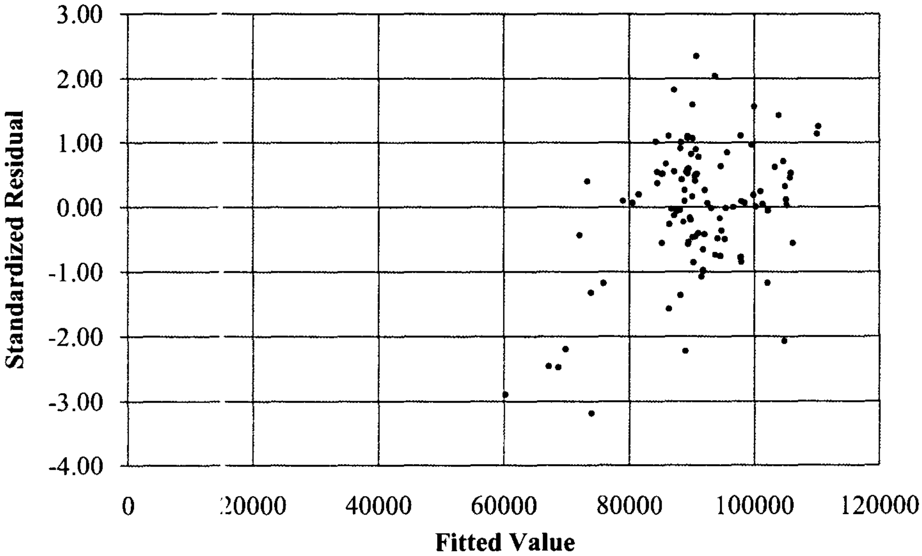

Figure B.17: Building Type R1 - Edmonton: Residuals vs. Fitted Values (Pump Load)

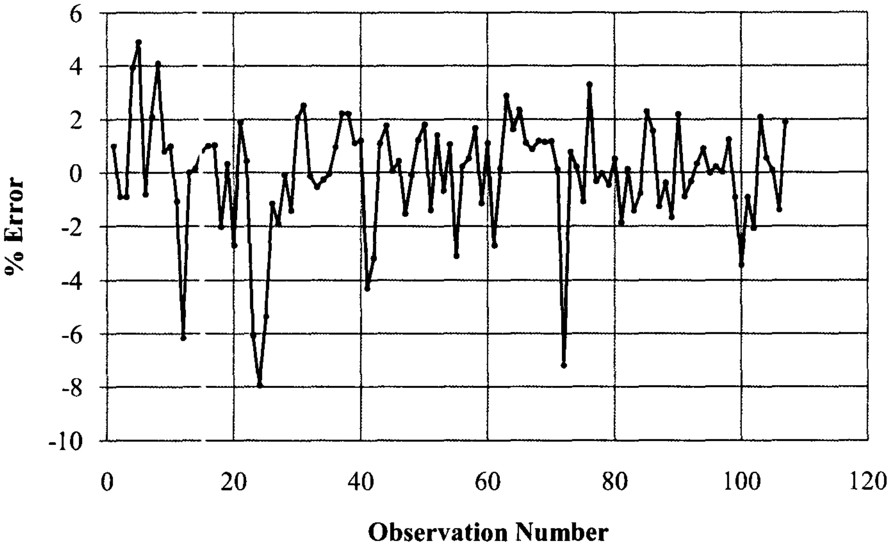

Figure B.18: Building Type R1 - Edmonton: % Error vs. Observation (Pump Load)

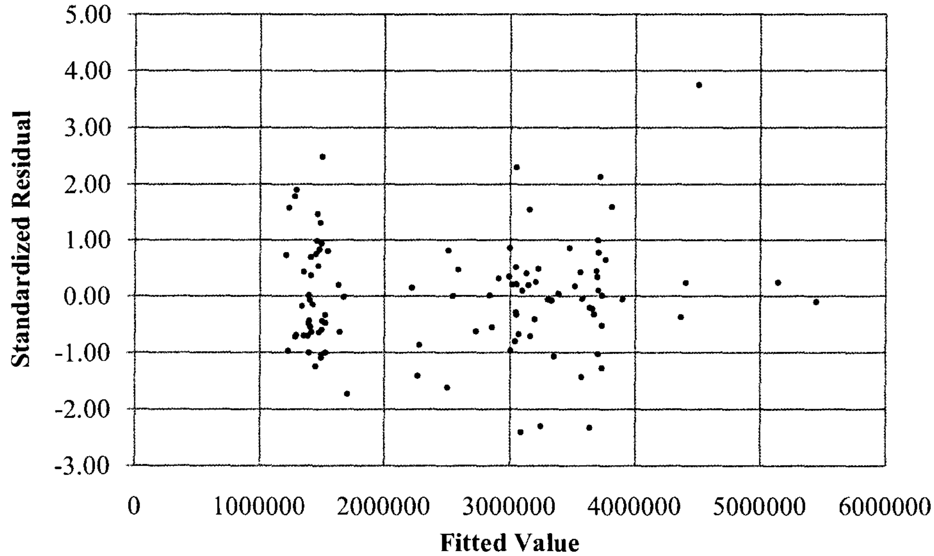

Figure B.19: Building Type R1 - Edmonton: Residuals vs. Fitted Values (Fan Load)

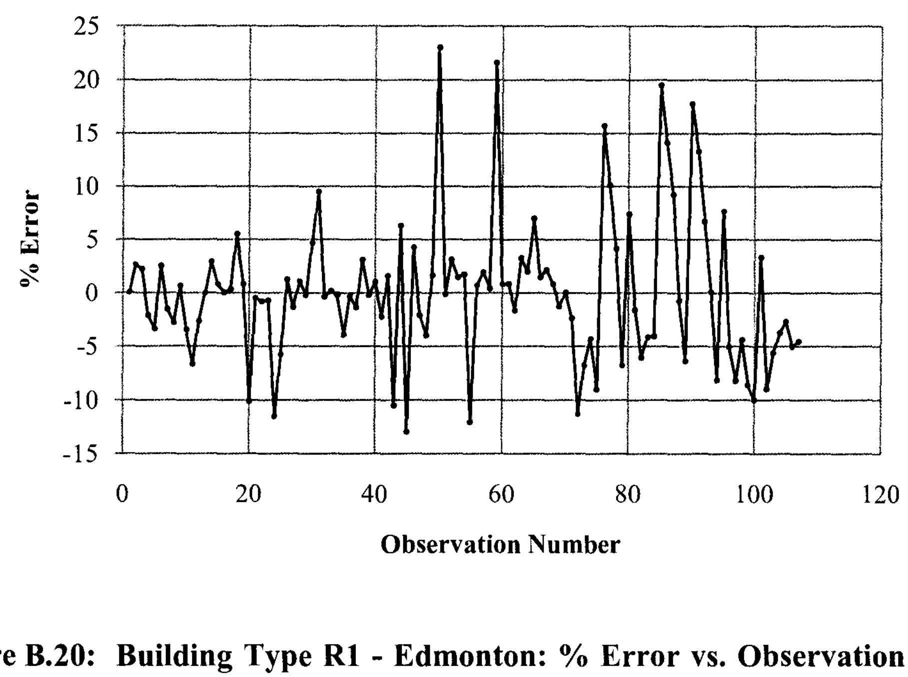

Figure B.20: Building Type R1 - Edmonton: % Error vs. Observation (Fan Load)

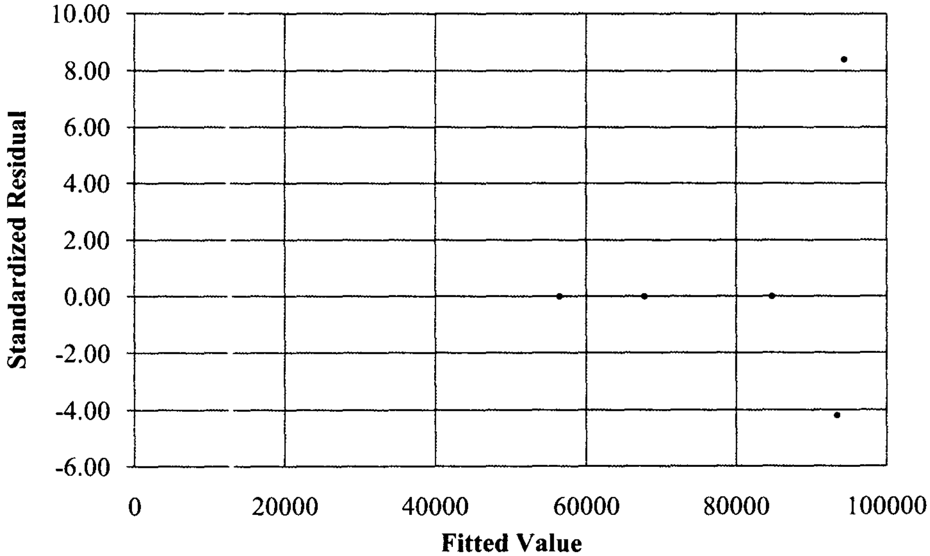

Figure B.21: Building Type R1 - Edmonton: Residuals vs. Fitted Values (DHW Loads)

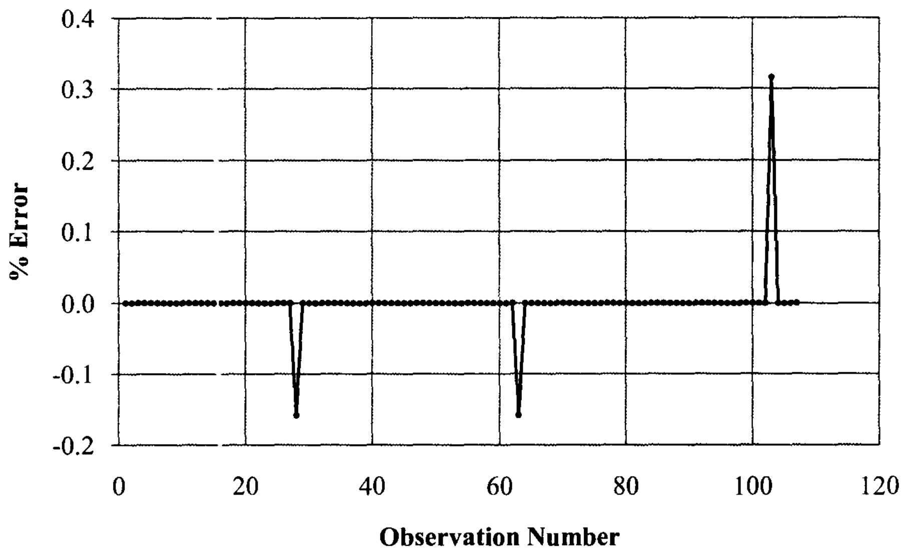

Figure B.22: Building Type R1 - Edmonton: % Error vs. Observation (DHW Load)

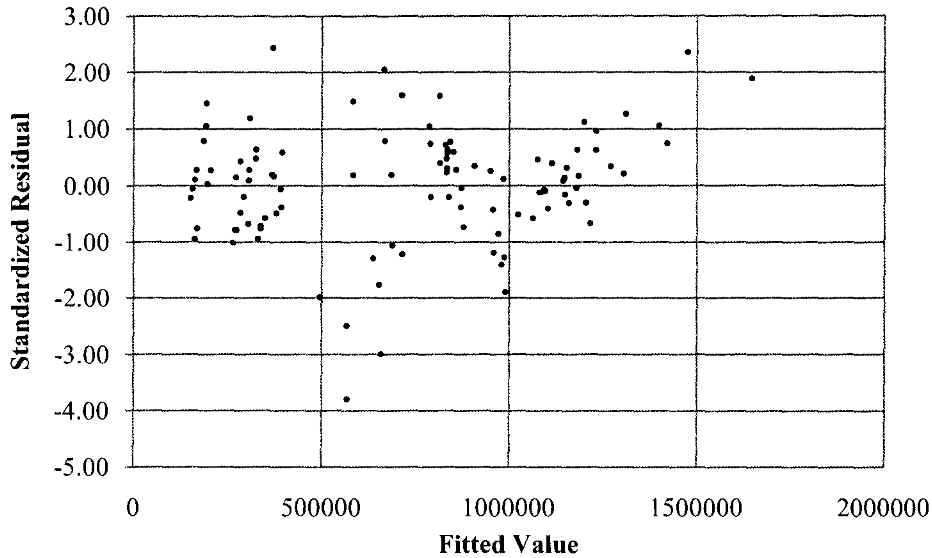

Figure B.23: Building Type R1 - Edmonton: Residuals vs. Fitted Values (Chiller Load)

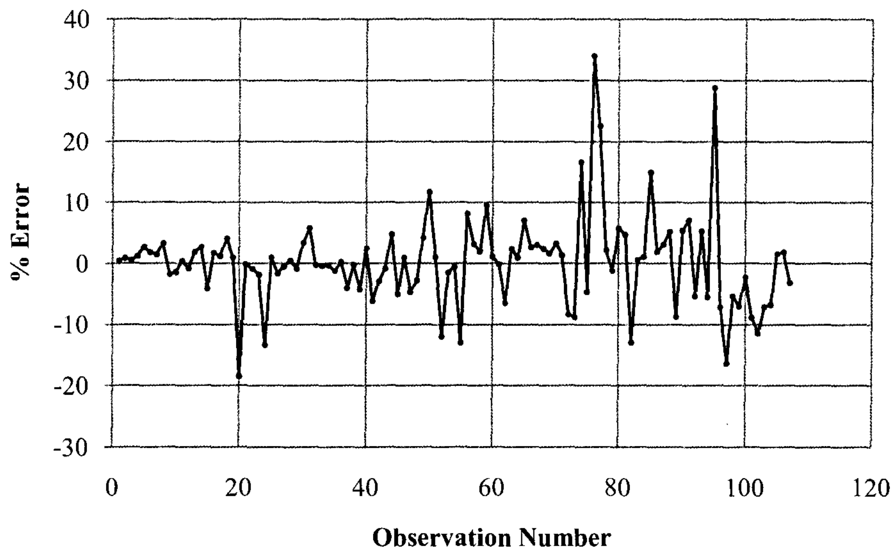

Figure B.24: Building Type R1 - Edmonton: % Error vs. Observation (Chiller Load)

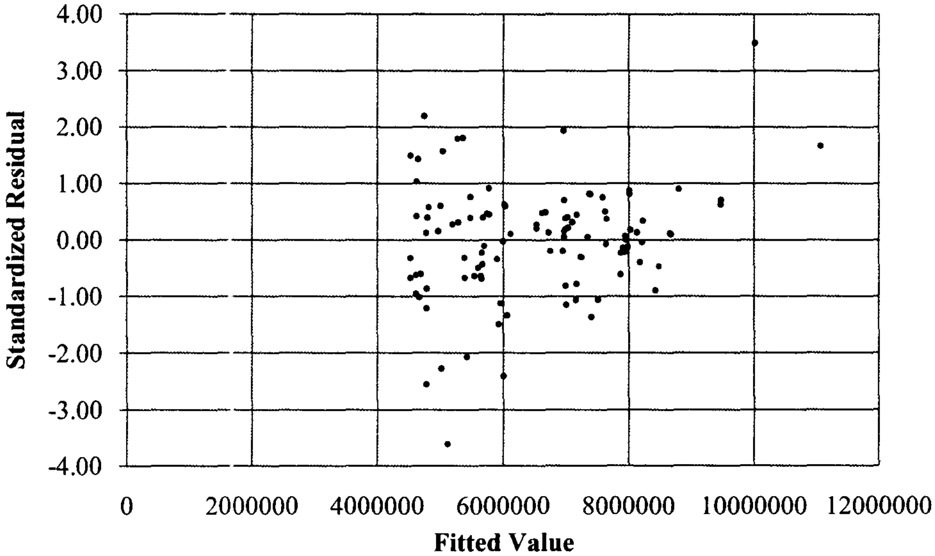

Figure B.25: Building Type R1 - Edmonton: Residuals vs. Fitted Values (Electrical Load)

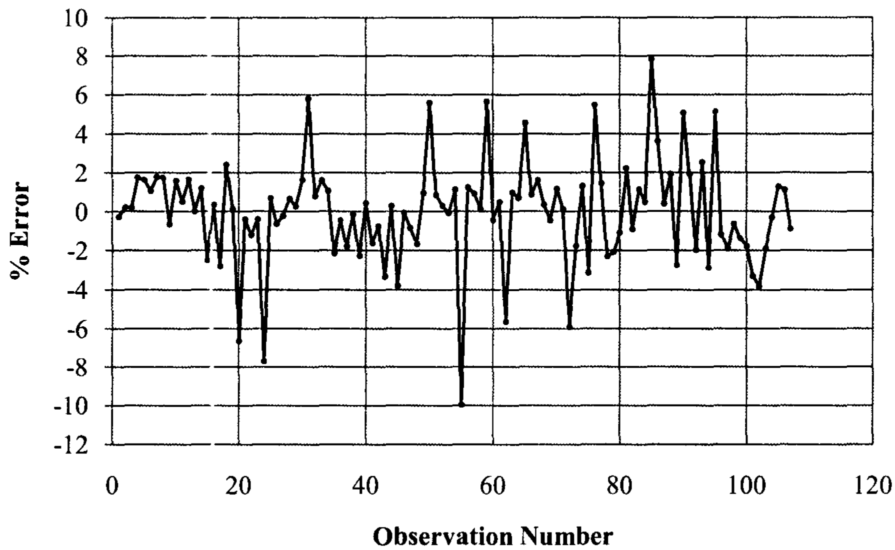

Figure B.26: Building Type R1 - Edmonton: % Error vs. Observation (Electrical Load)

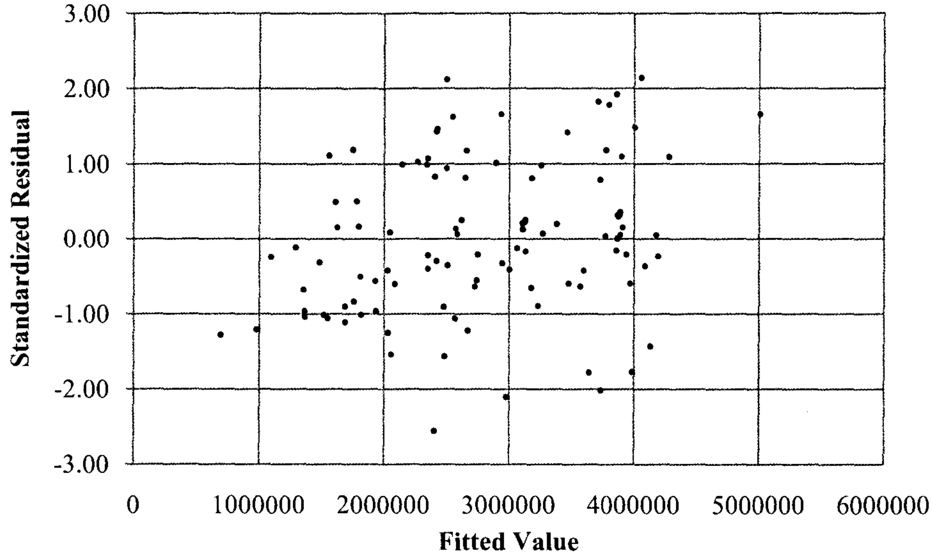

Figure B.27: Building Type R1 - Edmonton: Residuals vs. Fitted Values (Natural Gas Load)

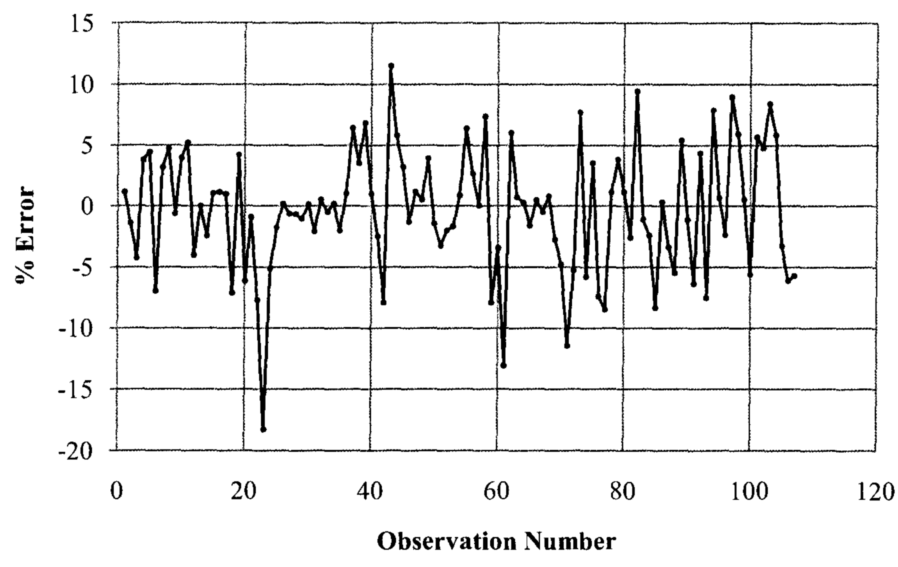

Figure B.28: Building Type R1 - Edmonton: % Error vs. Observation (Natural Gas Load)

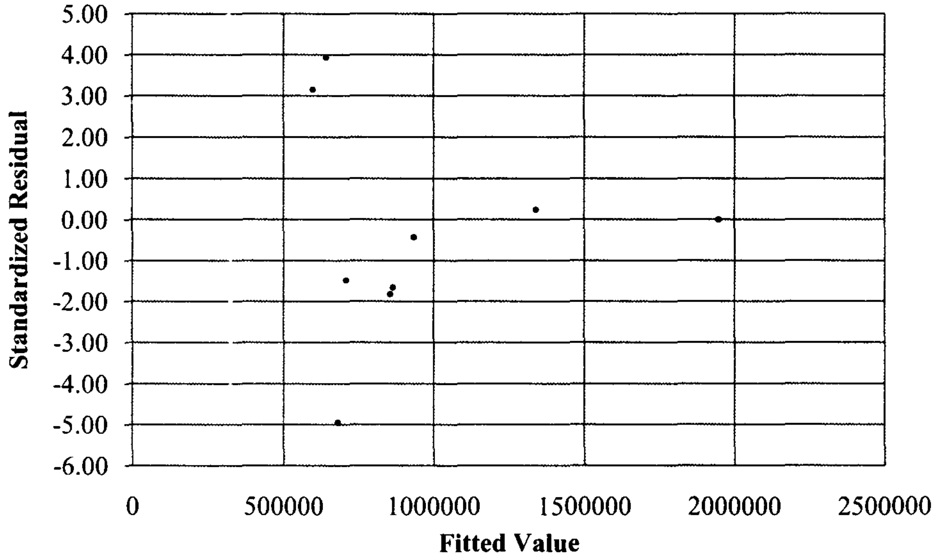

Figure B.29: Building Type R1 - Vancouver: Residuals vs. Fitted Values (Lighting Load)

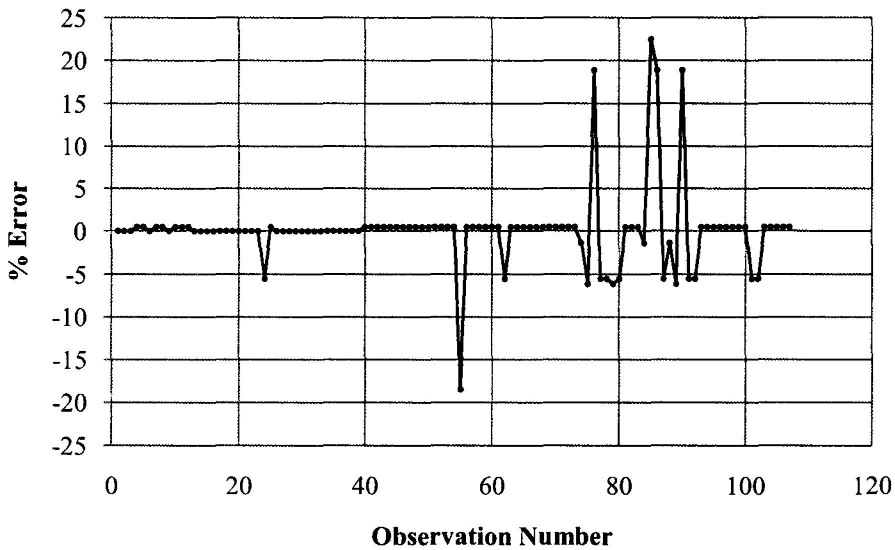

Figure B.30: Building Type R1 - Vancouver: % Error vs. Observation (Lighting Load)

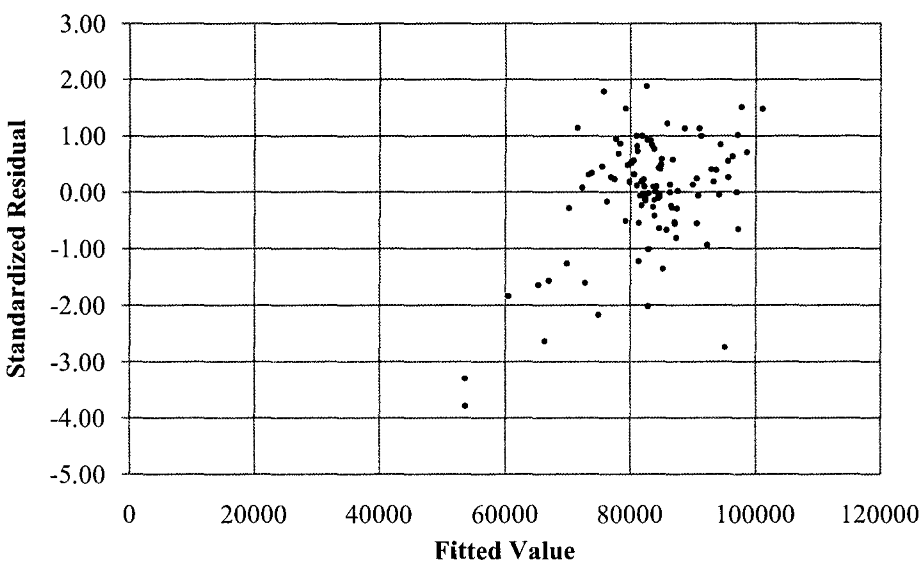

Figure B.31: Building Type R1 - Vancouver: Residuals vs. Fitted Values (Pump Load)

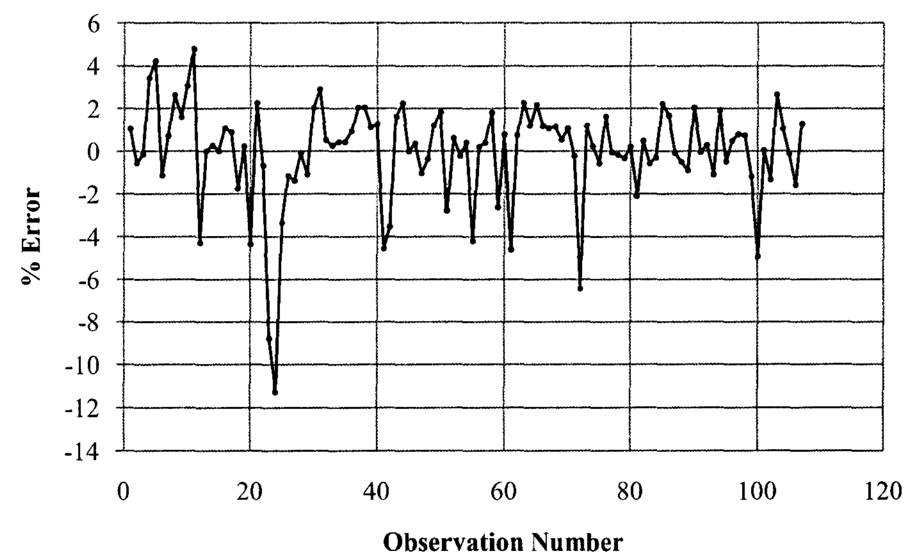

Figure B.32: Building Type R1 - Vancouver: % Error vs. Observation (Pump Load)

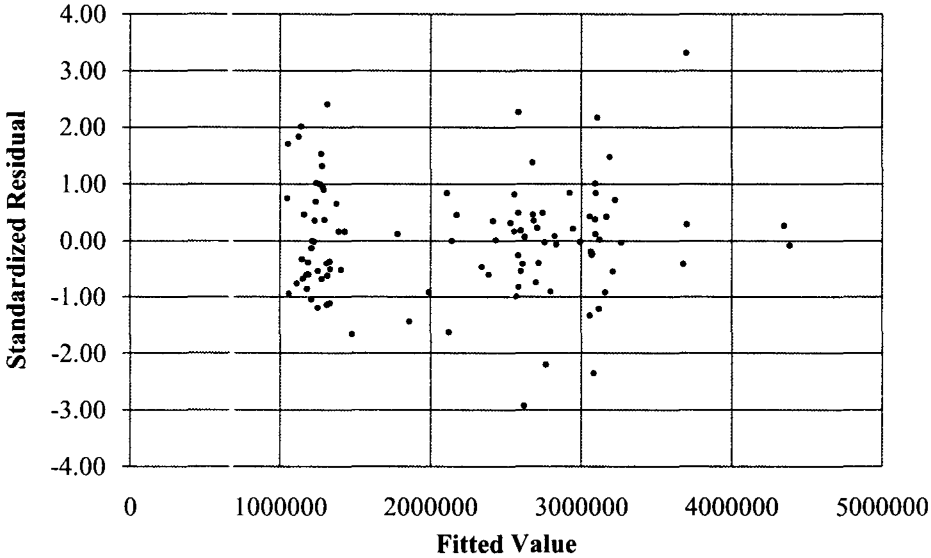

Figure B.33: Building Type R1 - Vancouver: Residuals vs. Fitted Values (Fan Load)

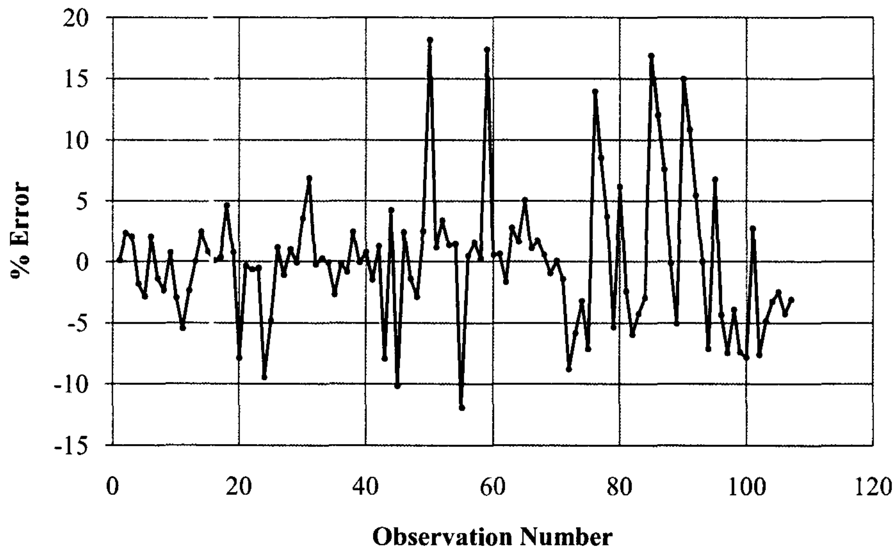

Figure B.34: Building Type R1 - Vancouver: % Error vs. Observation (Fan Load)

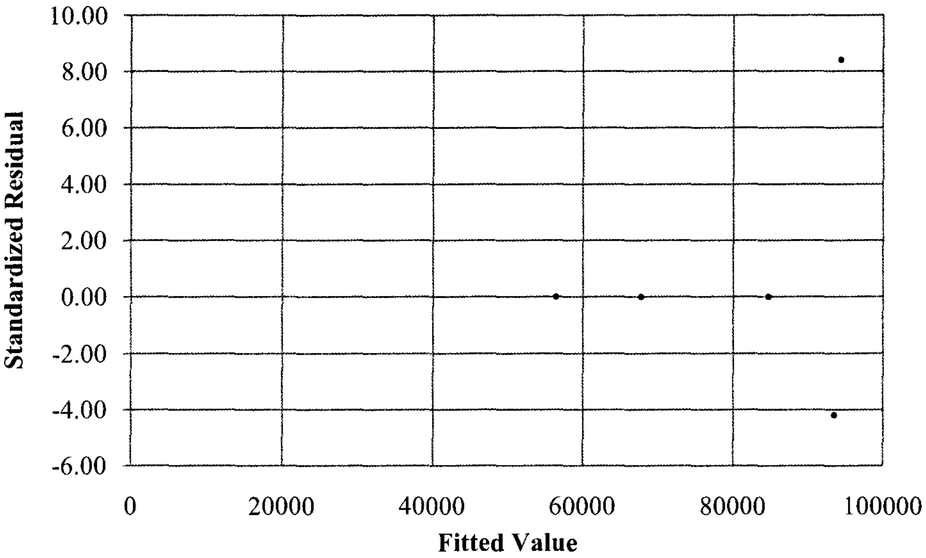

Figure B.35: Building Type R1 - Vancouver: Residuals vs. Fitted Values (DHW Loads)

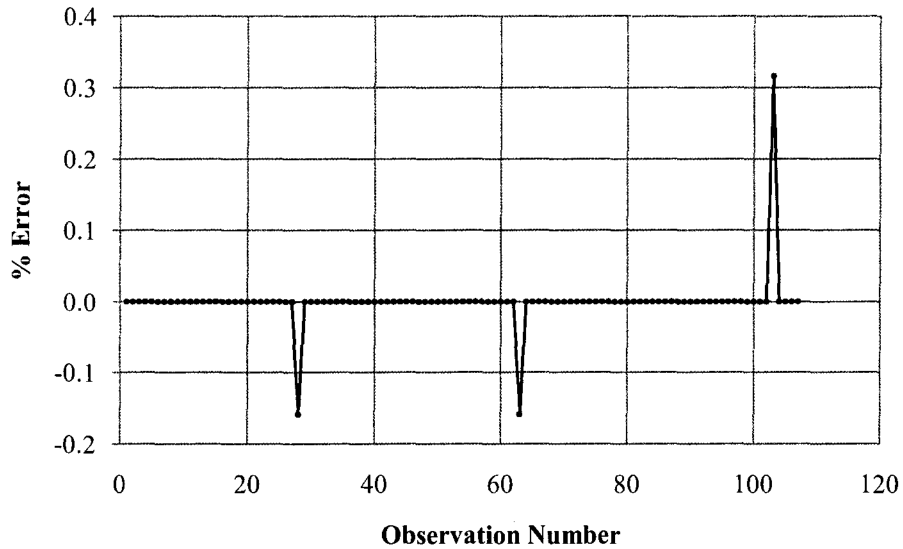

Figure B.36: Building Type R1 - Vancouver: % Error vs. Observation (DHW Load)

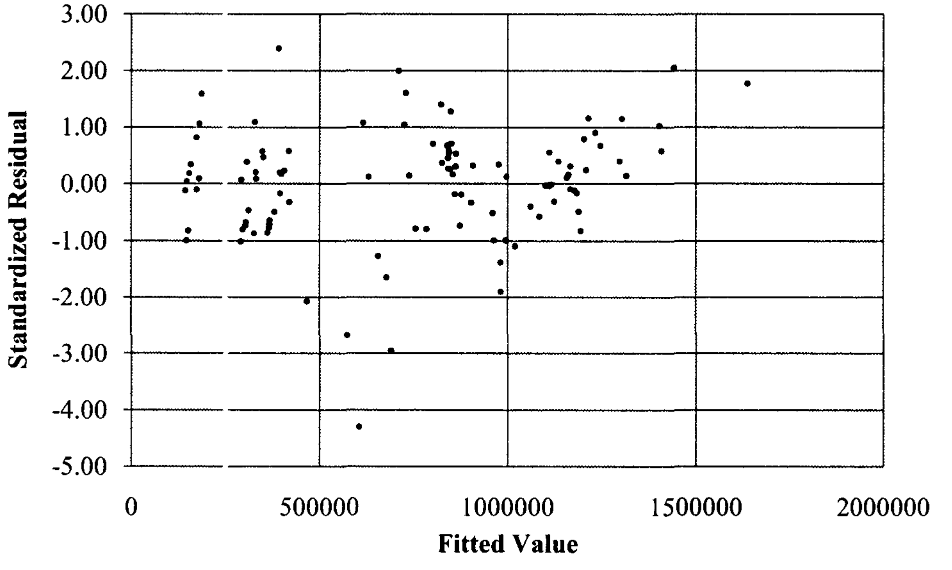

Figure B.37: Building Type R1 - Vancouver: Residuals vs. Fitted Values (Chiller Load)

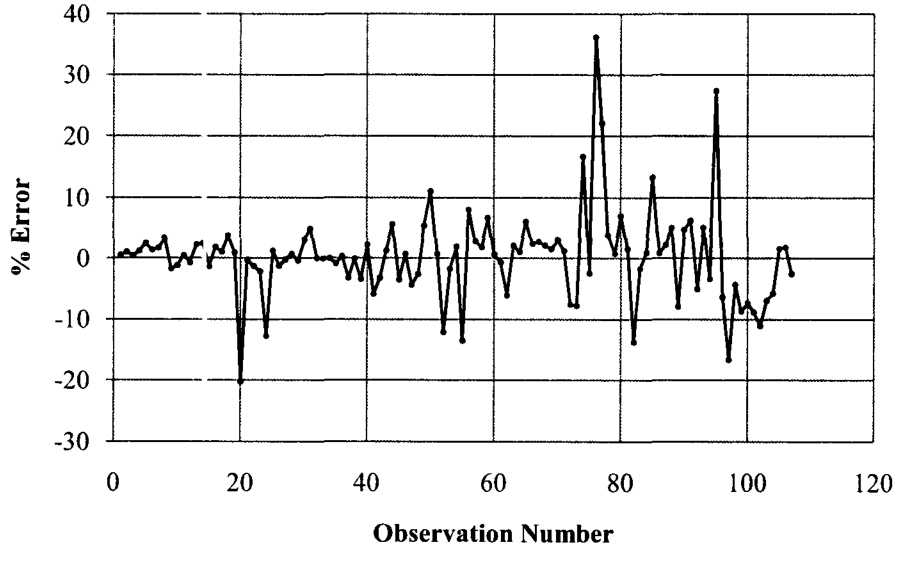

Figure B.38: Building Type R1 - Vancouver: % Error vs. Observation (Chiller Load)

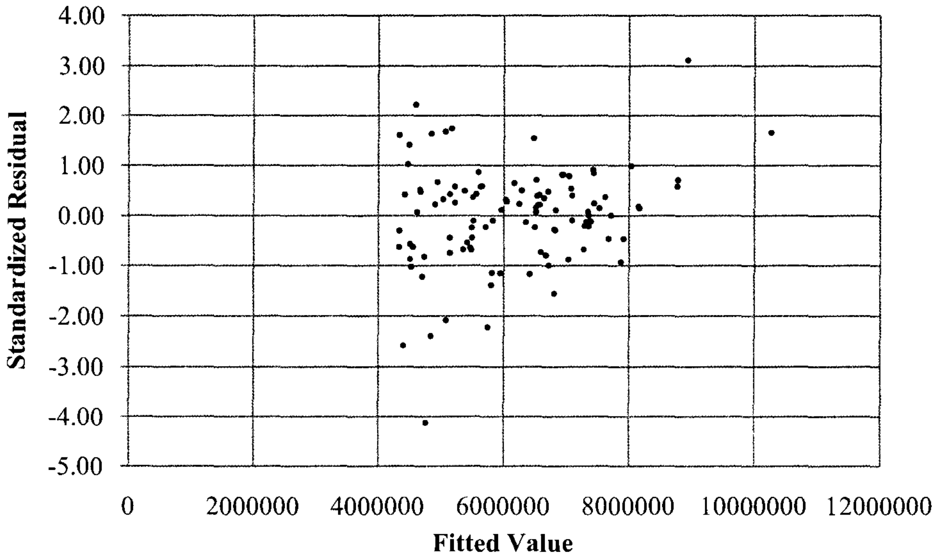

Figure B.39: Building Type R1 - Vancouver: Residuals vs. Fitted Values (Electrical Load)

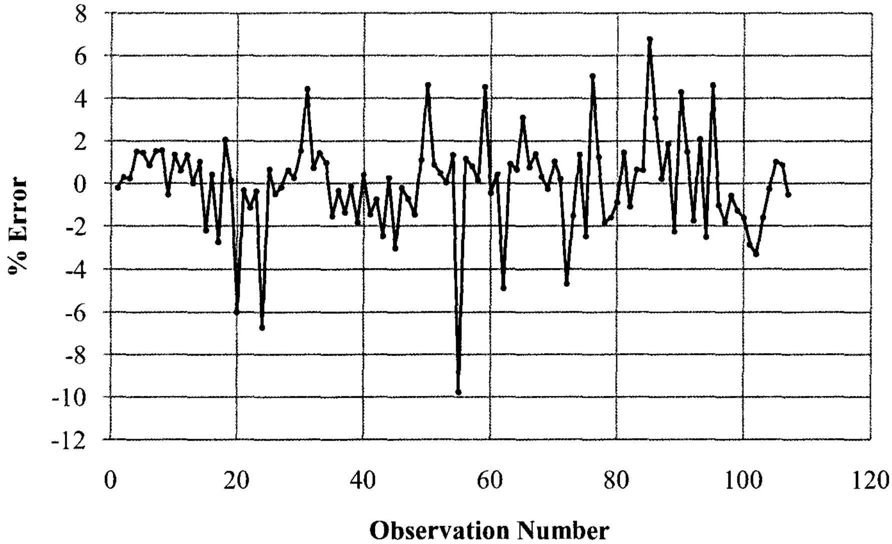

Figure B.40: Building Type R1 - Vancouver: % Error vs. Observation (Electrical Load)

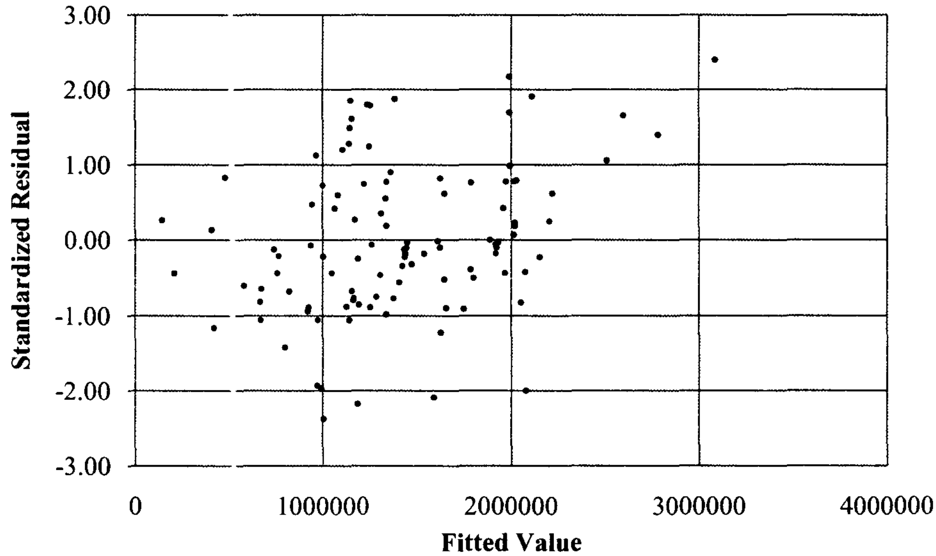

Figure B.41: Building Type R1 - Vancouver: Residuals vs. Fitted Values (Natural Gas Load)

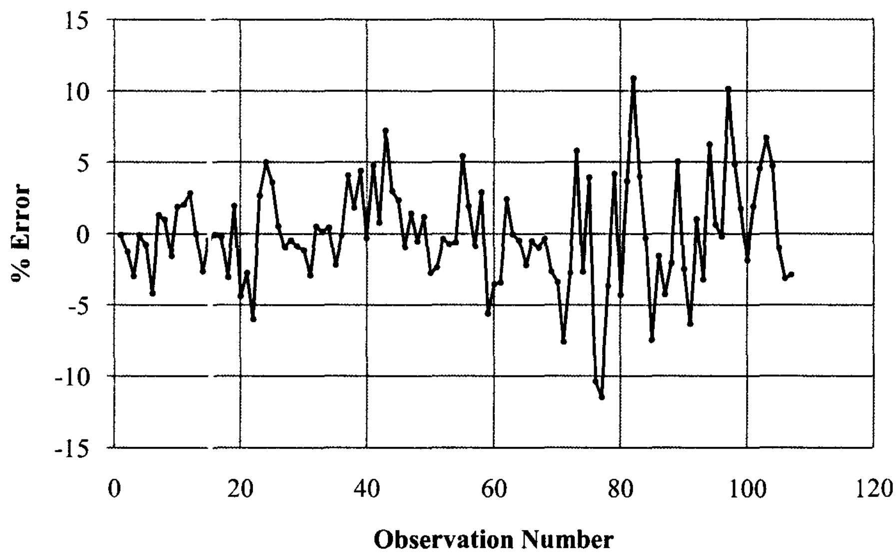

Figure B.42: Building Type R1 - Vancouver: % Error vs. Observation (Natural Gas Load)

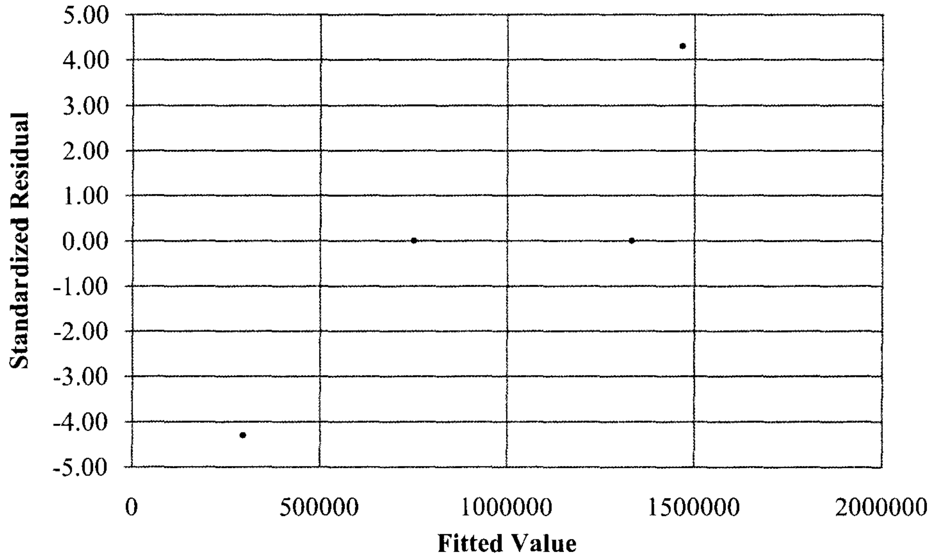

Figure B.43: Building Type R2 - Ottawa: Residuals vs. Fitted Values (Lighting Load)

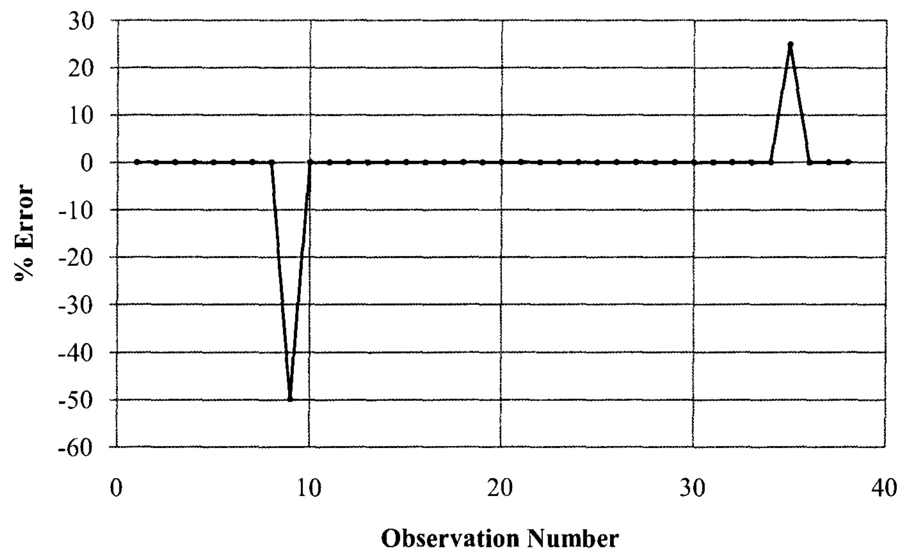

Figure B.44: Building Type R2 - Ottawa: % Error vs. Observation (Lighting Load)

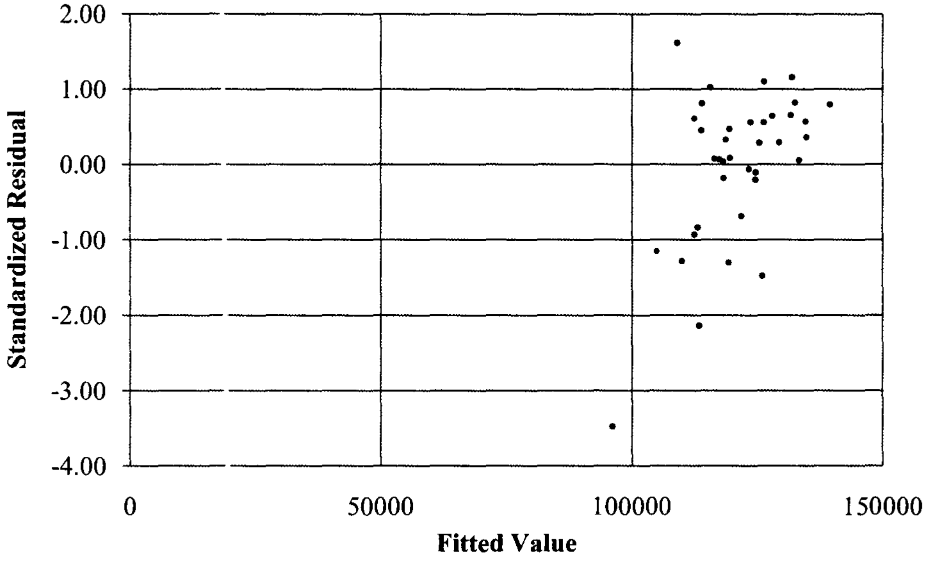

Figure B.45: Building Type R2 - Ottawa: Residuals vs. Fitted Values (Pump Load)

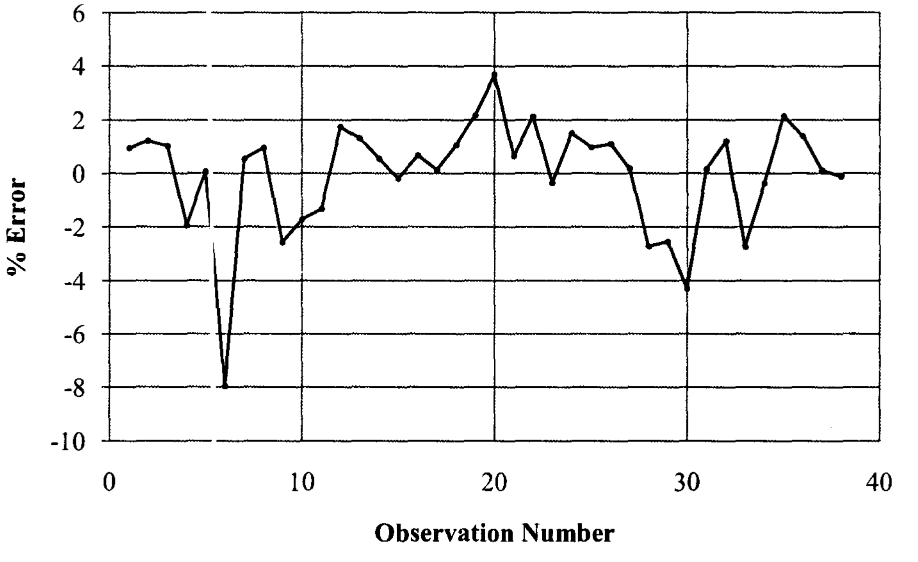

Figure B.46: Building Type R2 - Ottawa: % Error vs. Observation (Pump Load)

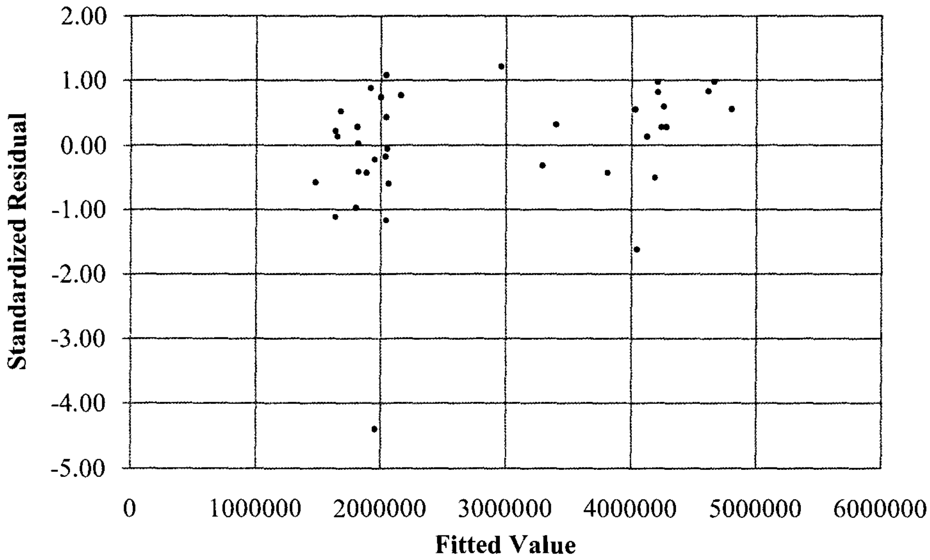

Figure B.47: Building Type R2 - Ottawa: Residuals vs. Fitted Values (Fan Load)

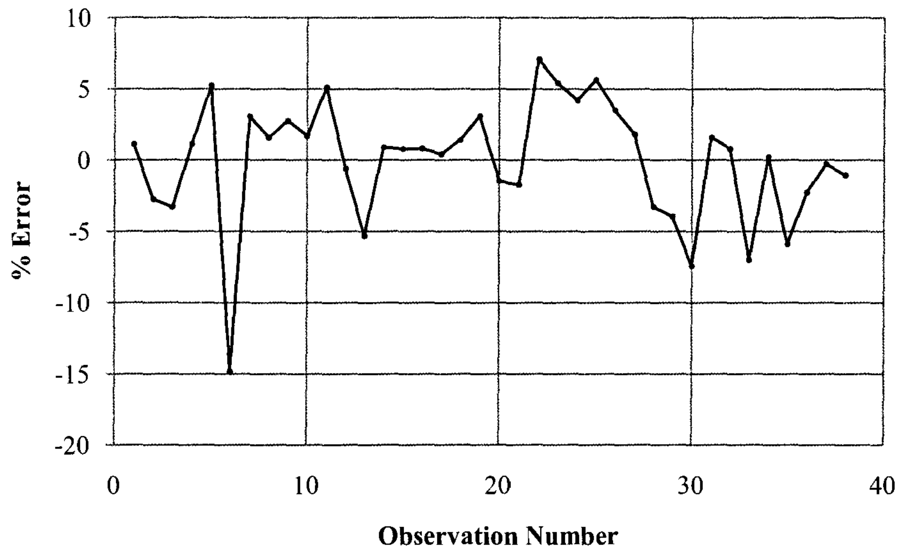

Figure B.48: Building Type R2 - Ottawa: % Error vs. Observation (Fan Load)

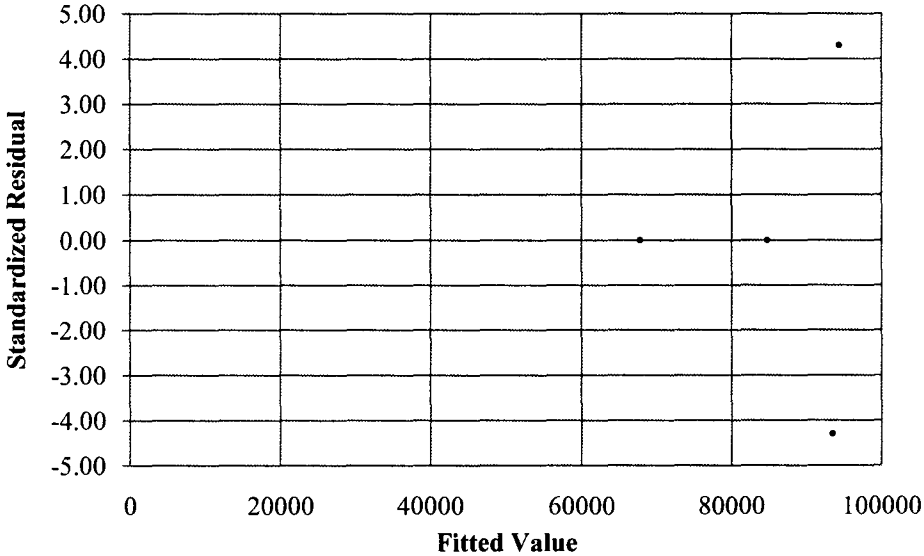

Figure B.49: Building Type R2 - Ottawa: Residuals vs. Fitted Values (DHW Loads)

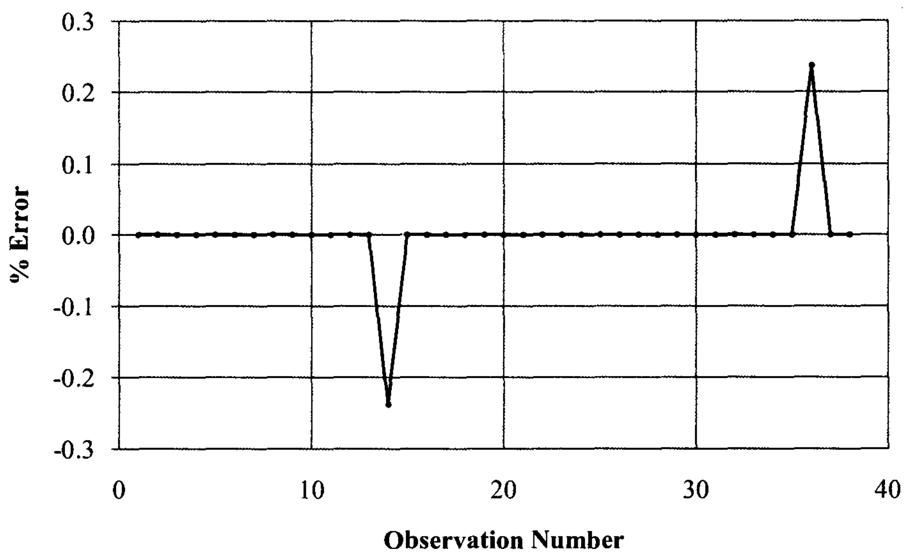

Figure B.50: Building Type R2 - Ottawa: % Error vs. Observation (DHW Load)

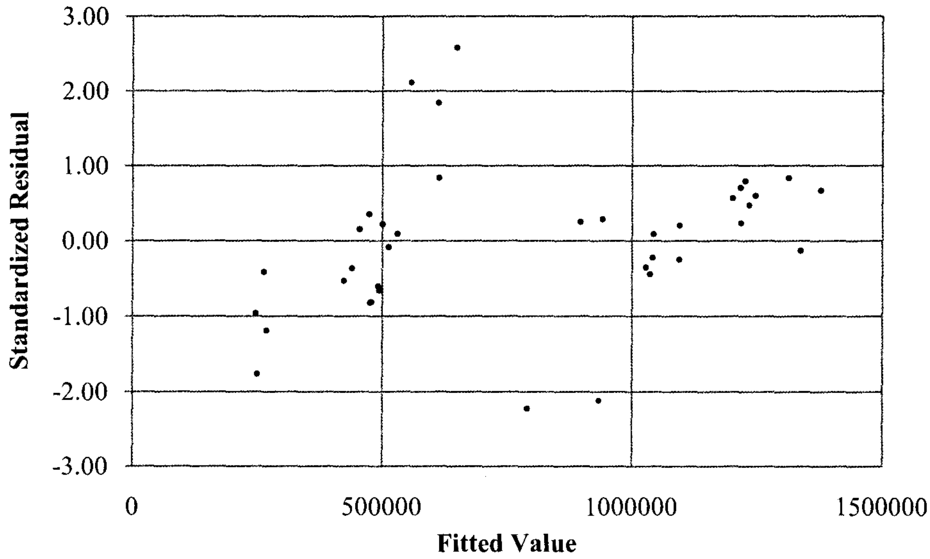

Figure B.51: Building Type R2 - Ottawa: Residuals vs. Fitted Values (Chiller Load)

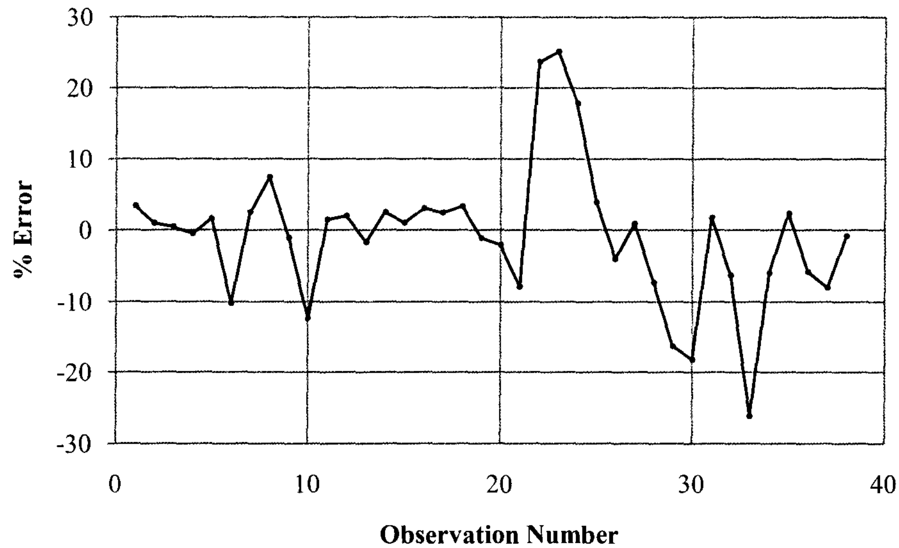

Figure B.52: Building Type R2 - Ottawa: % Error vs. Observation (Chiller Load)

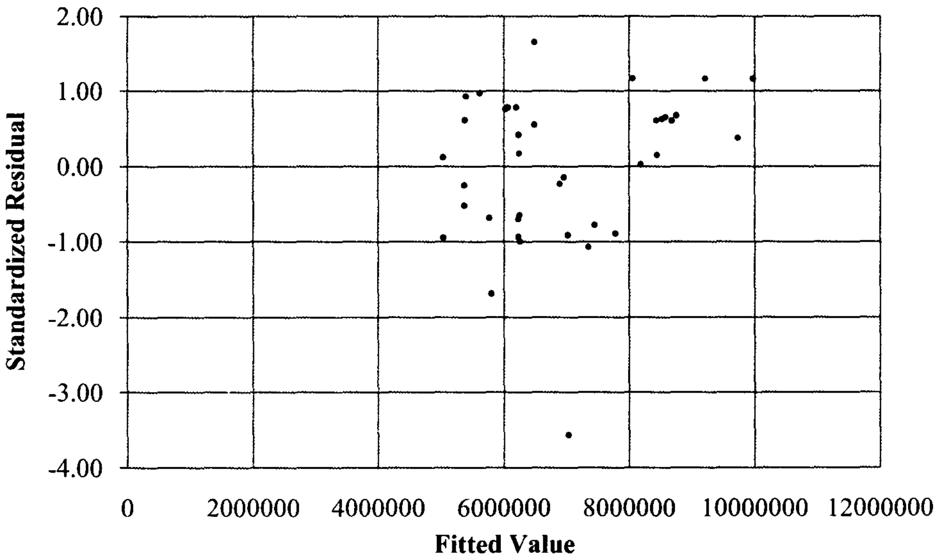

Figure B.53: Building Type R2 - Ottawa: Residuals vs. Fitted Values (Electrical Load)

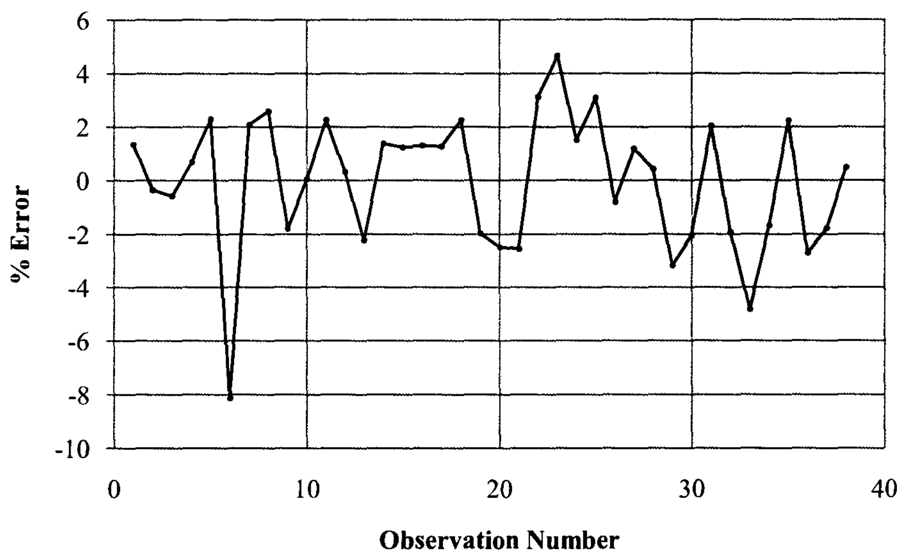

Figure B.54: Building Type R2 - Ottawa: % Error vs. Observation (Electrical Load)

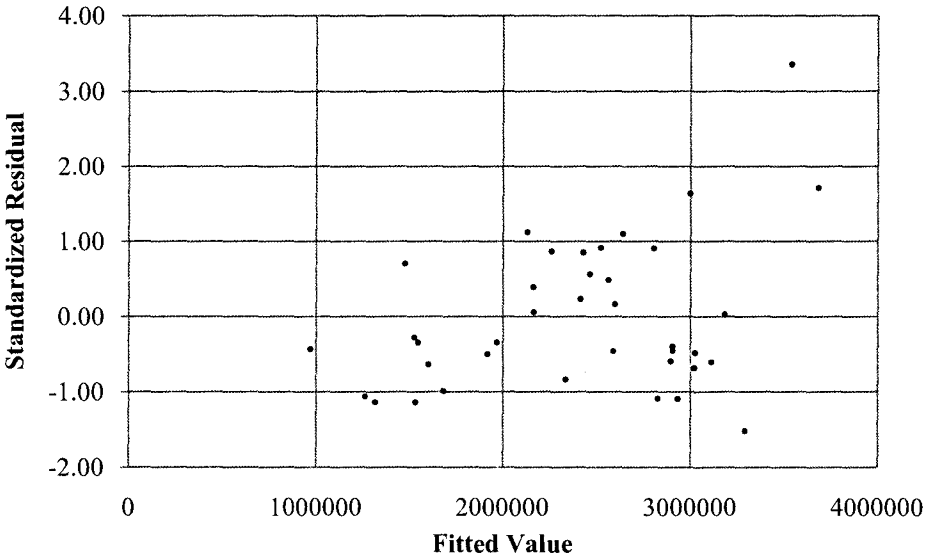

Figure B.55: Building Type R2 - Ottawa: Residuals vs. Fitted Values (Natural Gas Load)

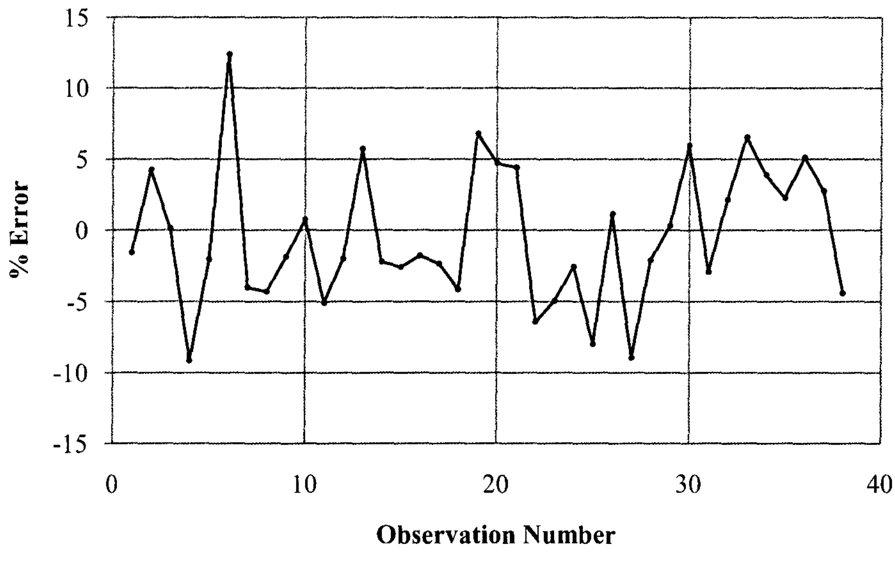

Figure B.56: Building Type R2 - Ottawa: % Error vs. Observation (Natural Gas Load)

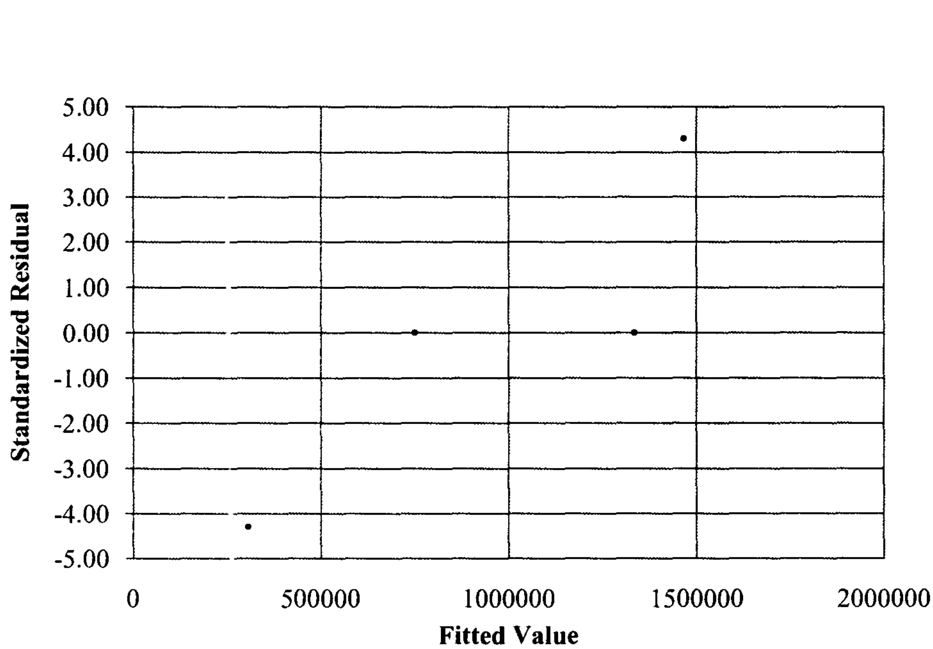

Figure B.57: Building Type R2 - Edmonton: Residuals vs. Fitted Values (Lighting Load)

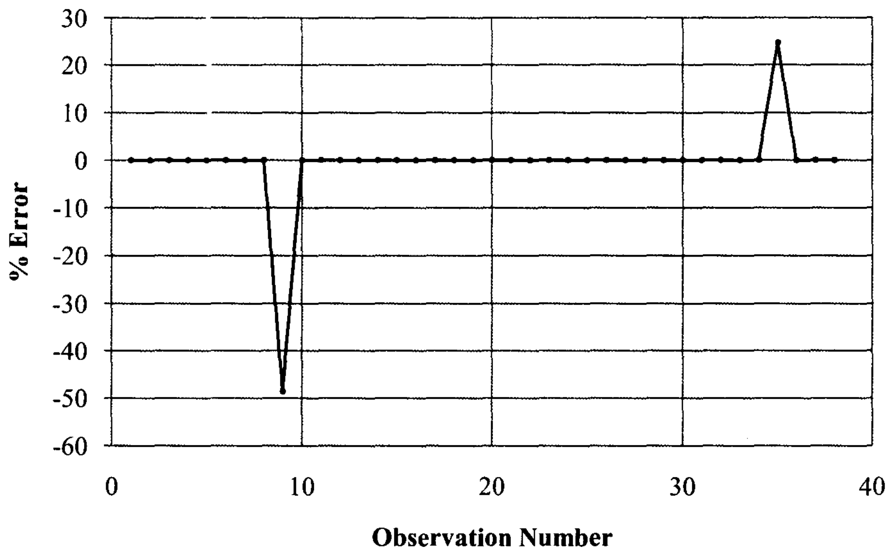

Figure B.58: Building Type R2 - Edmonton: % Error vs. Observation (Lighting Load)

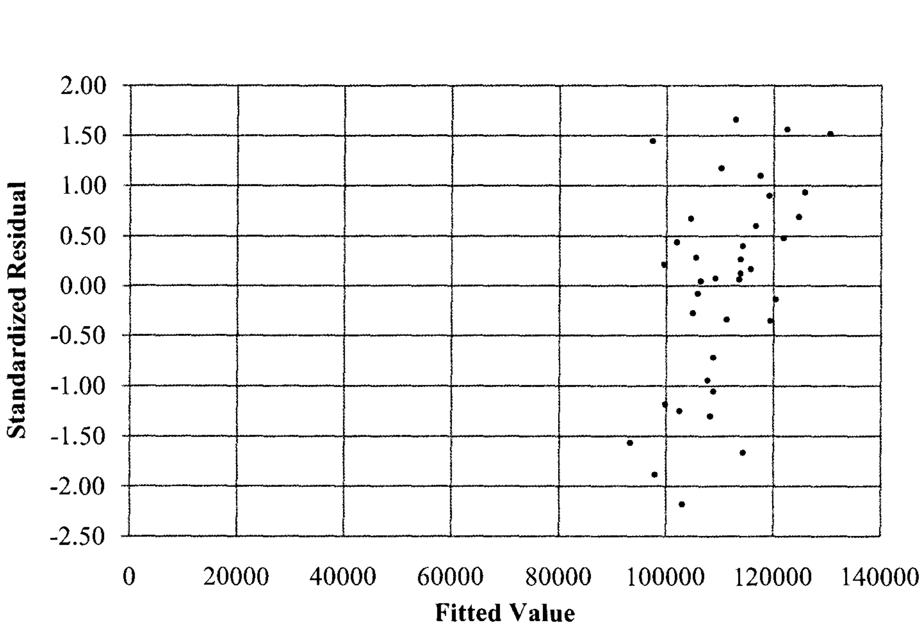

Figure B.59: Building Type R2 - Edmonton: Residuals vs. Fitted Values (Pump Load)

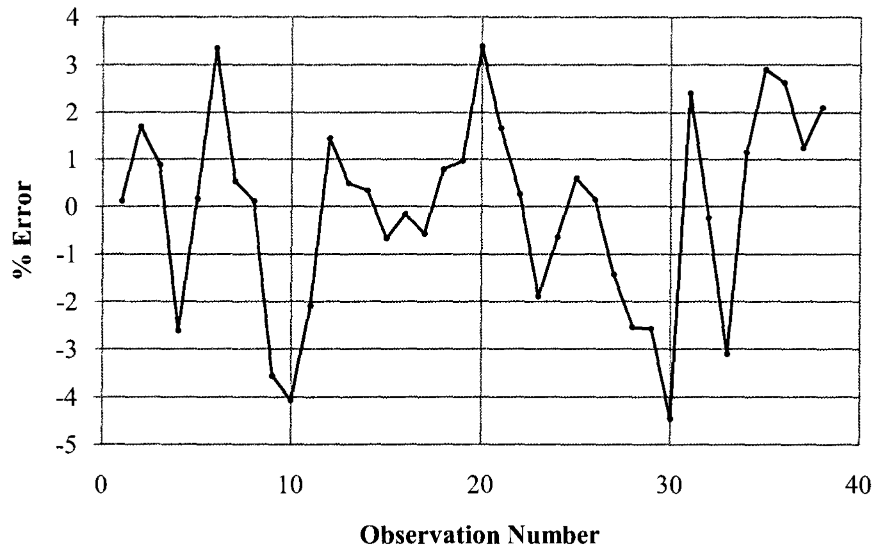

Figure B.60: Building Type R2 - Edmonton: % Error vs. Observation (Pump Load)

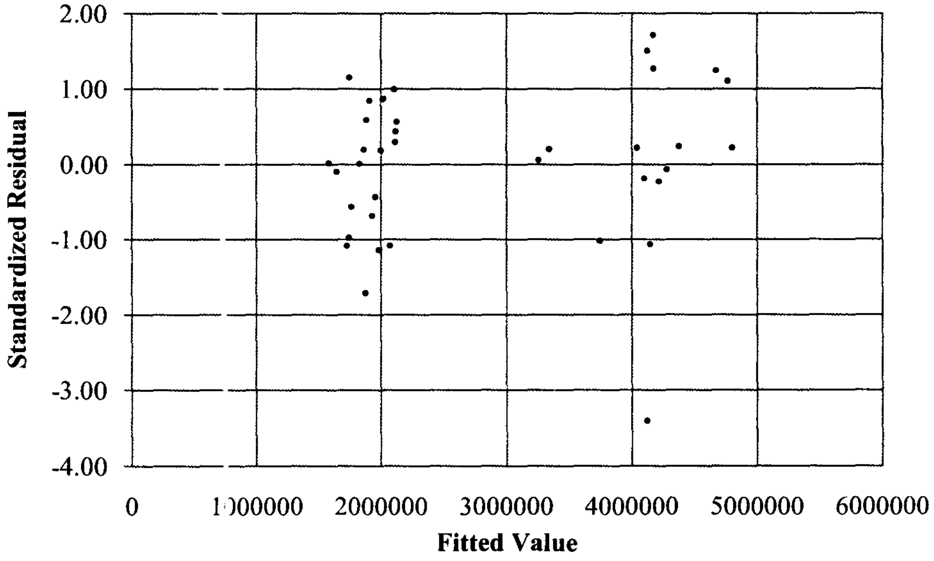

Figure B.61: Building Type R2 - Edmonton: Residuals vs. Fitted Values (Fan Load)

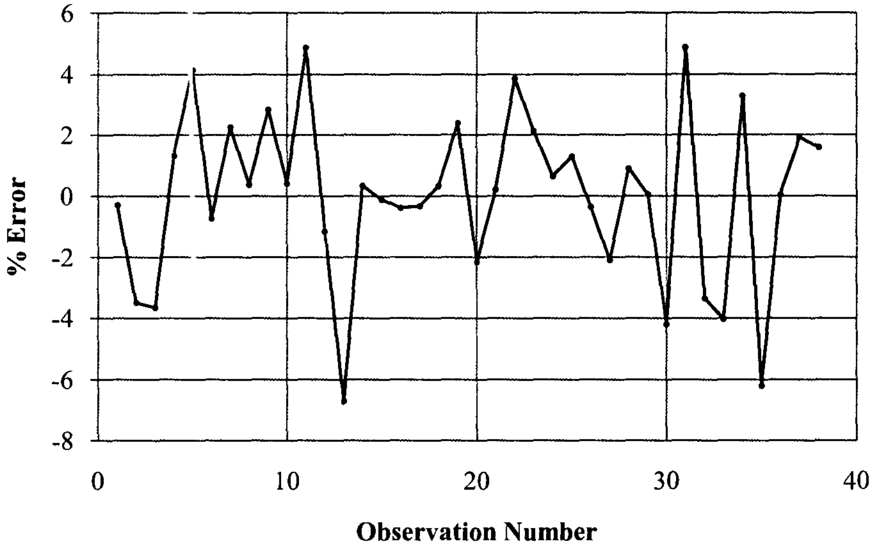

Figure B.62: Building Type R2 - Edmonton: % Error vs. Observation (Fan Load)

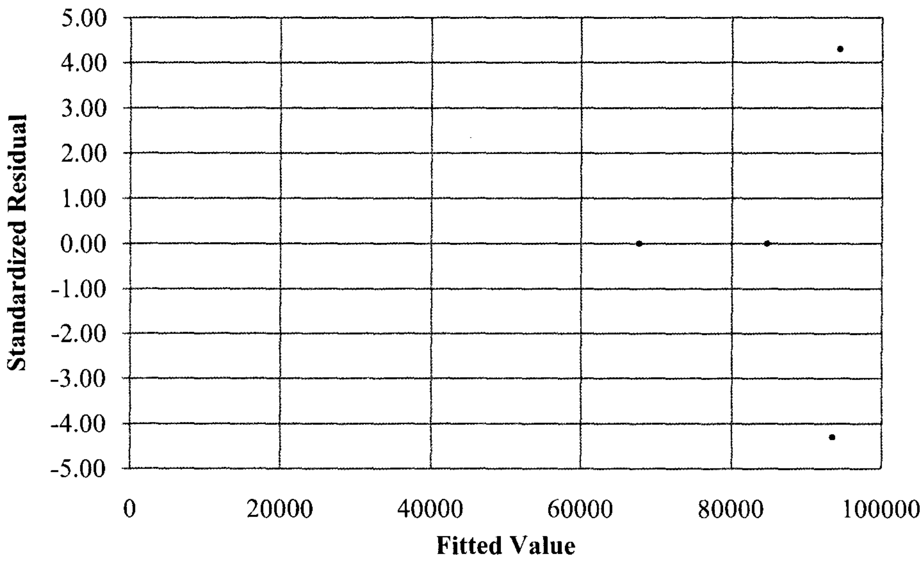

Figure B.63: Building Type R2 - Edmonton: Residuals vs. Fitted Values (DHW Loads)

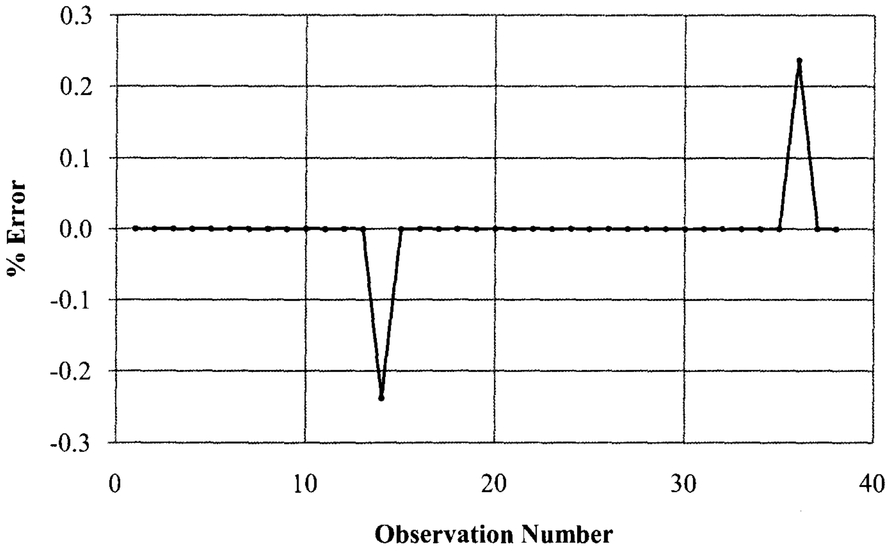

Figure B.64: Building Type R2 - Edmonton: % Error vs. Observation (DHW Load)

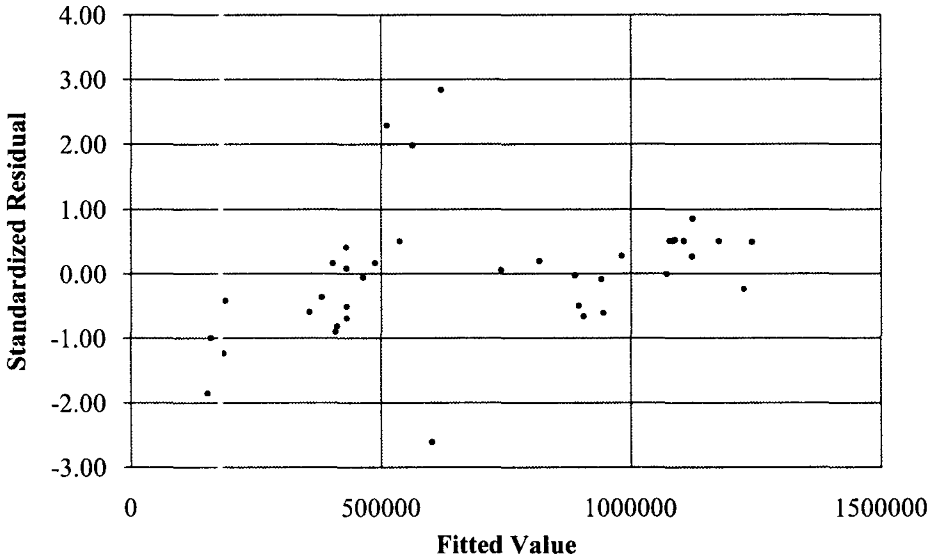

Figure B.65: Building Type R2 - Edmonton: Residuals vs. Fitted Values (Chiller Load)

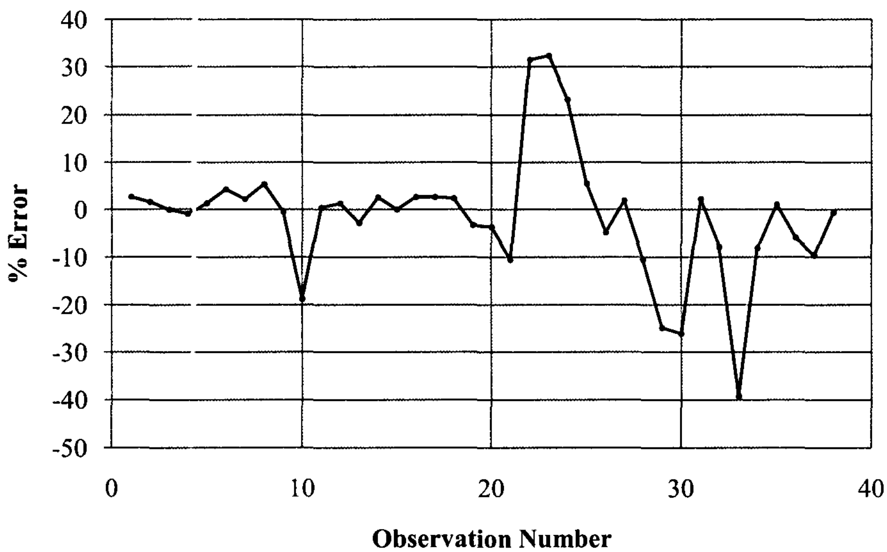

Figure B.66: Building Type R2 - Edmonton: % Error vs. Observation (Chiller Load)

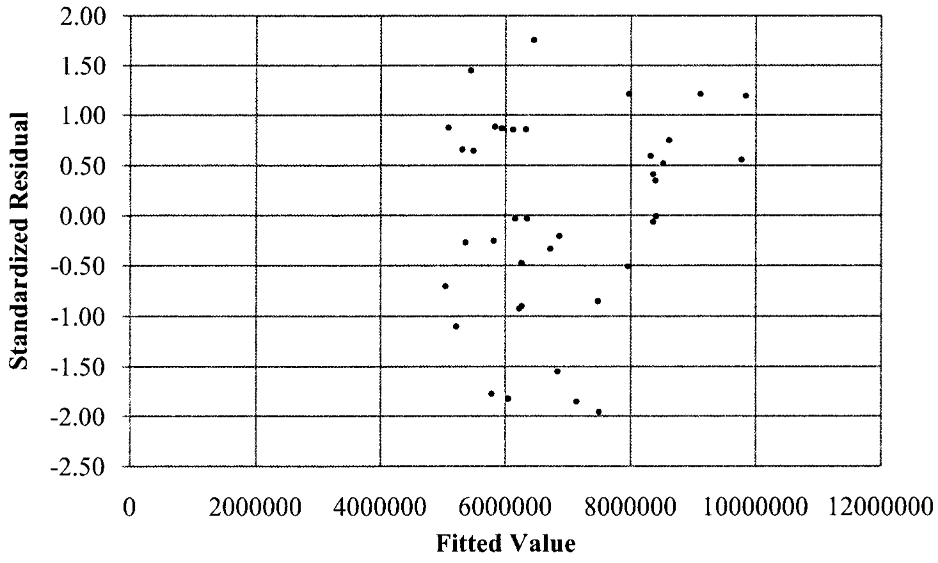

Figure B.67: Building Type R2 - Edmonton: Residuals vs. Fitted Values (Electrical Load)

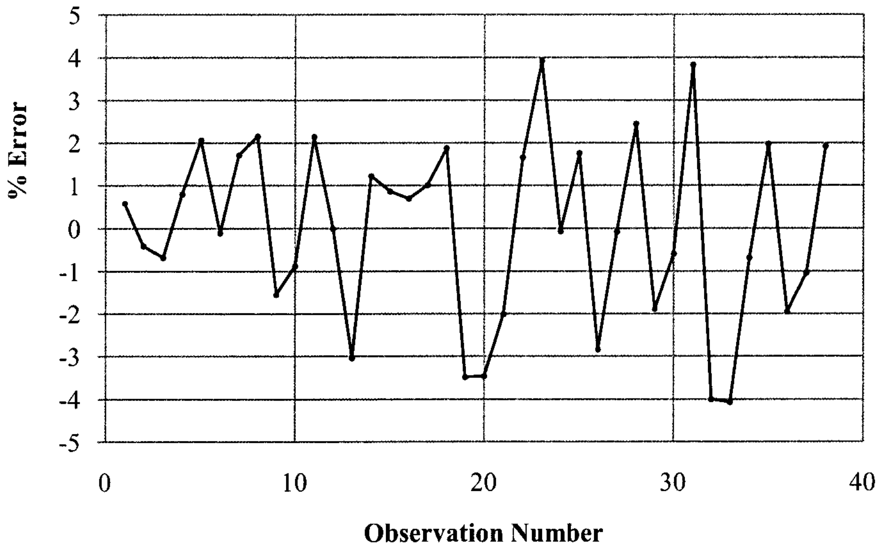

Figure B.68: Building Type R2 - Edmonton: % Error vs. Observation (Electrical Load)

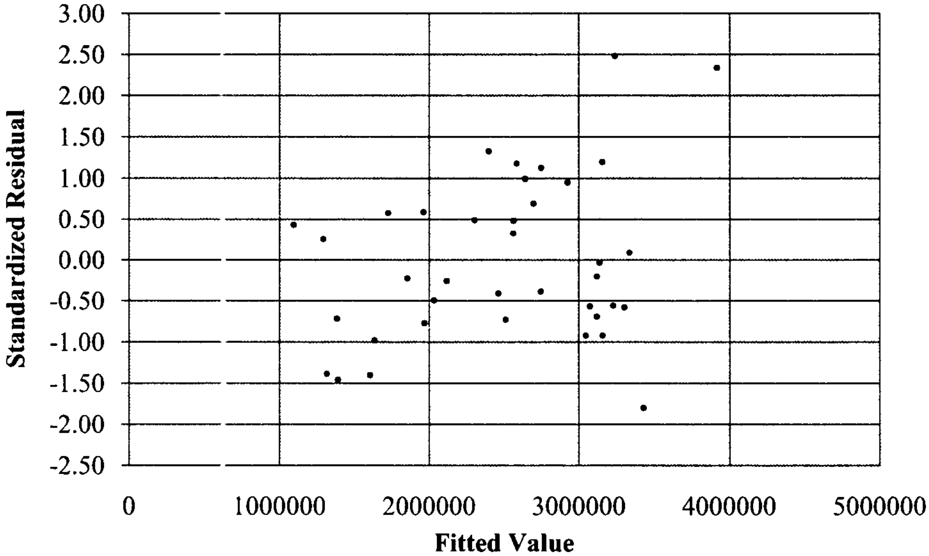

Figure B.69: Building Type R2 - Edmonton: Residuals vs. Fitted Values (Natural Gas Load)

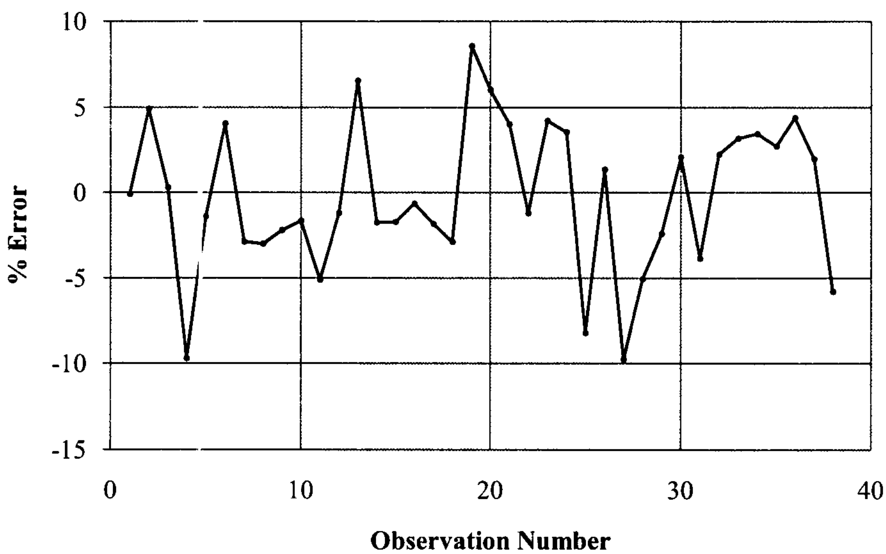

Figure B.70: Building Type R2 - Edmonton: % Error vs. Observation (Natural Gas Load)

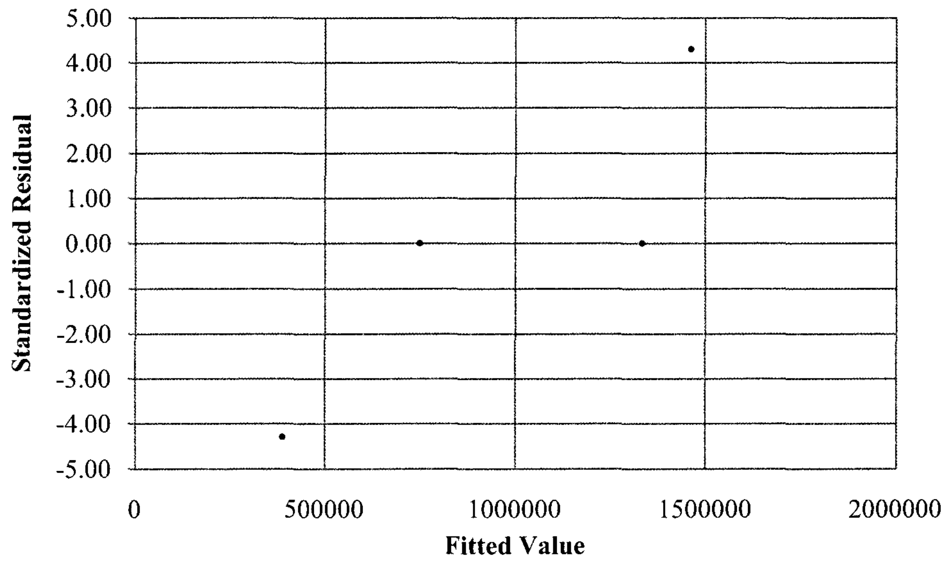

Figure B.71: Building Type R2 - Vancouver: Residuals vs. Fitted Values (Lighting Load)

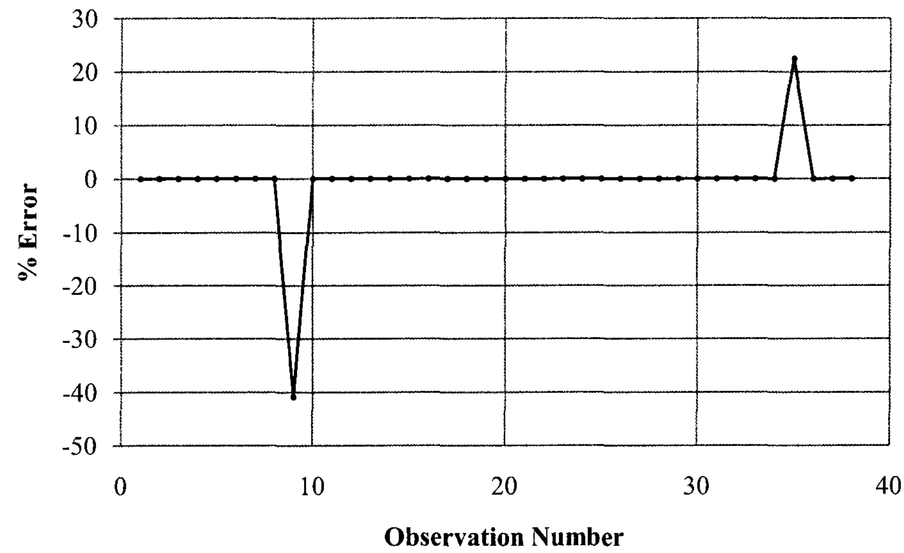

Figure B.72: Building Type R2 - Vancouver: % Error vs. Observation (Lighting Load)

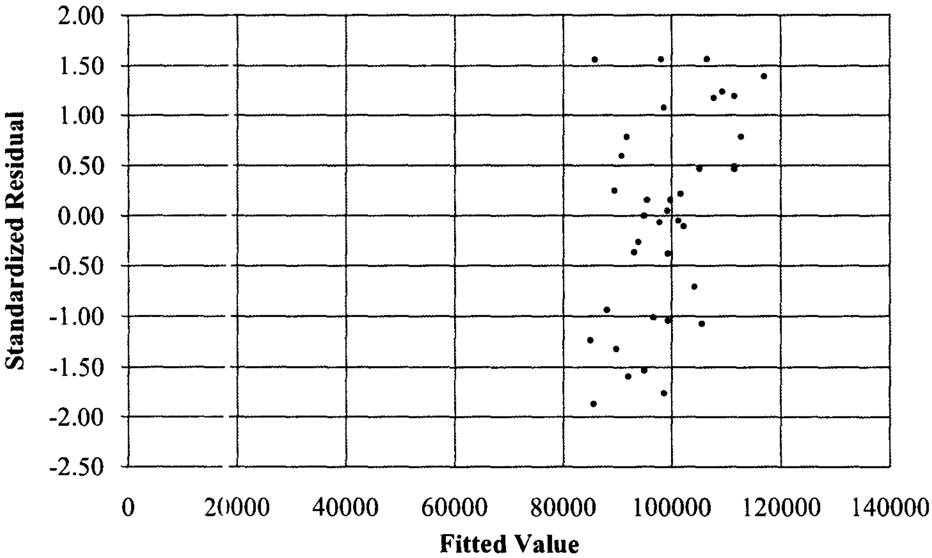

Figure B.73: Building Type R2 - Vancouver: Residuals vs. Fitted Values (Pump Load)

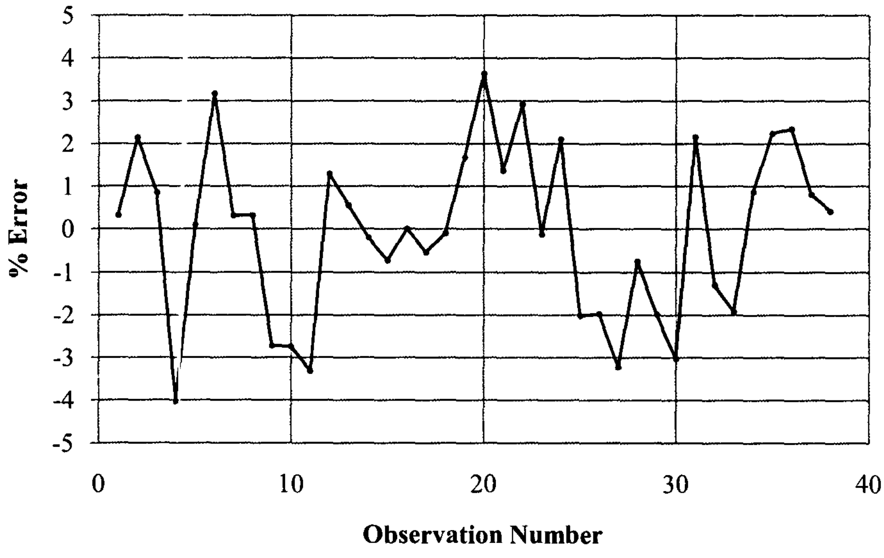

Figure B.74: Building Type R2 - Vancouver: % Error vs. Observation (Pump Load)

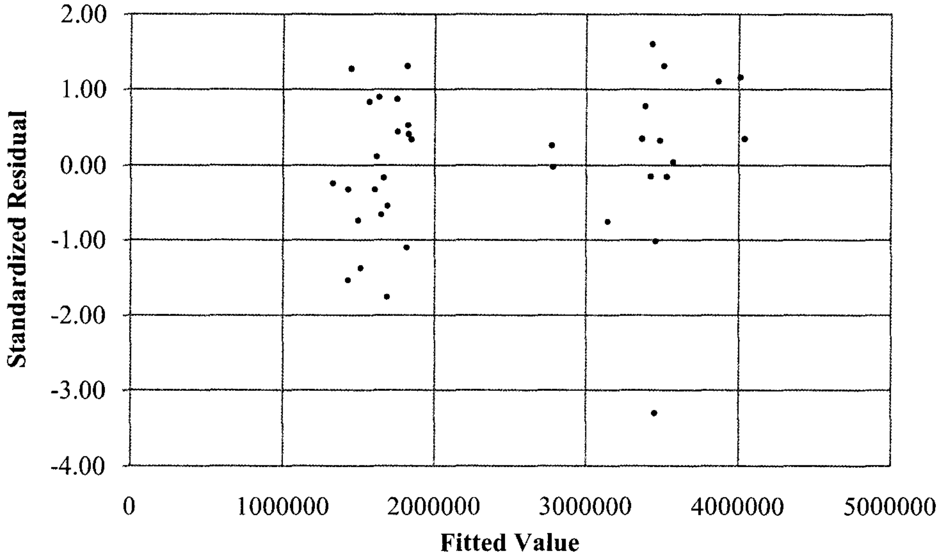

Figure B.75: Building Type R2 - Vancouver: Residuals vs. Fitted Values (Fan Load)

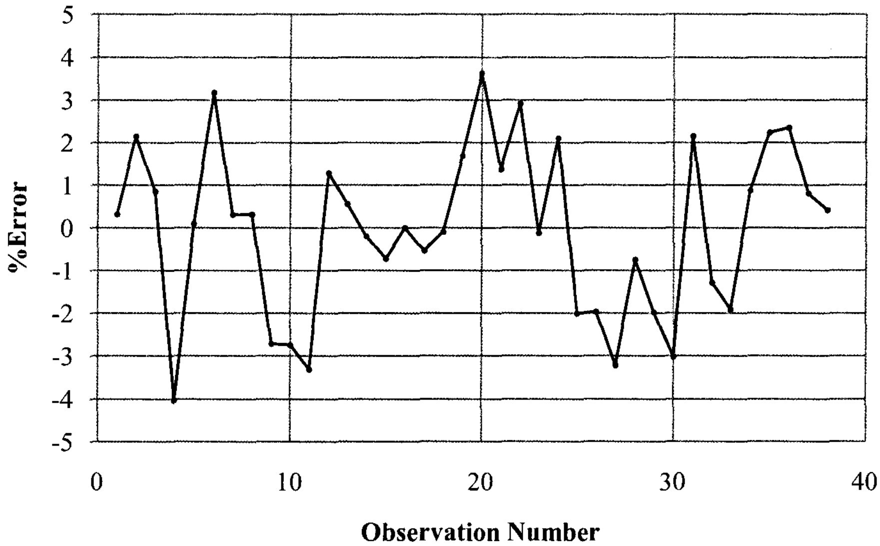

Figure B.76: Building Type R2 - Vancouver: % Error vs. Observation (Fan Load)

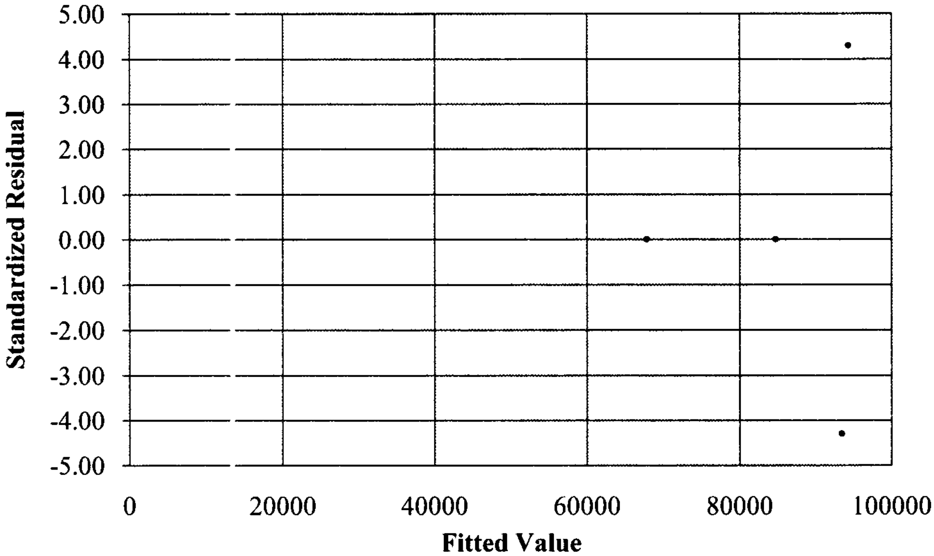

Figure B.77: Building Type R2 - Vancouver: Residuals vs. Fitted Values (DHW Loads)

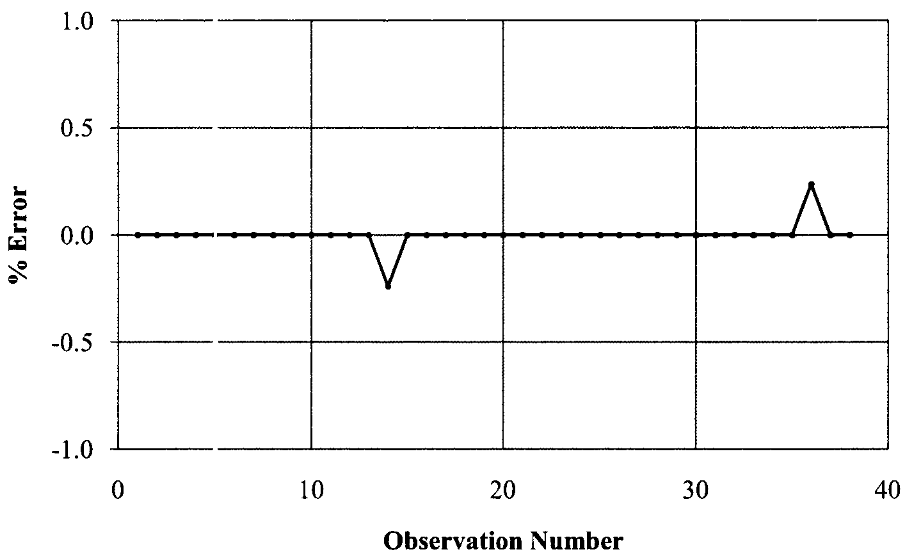

Figure B.78: Building Type R2 - Vancouver: % Error vs. Observation (DHW Load)

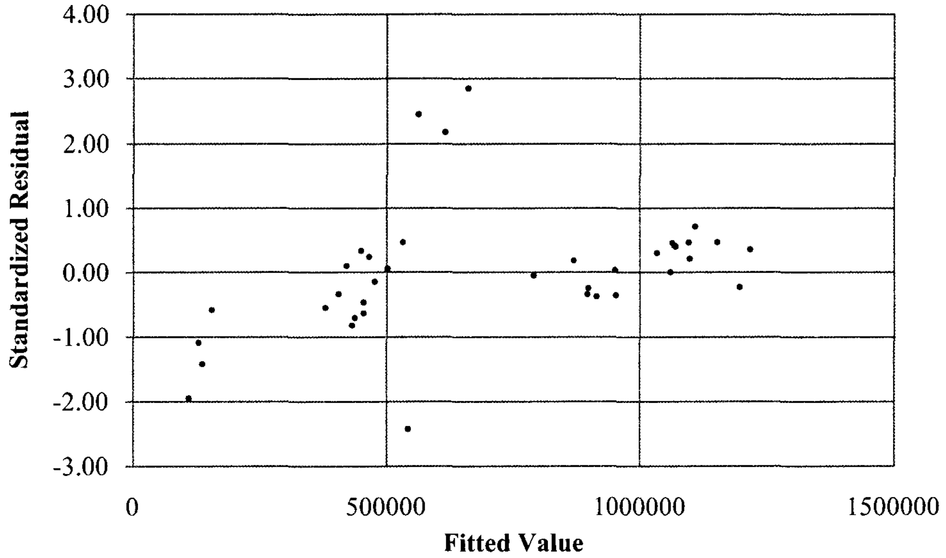

Figure B.79: Building Type R2 - Vancouver: Residuals vs. Fitted Values (Chiller Load)

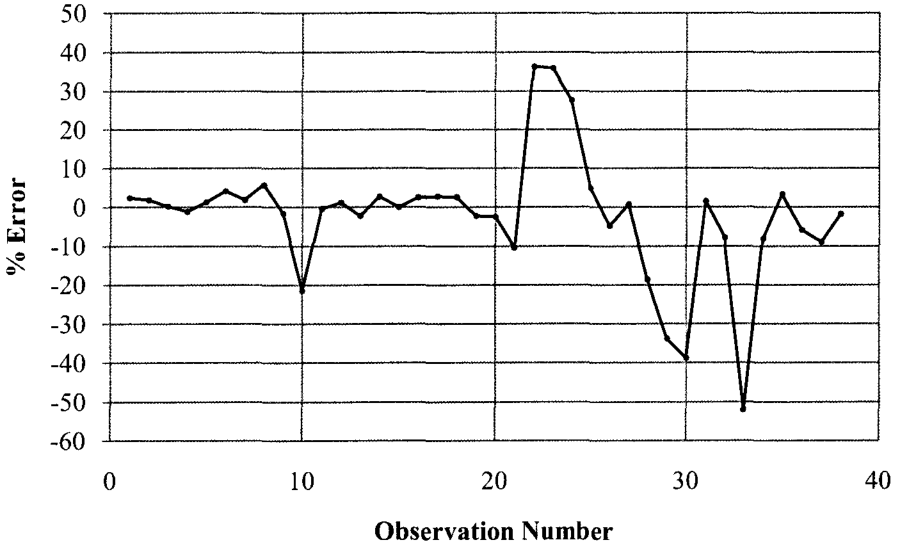

Figure B.80: Building Type R2 - Vancouver: % Error vs. Observation (Chiller Load)

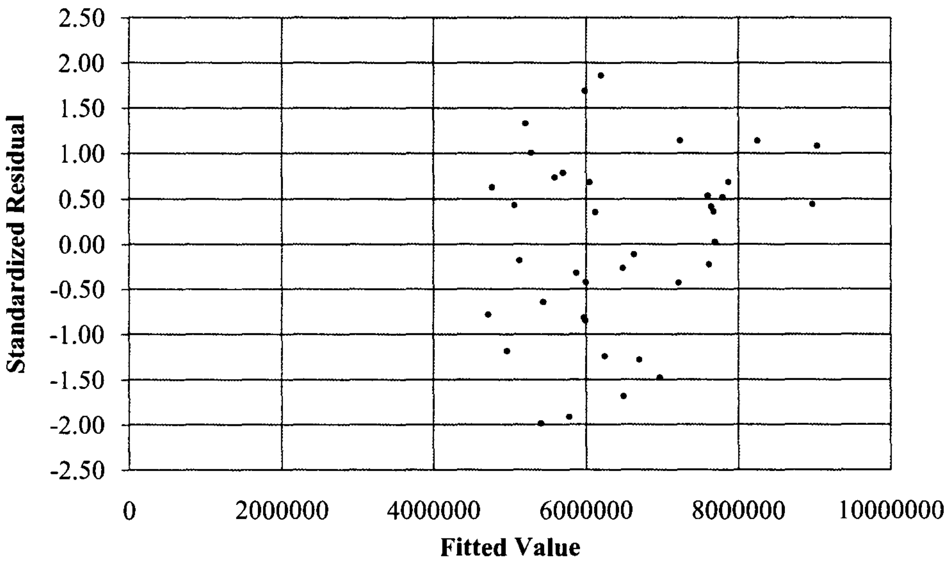

Figure B.81: Building Type R2 - Vancouver: Residuals vs. Fitted Values (Electrical Load)

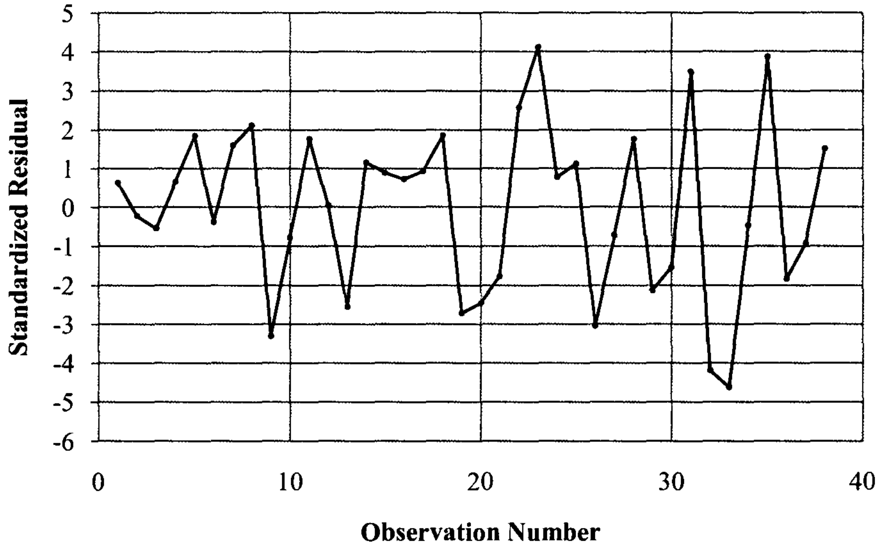

Figure B.82: Building Type R2 - Vancouver: % Error vs. Observation (Electrical Load)

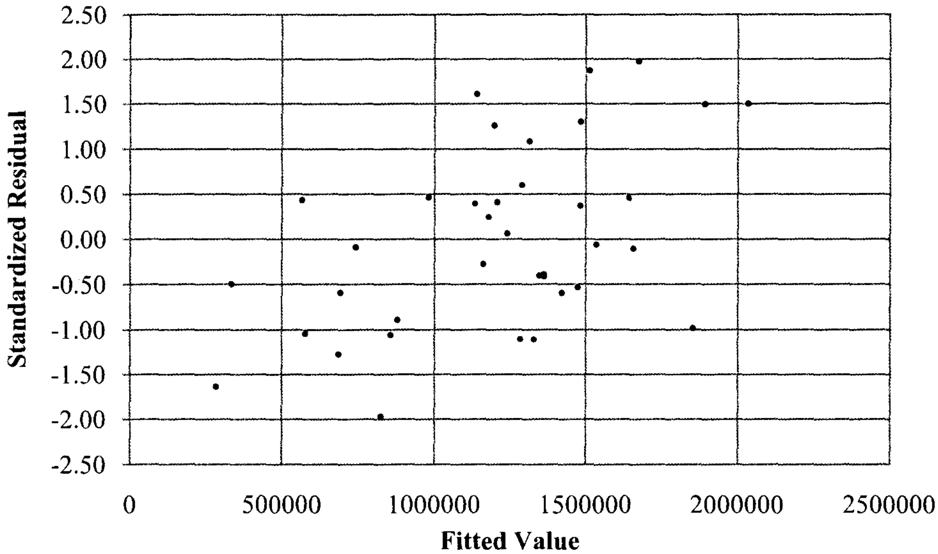

Figure B.83: Building Type R2 - Vancouver: Residuals vs. Fitted Values (Natural Gas Load)

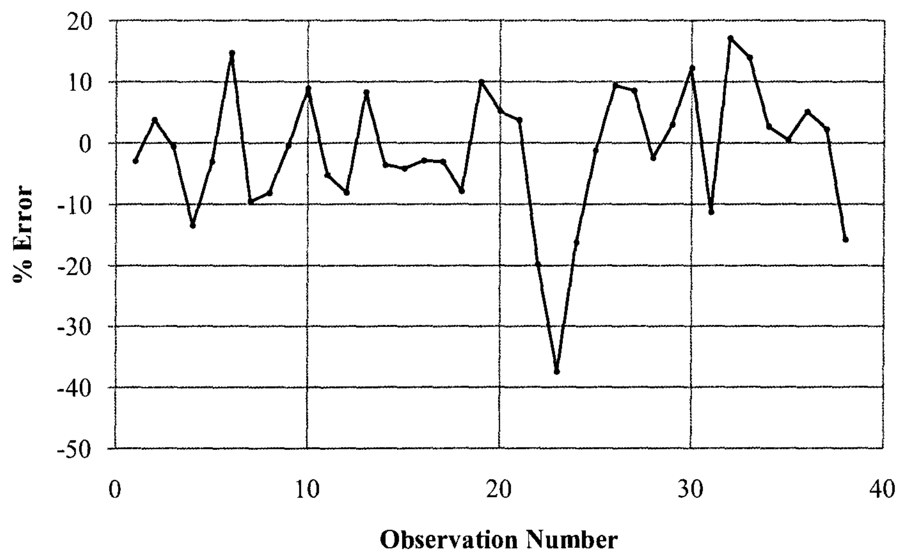

Figure B.84: Building Type R2 - Vancouver: % Error vs. Observation (Natural Gas Load)

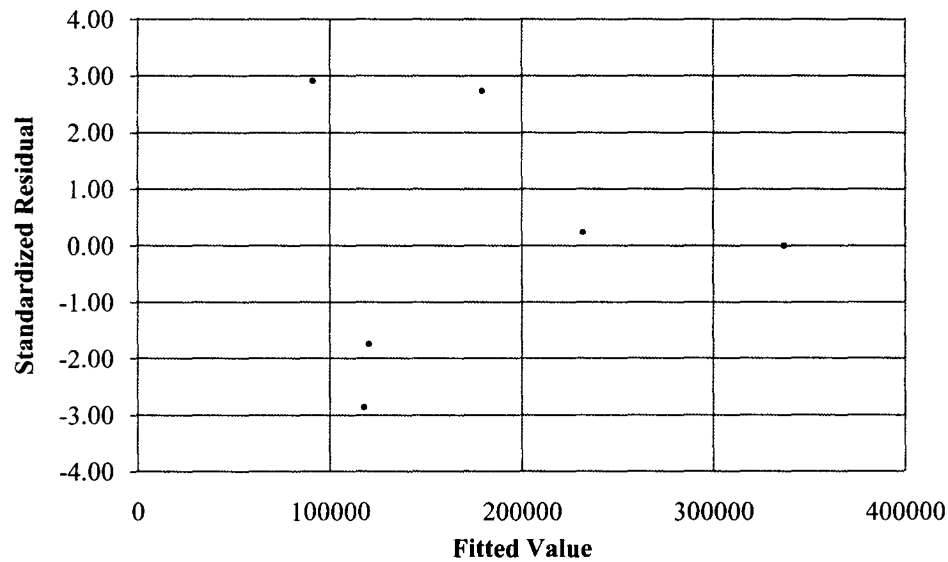

Figure B.85: Building Type R3 - Ottawa: Residuals vs. Fitted Values (Lighting Load)

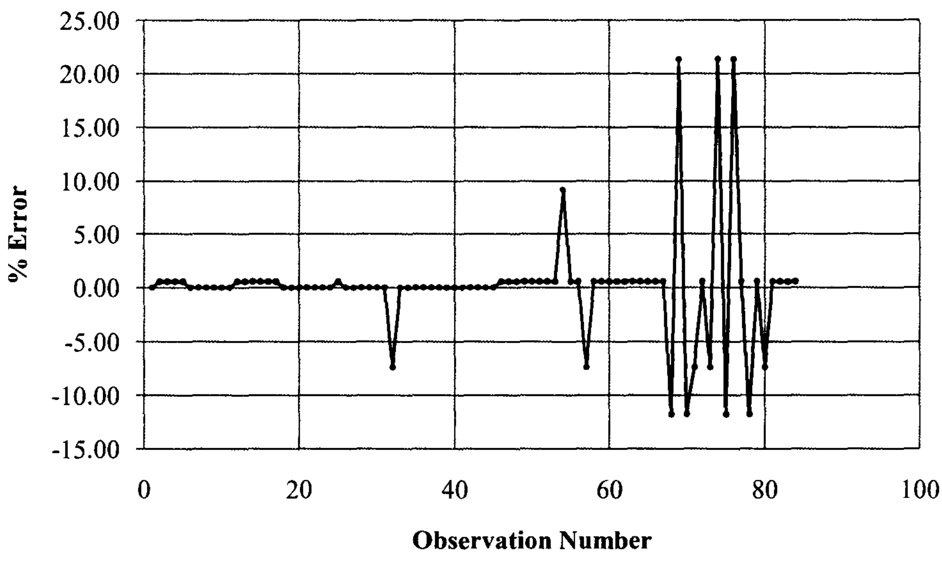

Figure B.86: Building Type R3 - Ottawa: % Error vs. Observation (Lighting Load)

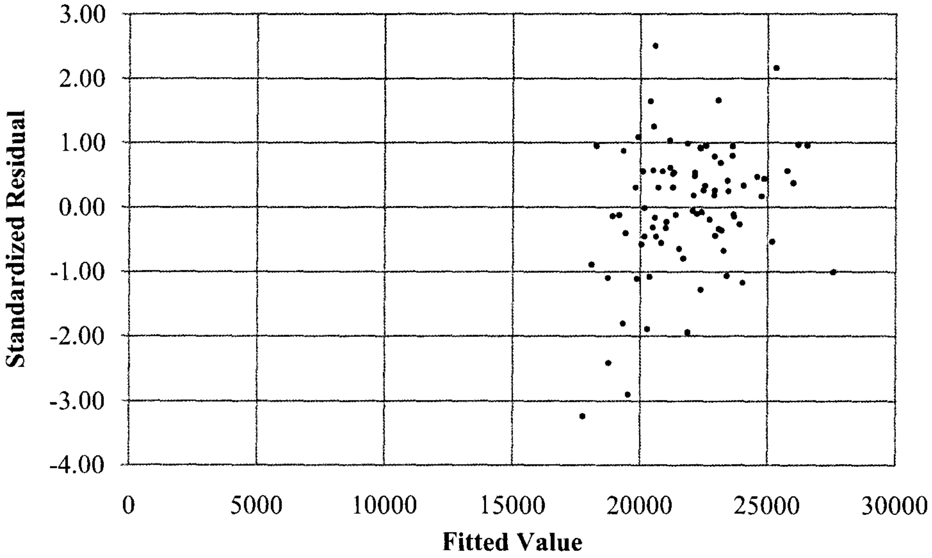

Figure B.87: Building Type R3 - Ottawa: Residuals vs. Fitted Values (Pump Load)

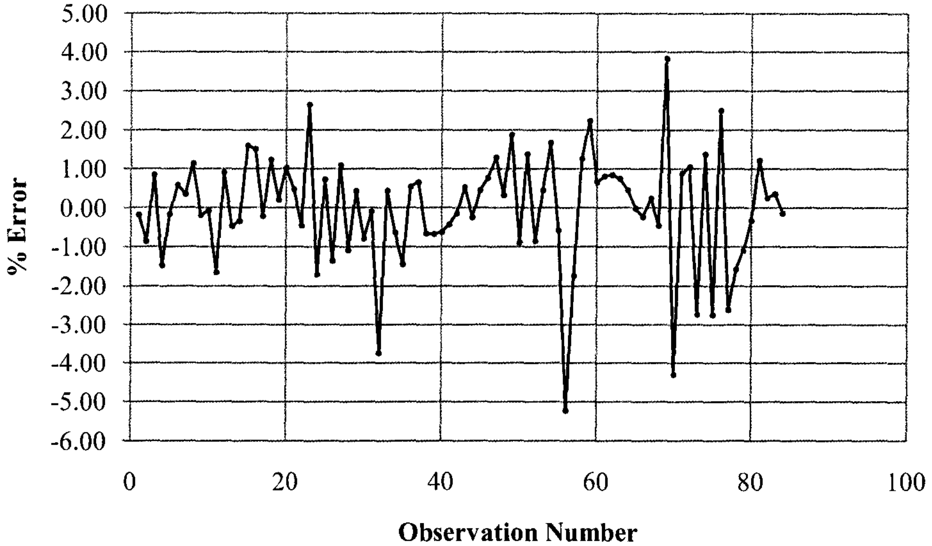

Figure B.88: Building Type R3 - Ottawa: % Error vs. Observation (Pump Load)

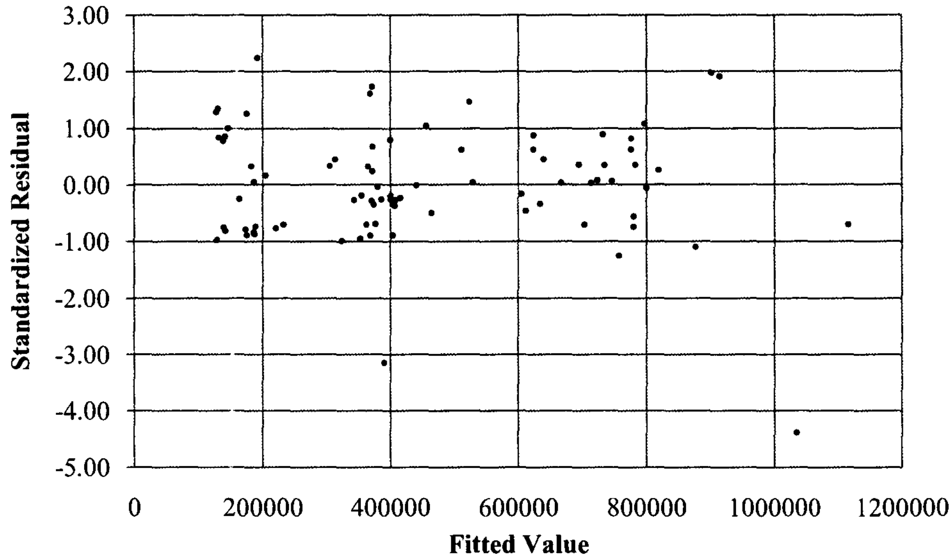

Figure B.89: Building Type R3 - Ottawa: Residuals vs. Fitted Values (Fan Load)

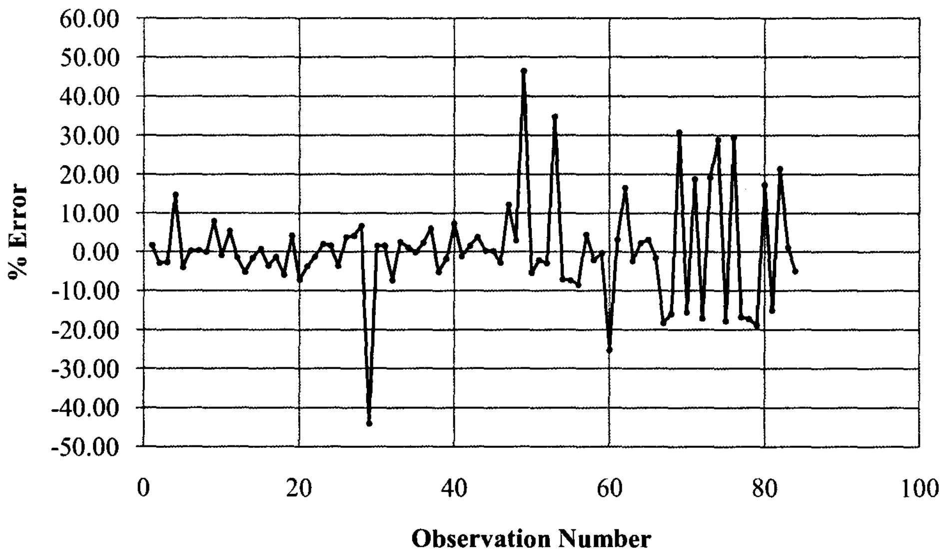

Figure B.90: Building Type R3 - Ottawa: % Error vs. Observation (Fan Load)

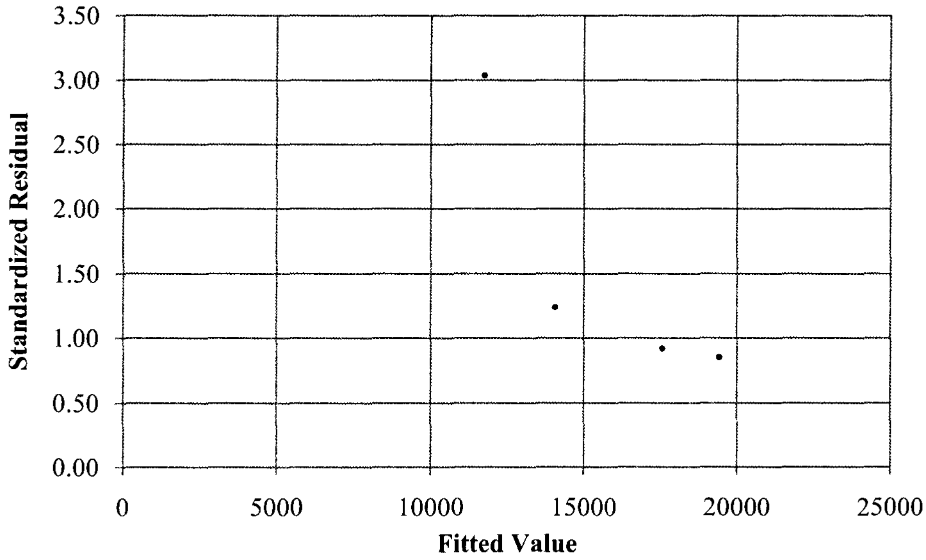

Figure B.91: Building Type R3 - Ottawa: Residuals vs. Fitted Values (DHW Loads)

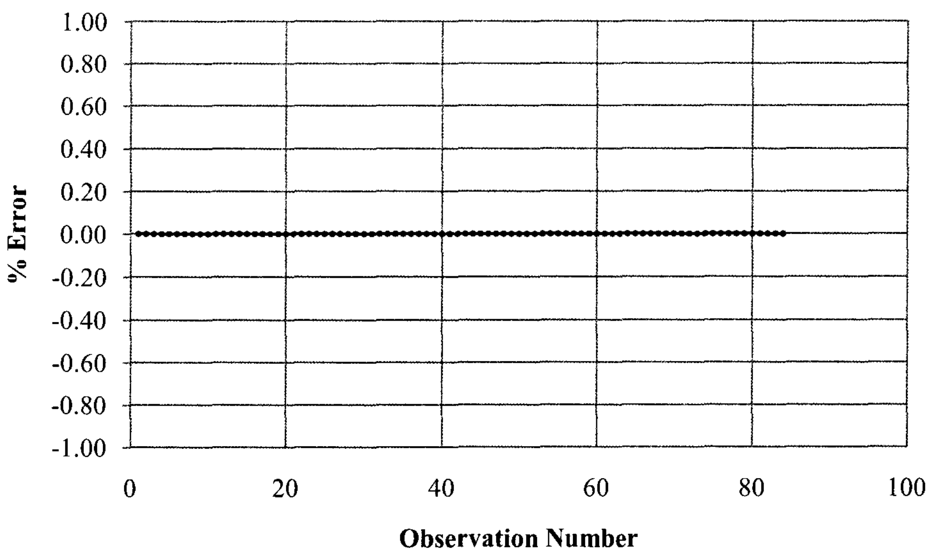

Figure B.92: Building Type R3 - Ottawa: % Error vs. Observation (DHW Load)

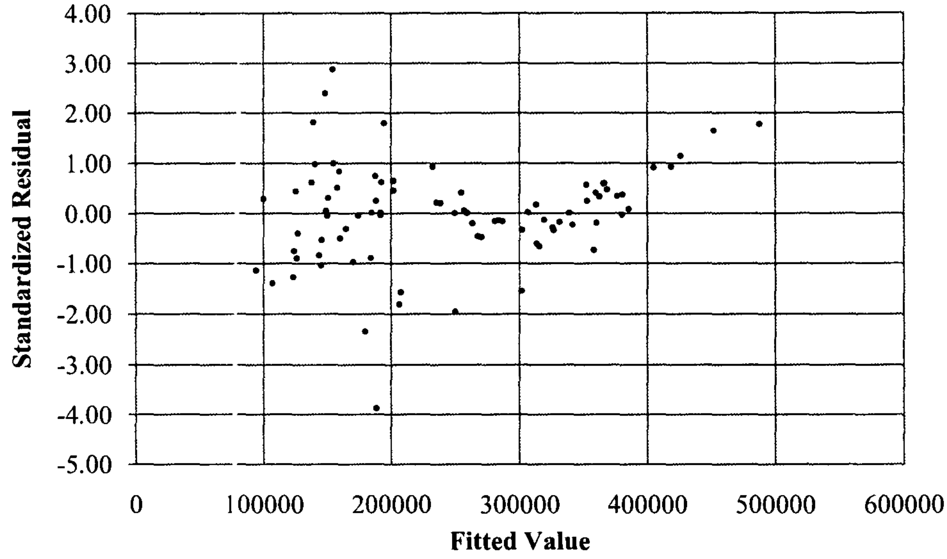

Figure B.93: Building Type R3 - Ottawa: Residuals vs. Fitted Values (Chiller Load)

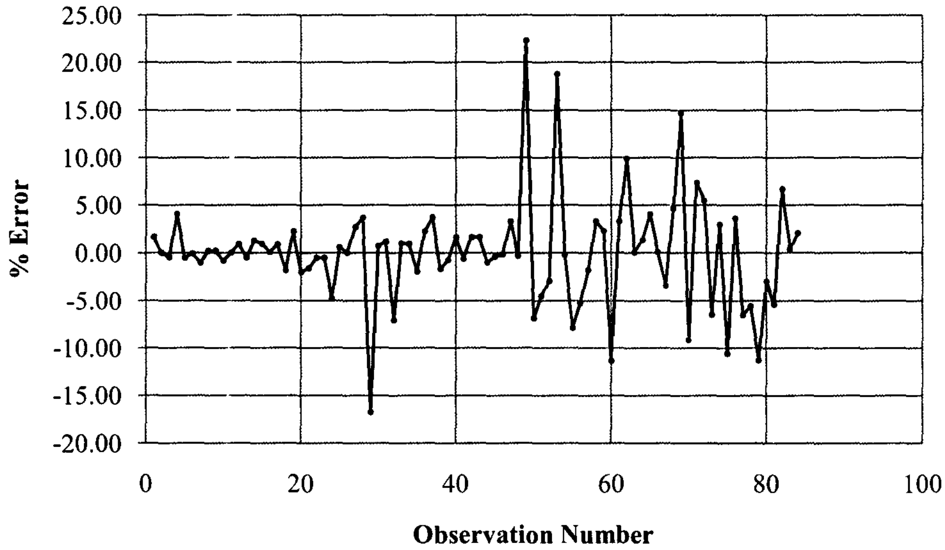

Figure B.94: Building Type R3 - Ottawa: % Error vs. Observation (Chiller Load)

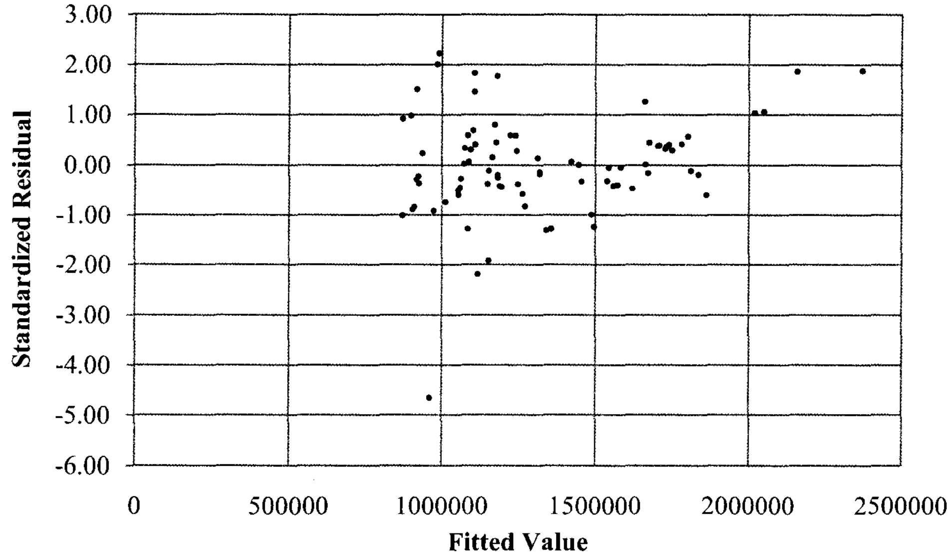

Figure B.95: Building Type R3 - Ottawa: Residuals vs. Fitted Values (Electrical Load)

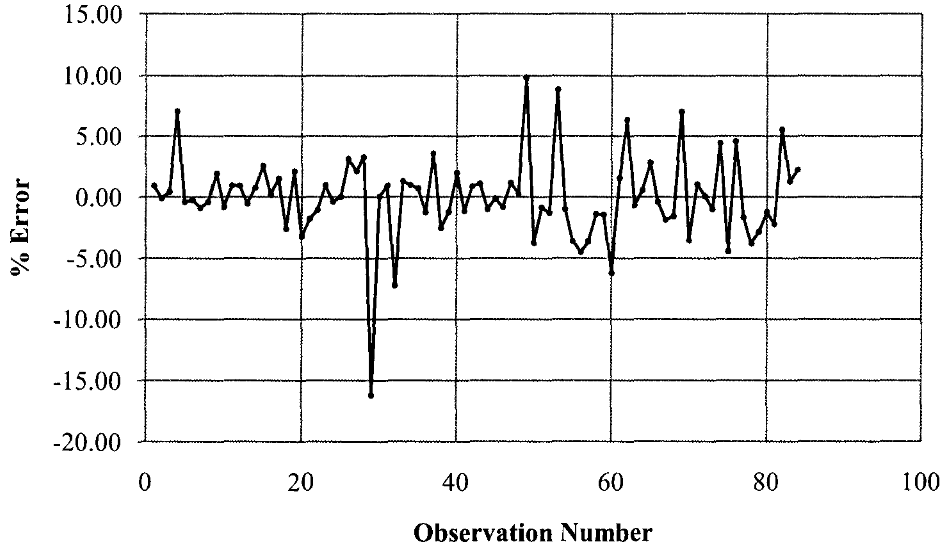

Figure B.96: Building Type R3 - Ottawa: % Error vs. Observation (Electrical Load)

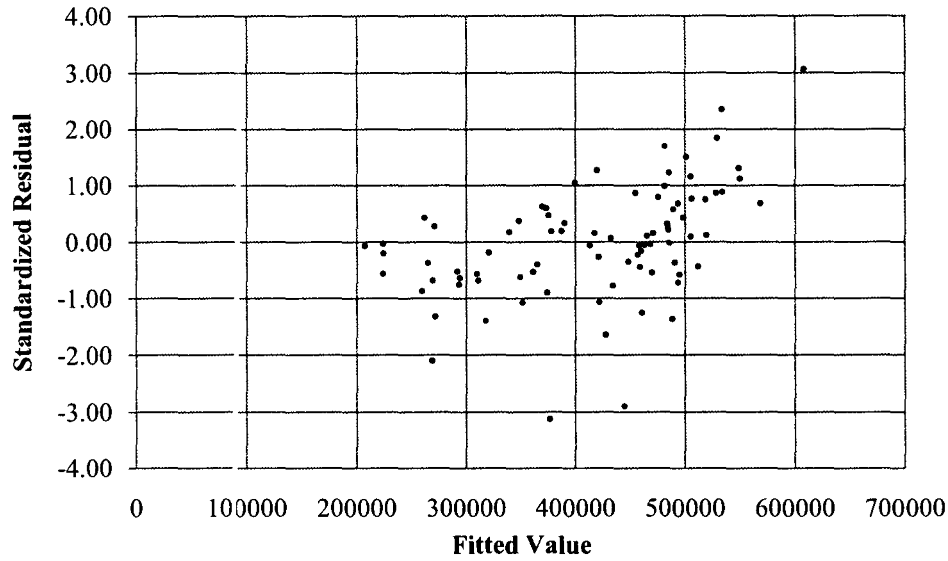

Figure B.97: Building Type R3 - Ottawa: Residuals vs. Fitted Values (Natural Gas Load)

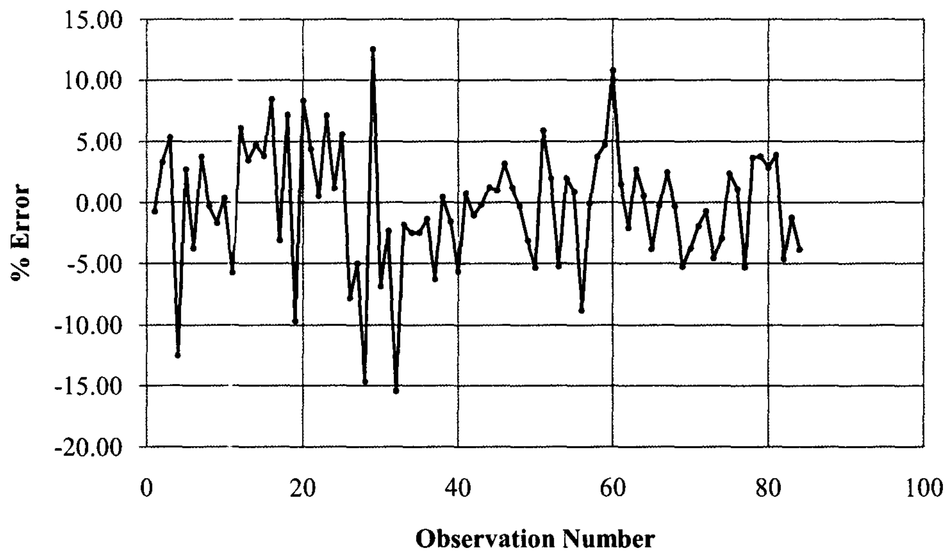

Figure B.98: Building Type R3 - Ottawa: % Error vs. Observation (Natural Gas Load)

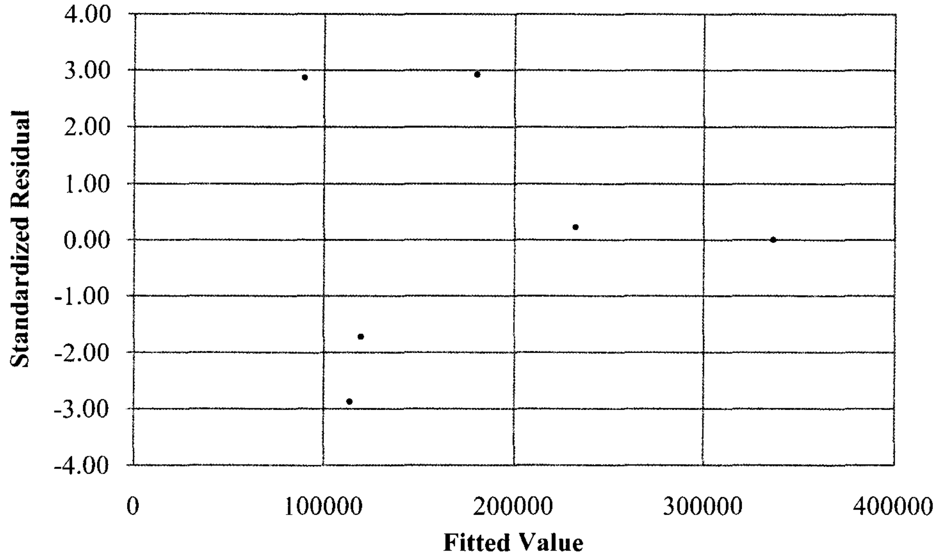

Figure B.99: Building Type R3 - Edmonton: Residuals vs. Fitted Values (Lighting Load)

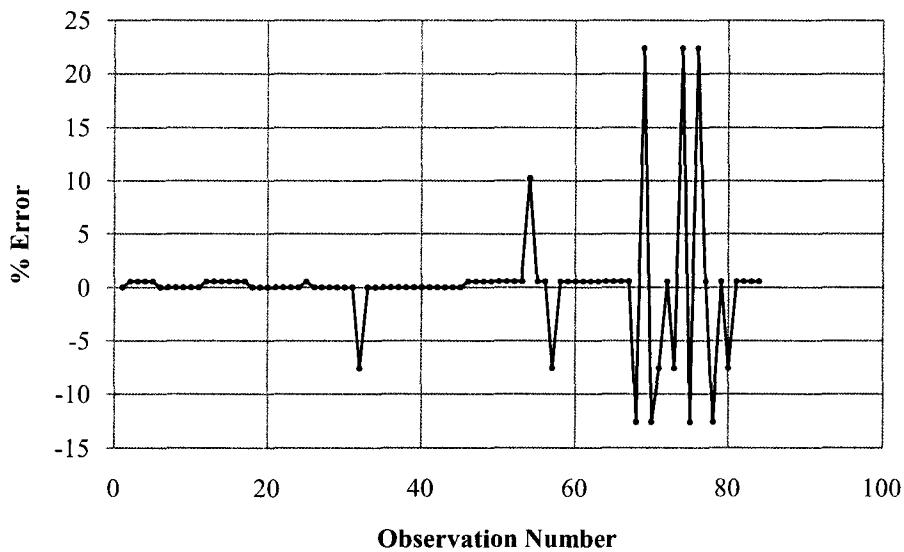

Figure B.100: Building Type R3 - Edmonton: % Error vs. Observation (Lighting Load)

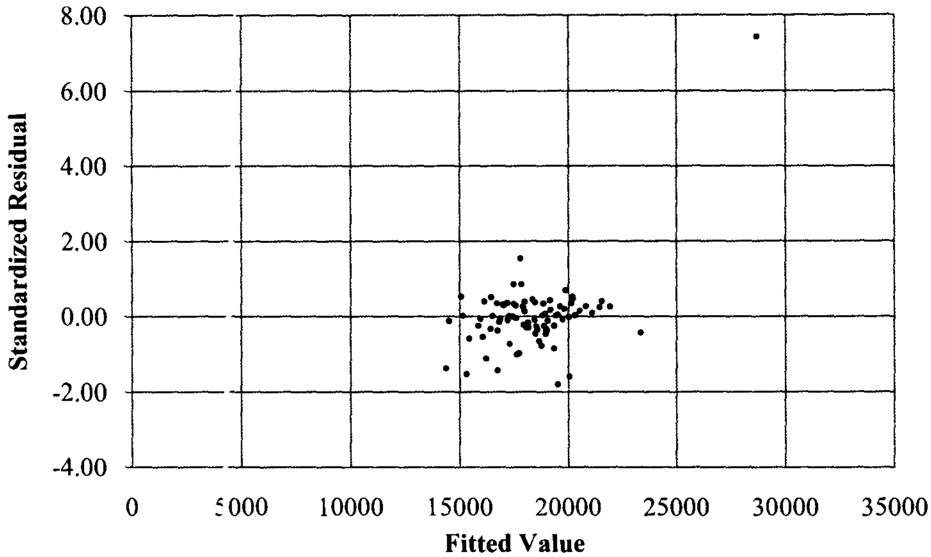

Figure B.101: Building Type R3 - Edmonton: Residuals vs. Fitted Values (Pump Load)

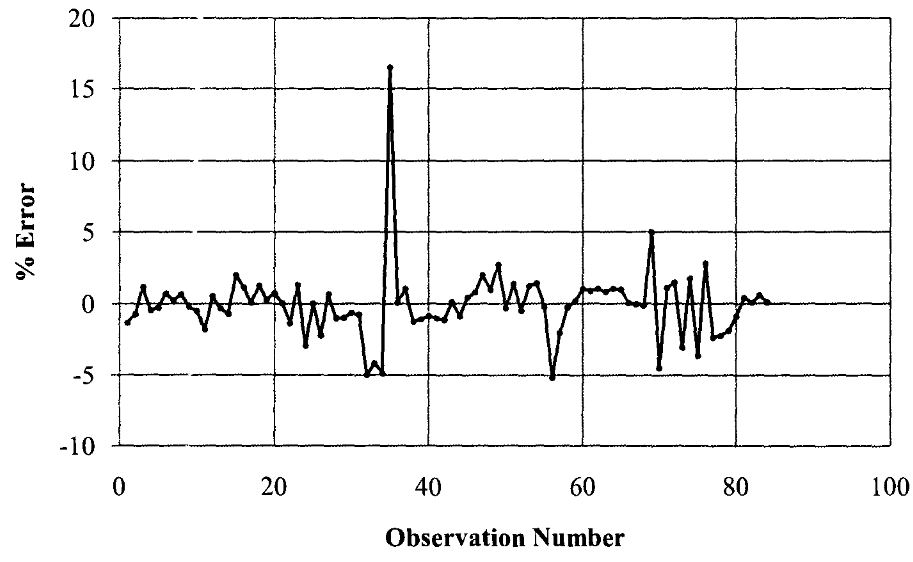

Figure B.102: Building Type R3 - Edmonton: % Error vs. Observation (Pump Load)

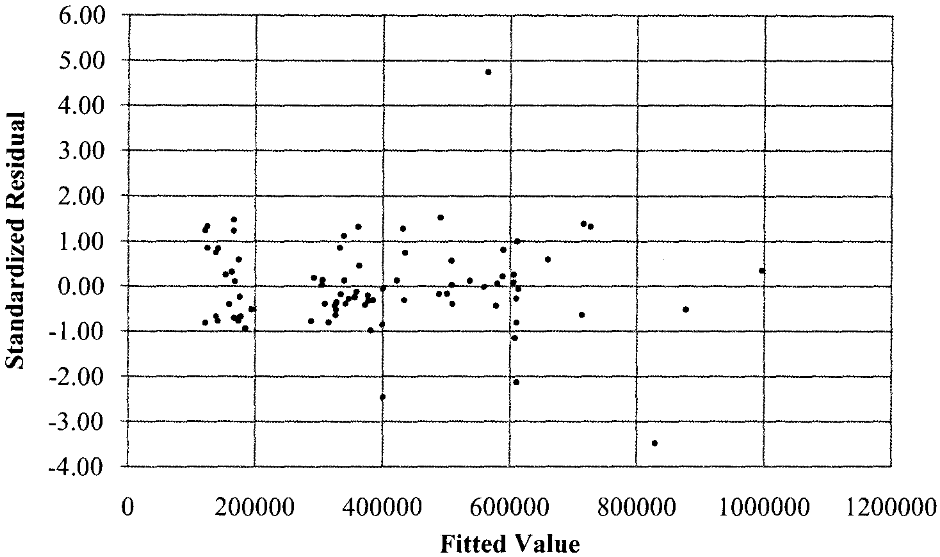

Figure B.103: Building Type R3 - Edmonton: Residuals vs. Fitted Values (Fan Load)

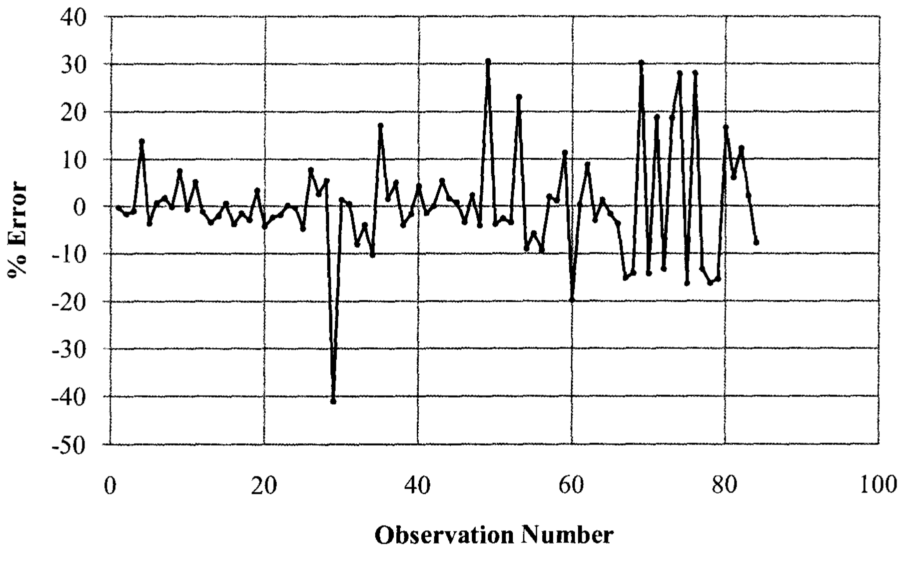

Figure B.104: Building Type R3 - Edmonton: % Error vs. Observation (Fan Load)

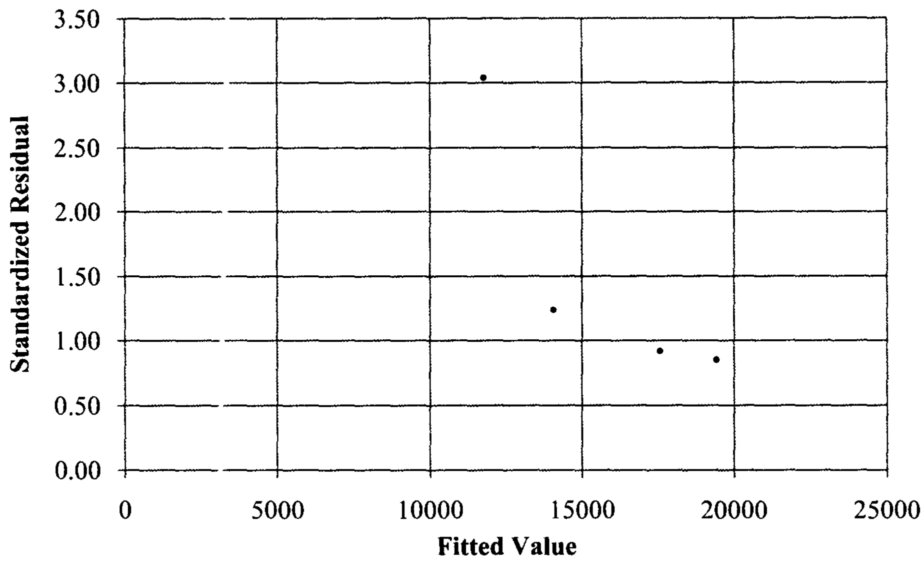

Figure B.105: Building Type R3 - Edmonton: Residuals vs. Fitted Values (DHW Loads)

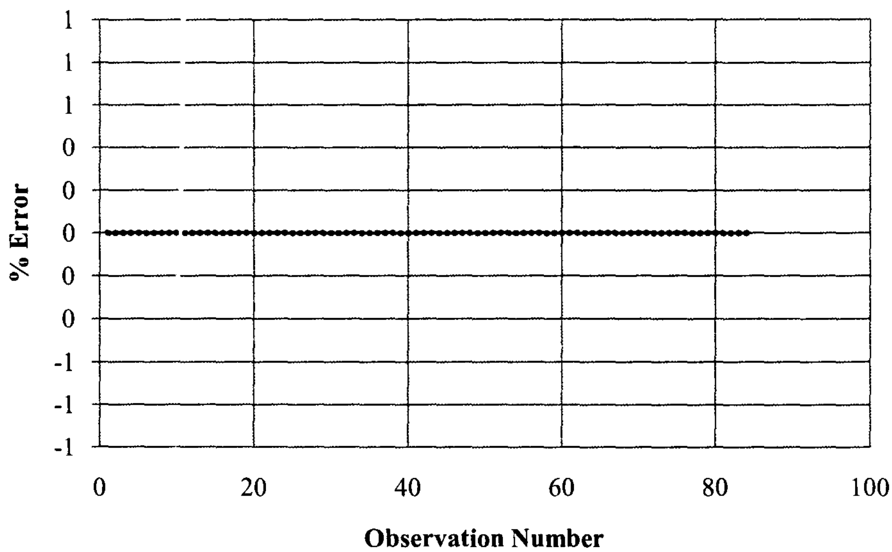

Figure B.106: Building Type R3 - Edmonton: % Error vs. Observation (DHW Load)

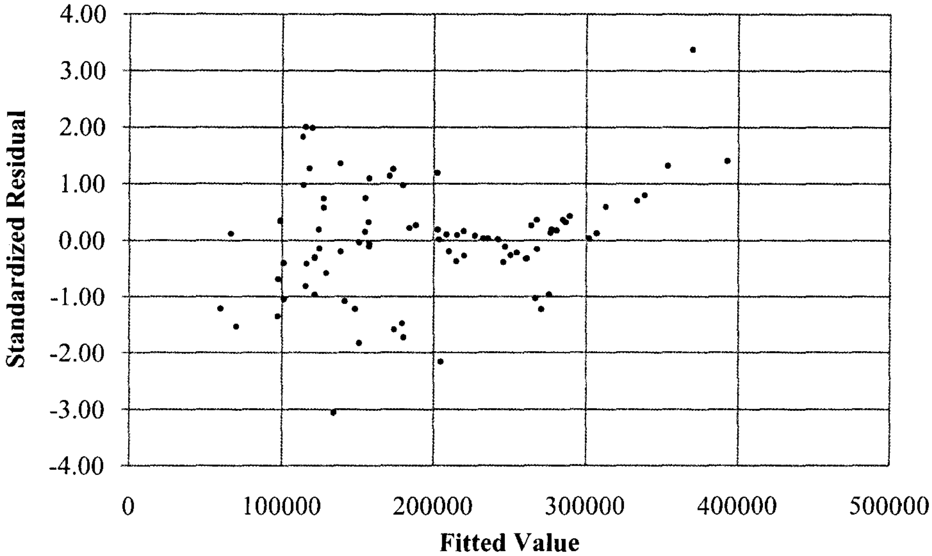

Figure B.107: Building Type R3 - Edmonton: Residuals vs. Fitted Values (Chiller Load)

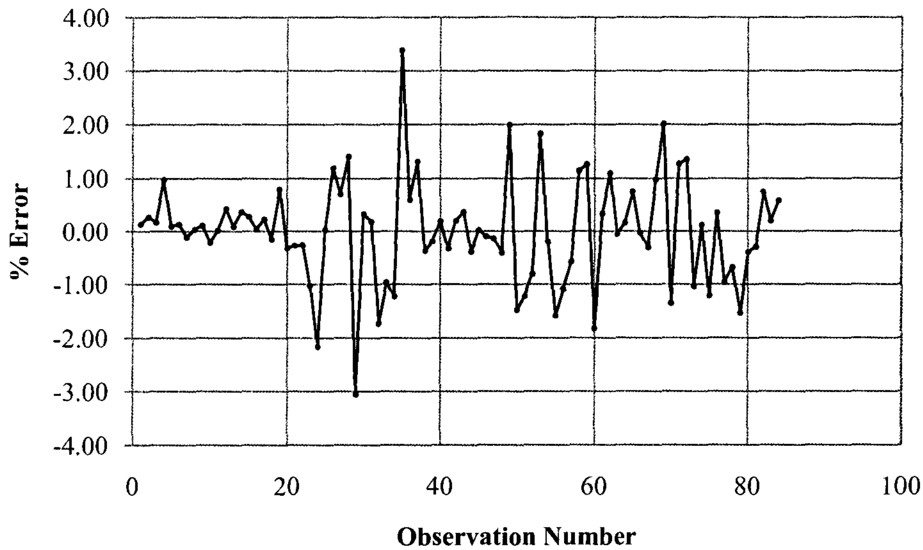

Figure B.108: Building Type R3 - Edmonton: % Error vs. Observation (Chiller Load)

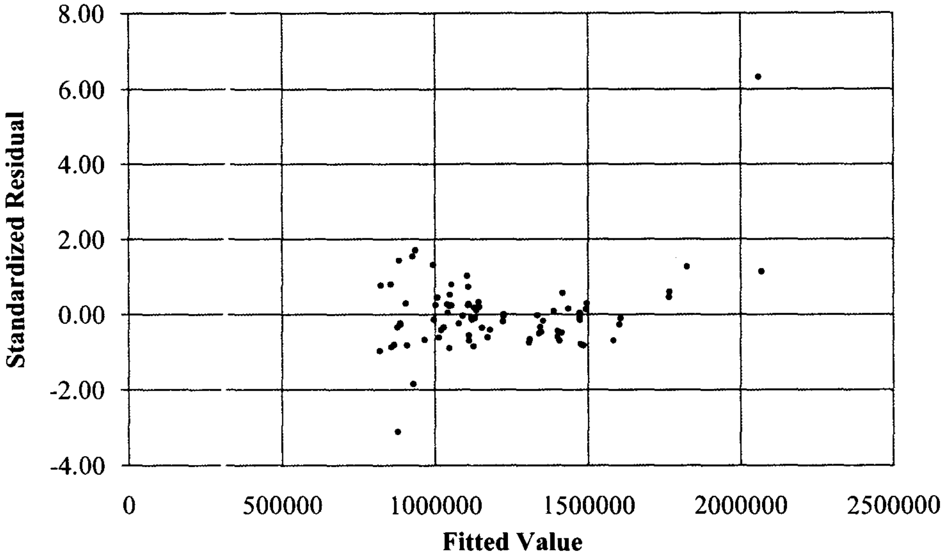

Figure B.109: Building Type R3 - Edmonton: Residuals vs. Fitted Values (Electrical Load)

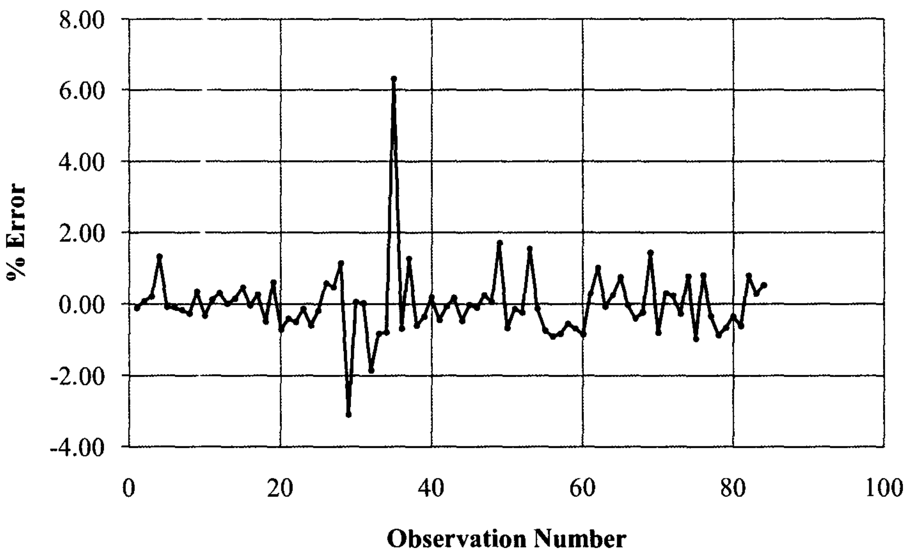

Figure B.110: Building Type R3 - Edmonton: % Error vs. Observation (Electrical Load)

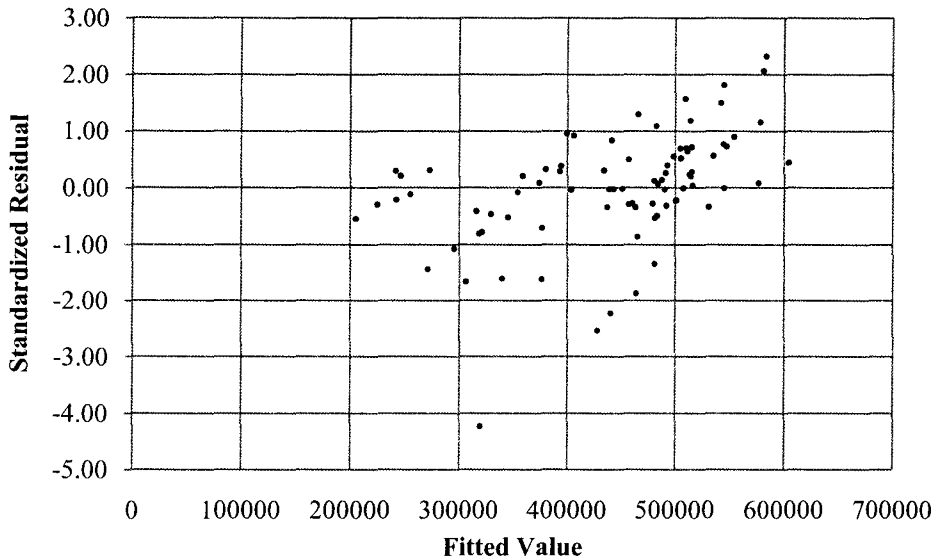

Figure B.111: Building Type R3 - Edmonton: Residuals vs. Fitted Values (Natural Gas Load)

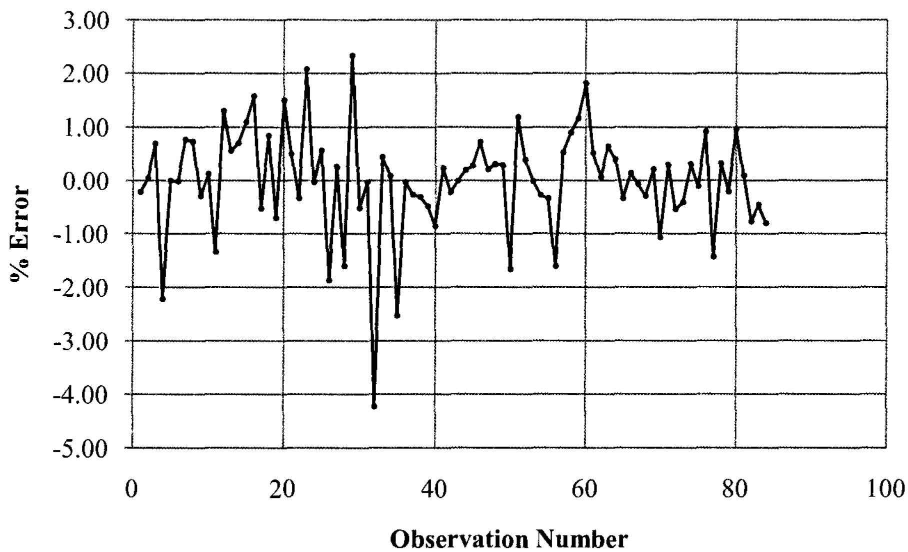

Figure B.112: Building Type R3 - Edmonton: % Error vs. Observation (Natural Gas Load)

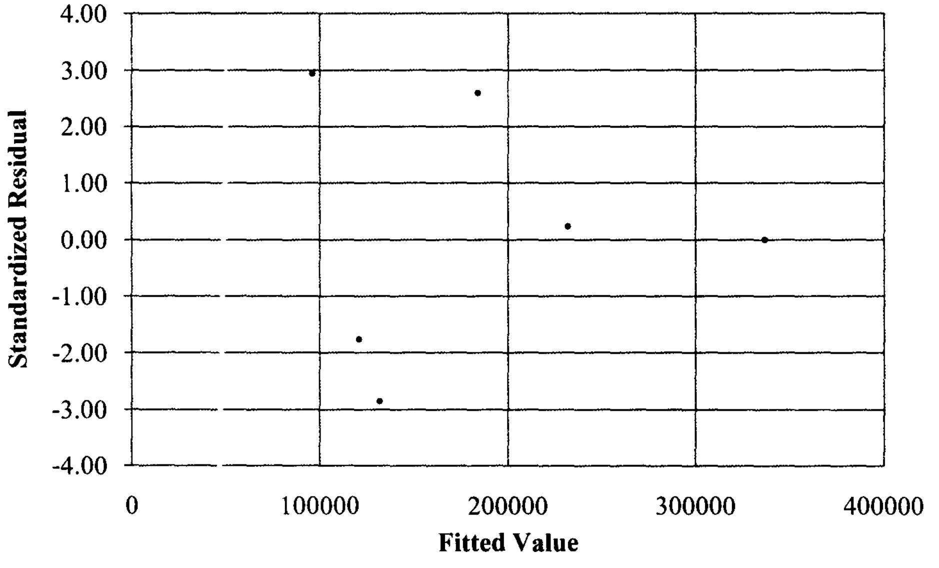

Figure B.113: Building Type R3 - Vancouver: Residuals vs. Fitted Values (Lighting Load)

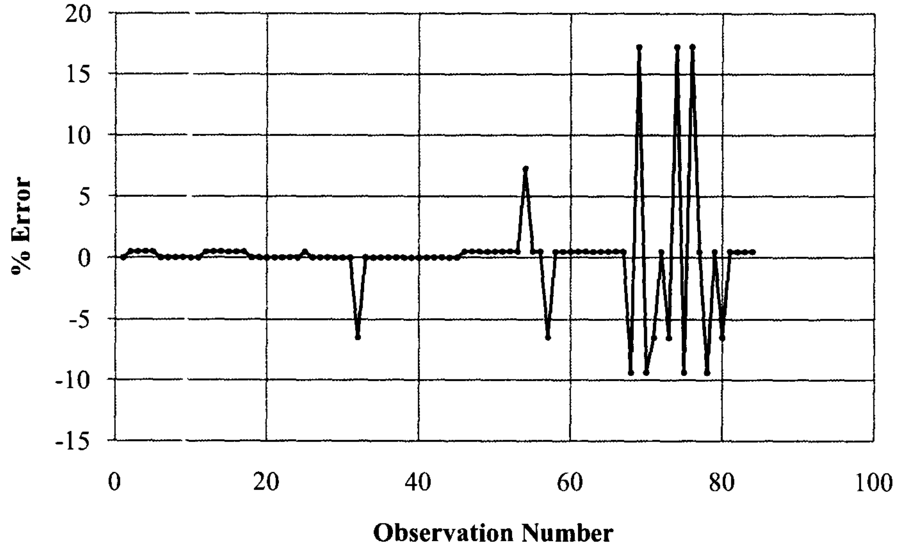

Figure B.114: Building Type R3 - Vancouver: % Error vs. Observation (Lighting Load)

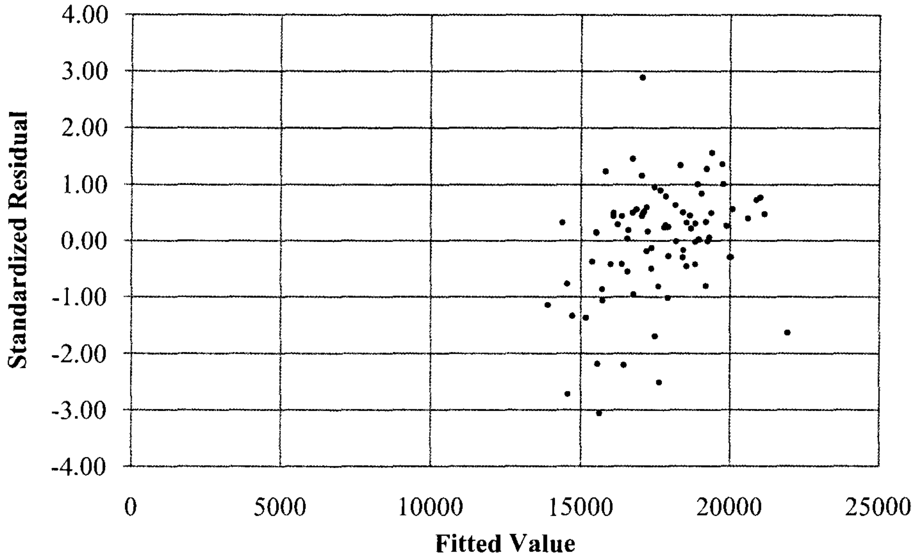

Figure B.115: Building Type R3 - Vancouver: Residuals vs. Fitted Values (Pump Load)

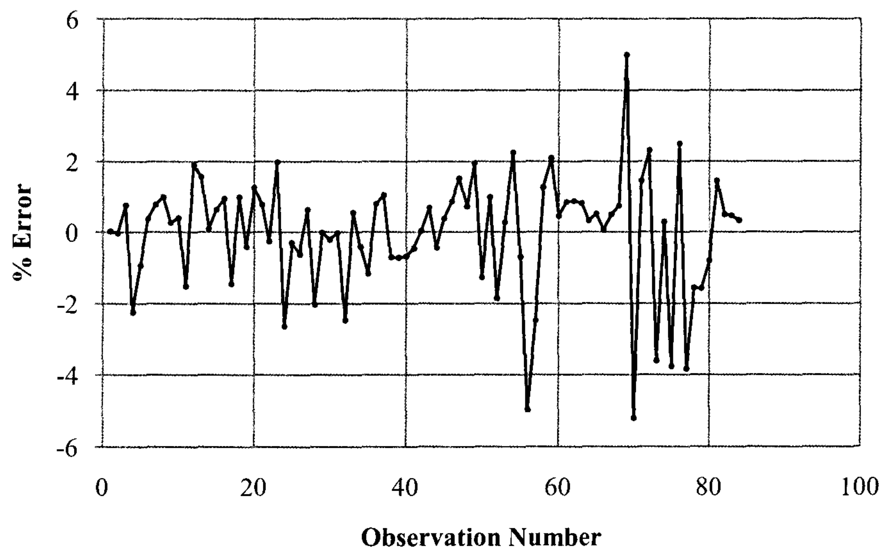

Figure B.116: Building Type R3 - Vancouver: % Error vs. Observation (Pump Load)

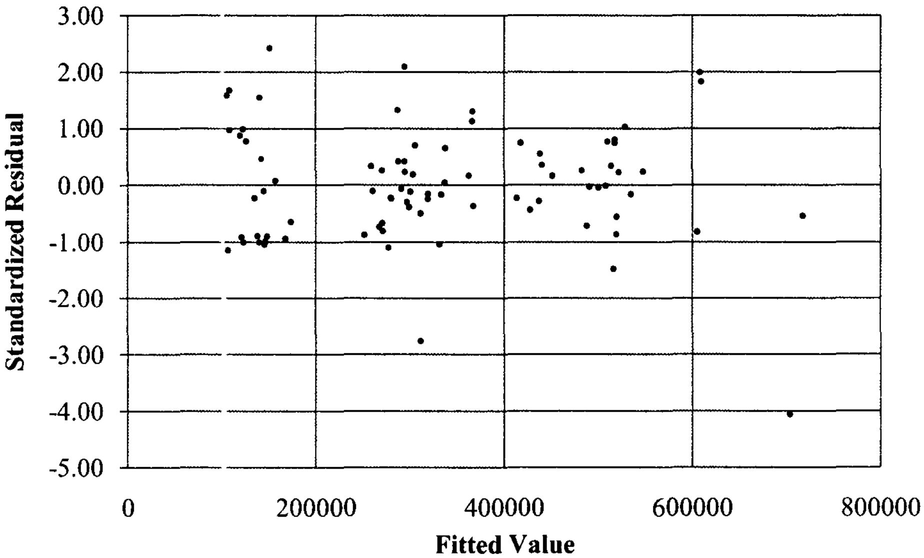

Figure B.117: Building Type R3 - Vancouver: Residuals vs. Fitted Values (Fan Load)

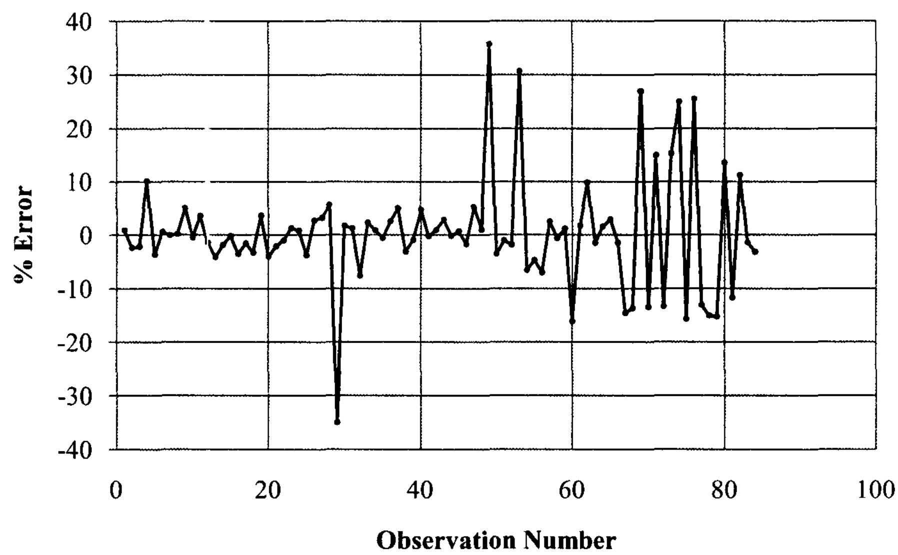

Figure B.118: Building Type R3 - Vancouver: % Error vs. Observation (Fan Load)

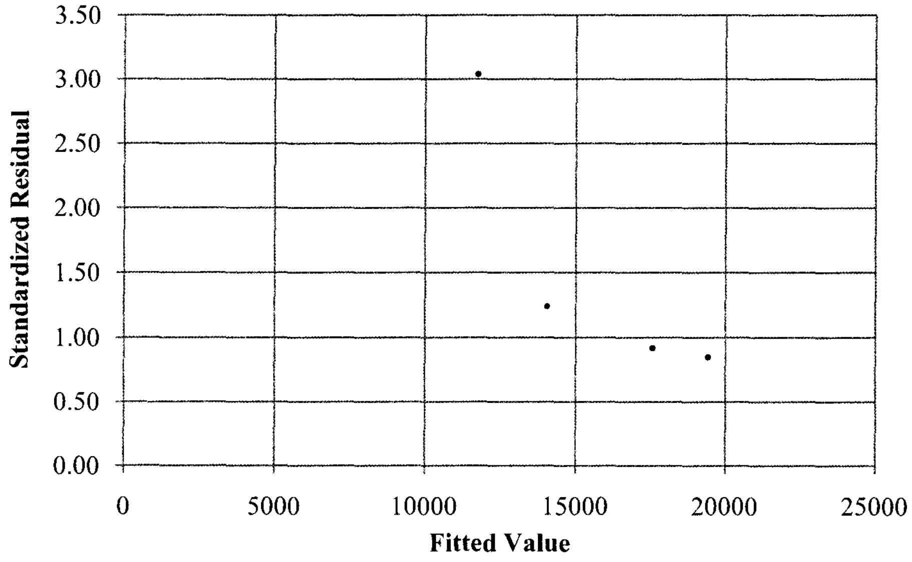

Figure B.119: Building Type R3 - Vancouver: Residuals vs. Fitted Values (DHW Loads)

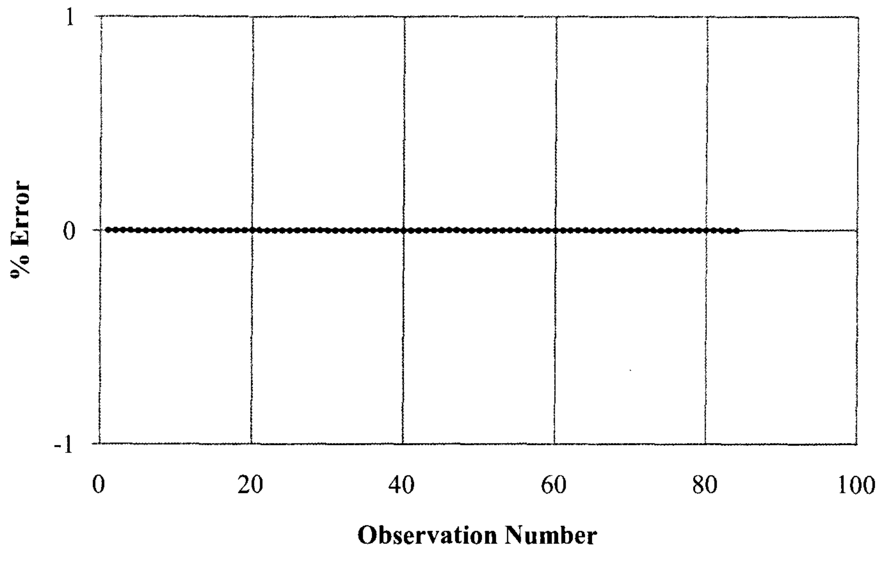

Figure B.120: Building Type R3 - Vancouver: % Error vs. Observation (DHW Load)

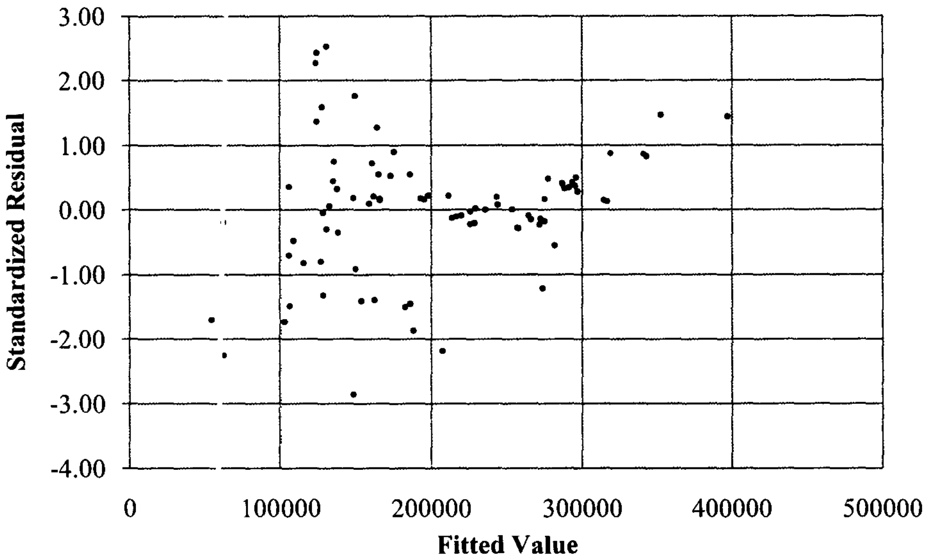

Figure B.121: Building Type R3 - Vancouver: Residuals vs. Fitted Values (Chiller Load)

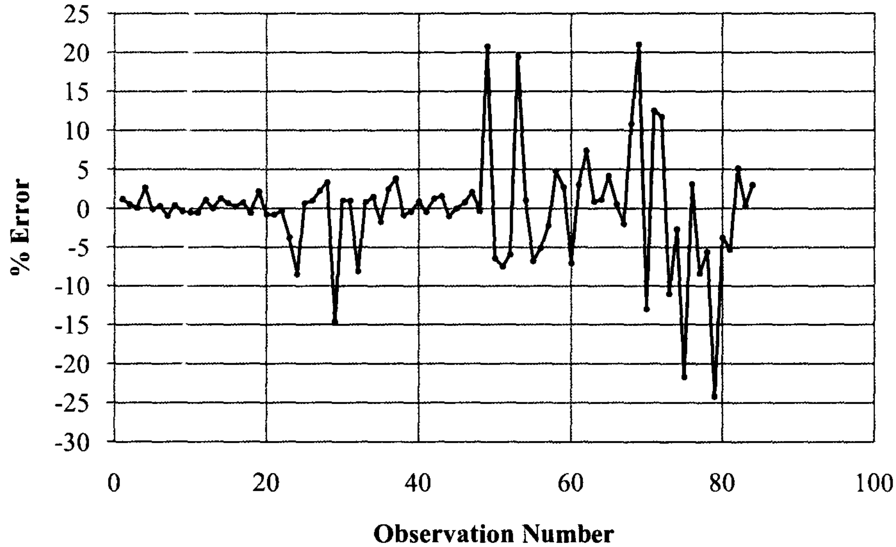

Figure B.122: Building Type R3 - Vancouver: % Error vs. Observation (Chiller Load)

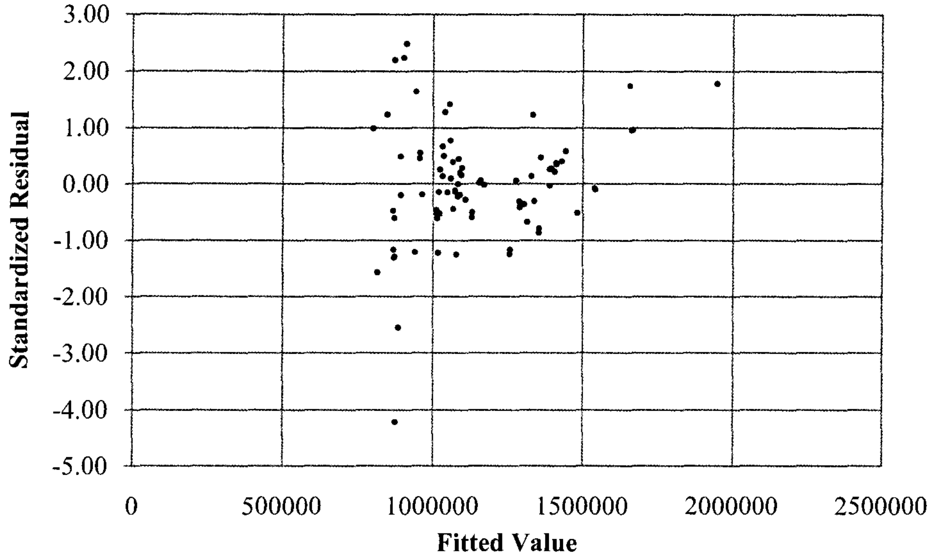

Figure B.123: Building Type R3 - Vancouver: Residuals vs. Fitted Values (Electrical Load)

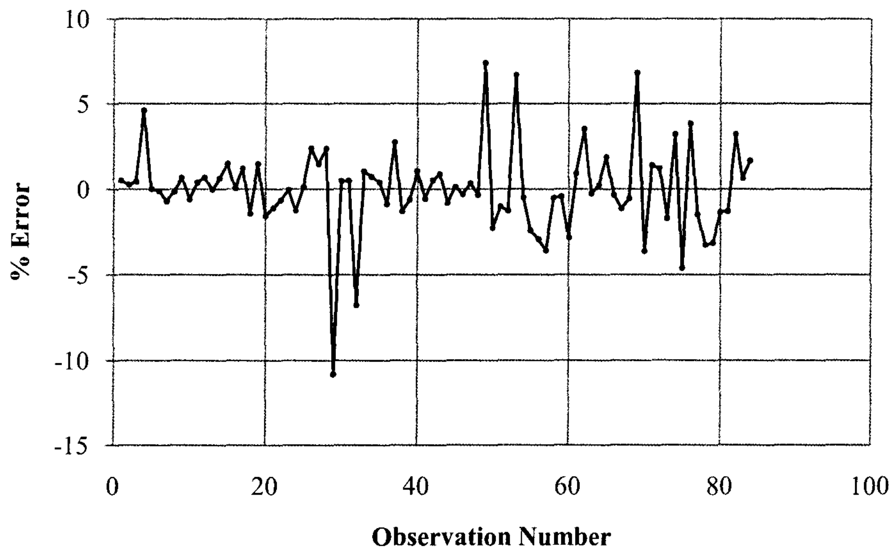

Figure B.124: Building Type R3 - Vancouver: % Error vs. Observation (Electrical Load)

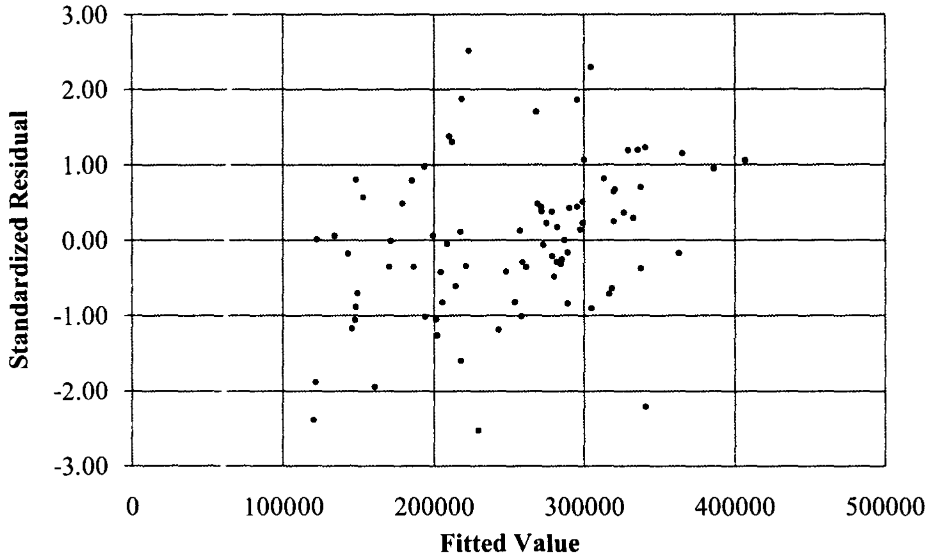

Figure B.125: Building Type R3 - Vancouver: Residuals vs. Fitted Values (Natural Gas Load)

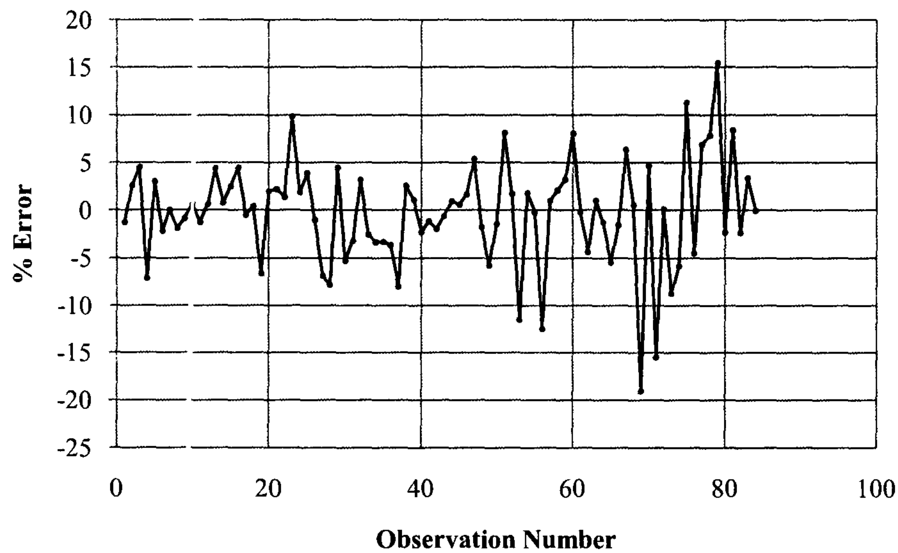

Figure B.126: Building Type R3 - Vancouver: % Error vs. Observation (Natural Gas Load)