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Calibrated whole building energy simulation: An evidence-based methodology

by Paul Raftery

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A thesis submitted in partial fulfilment of the requirements for the degree of
Doctor of Philosophy,
in the College of Engineering and Informatics

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Abstract

Climate change, driven by global energy consumption, is one of the major challenges to humanity today. The buildings sector consumes a significant portion of global energy resources and much of this is due to inefficient design and operation. Whole building energy simulation provides a means of assessing building performance at the design stage of the building life cycle. Calibration of these models allows for performance assessment and efficiency improvements at the operational stage. Also, the information output from the calibration process can be used to identify mistaken assumptions made in design stage models, to improve best practice modelling techniques and to drive the development of simulation tools. However, there are issues with current approaches to calibrated simulation. Many existing methodologies are informal, ad-hoc, and not firmly based on clearly referenced evidence. In addition, many calibrated simulation case studies use simplified models and limited measured data.

This thesis presents a novel, evidence-based methodology that uses version control techniques to track the entire calibration process. This improves the reproducibility and credibility of the calibrated model as future users can review the model and the evidence on which it is based at any stage of the calibration process. The methodology also includes a new zoning-strategy that more closely represents the actual building than current strategies, and is particularly applicable to deep floor plan buildings.

This methodology was applied to a 4-storey, 30,000m^2 industrial office building - the Intel IR6 building in Leixlip, Co. Kildare, Ireland. The final calibrated model uses measured hourly internal load data in the simulation instead of scheduled approximations. The calibrated model has a MBE of 4.16% MBE and a CVRMSE(hourly) of 7.80% when compared to measured hourly HVAC electricity consumption for 2007. The data from this case study was also used to present a new visualisation technique that combines 'bin' analysis with 3-dimensional surface plots.

Table of contents

List of tables

List of figures

Declarations

This thesis or any part thereof, has not been, or is not currently being submitted for any degree at any other university.

Paul Kevin Raftery

The work reported herein is as a result of my own investigations, except where acknowledged and referenced.

Paul Kevin Raftery

Dedication

For my wife, Lidia, who has always been there for me. Thank you for your love and support.

Acknowledgments

Firstly, I am deeply grateful to my parents, Gerry and Helen, for their endless support and for getting me this far in life. Thanks also to my sisters, Gillian and Niamh, for putting up with me this long!

I would like to thank my supervisor, Dr. Marcus Keane at NUI Galway, for his guidance, consideration and friendship over the last three years.

I'm very grateful to my colleagues in Ireland: James for his contributions to the quality of my work; Andrea for his technical assistance and support; Kevin Geoghegan and Luke Fenner for their assistance with the Intel building; and my fellow occupants of E304, who have provided a welcome outlet from the occasional stresses of research. I owe you all a debt of gratitude.

Special thanks to my fellow researchers in Berkeley: my supervisor, Dr. Vladimir Bazjanac at LBNL for aiding in my development as a researcher; Dr. Tobias Maile for his EnergyPlus expertise; and Fred Baumann, Tom Webster and Dr. Kwang Ho Lee at the CBE for bringing along my HVAC knowledge in leaps and bounds. I hope that our paths cross again in the future.

Many thanks to my friends: Andy, Eric, Humphrey, Kate, Mark, Paddy, Sara and Viv for their support and encouragement throughout the years in Ireland. Thanks also to Chris for his enthusiasm and showing me what life in California is all about!

I am very grateful to the Irish Research Council for Science, Engineering and Technology (IRCSET) and the Fulbright Commission, who jointly funded this research.

Finally, thanks to Professor O'Donoghue for the use of the facilities at the Department of Civil Engineering at NUI Galway.

List of abbreviations

AHU	Air Handling Unit
ASHRAE	American Society of Heating Refrigeration Air Conditioning Engineers
BAS	Building Automation System
BIM	Building Information Model
BER	Building Energy Rating
BLC	Building Life Cycle
BMS	Building Management System
BREEAM	Building Research Establishment's Environmental Assessment Method
BWM	Box Whisker Mean
CAD	Computer Aided Design
CASBEE	Comprehensive Assessment System for Building Environmental Efficiency
CBE	Center for the Built Environment
CEC	California Energy Commission
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
ChW	Chilled Water
CIBSE	Chartered Institute of Building Services Engineers
COAG	Council of Australian Governments

CVRMSE	Cumulative Variation of Root Mean Squared Error
DCV	Demand Controlled Ventilation
ECM	Energy Conservation Measure
EMS	Energy Monitoring System
EMCS	Energy Management and Control Systems
EPBD	Energy Performance of Buildings Directive
EPI	Energy Performance Indicator
ERI	Environmental Research Institute
ERV	Energy Recovery Ventilation
EUI	Energy Use Intensity
FEMP	Federal Energy Management Protocol
FDD	Fault Detection and Diagnosis
GUI	Graphical User Interface
HVAC	Heating Ventilation and Air Conditioning
HW	Hot Water
IAQ	Indoor Air Quality
IAI	International Alliance for Interoperability
IDF	Input Data File (EnergyPlus input syntax for simulation)
IFC	Industry Foundation Class
IPCC	Intergovernmental Panel on Climate Change
IMPVP	International Performance Measurement & Verification Protocol
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JSBC	Japan Sustainable Building Consortium
LEED	Leadership in Energy and Environmental Design
LBNL	Lawrence Berkeley National Laboratory

MBE	Mean Bias Error
MCC	Motor Control Center
MM	Mixed Mode
NSAI	National Standards Authority of Ireland
O&M	Operation & Maintenance manual
pmv	predicted mean vote (Fanger)
ppd	predicted percentage dissatisfied (Fanger)
NUI	National University of Ireland
RH	Relative Humidity
RTU	Roof-Top Unit
TABS	Thermally Activated Building Systems
TMY	Typical Meteorological Year
UC	University of California
UFAD	Underfloor Air Distribution
US DOE	United States Department Of Energy
USGBC	United States Green Building Council
VAV	Variable Air Volume
VFD	Variable Frequency Drive
VSF	Variable Speed Fan
WHO	World Health Organisation

Chapter 1: Introduction

"Human beings are now carrying out a large scale geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future."

- Roger Revelle

1.1 Overview

Buildings consume a large portion of global energy resources and therefore significantly contribute to climate change. It is widely recognised that buildings are inefficient consumers of energy. Calibrated building energy models offer a means of reducing these inefficiencies. However, there are issues with current calibration methodologies that limit their effectiveness.

This chapter establishes the research context, concisely defines the research question and outlines the thesis structure.

1.2 Climate change

Humankind's activities on the planet have significantly affected the environment by consuming natural resources at an alarming rate and releasing significant amounts of pollutants. Some of these pollutants have effects that appear over the relatively short term, such as chlorofluorocarbons, which deplete the ozone layer, and sulphur dioxide, which causes acid rain. However, many of the pollutants will have significant detrimental effects over longer periods, such as greenhouse gases. These gases primarily consist of carbon dioxide, which is released during the process of converting chemical energy (fossil fuels) into the energy we use to support the quality of life we currently enjoy. However, over the past century it has become apparent that this is causing global warming. Beginning with the first paper to identify the problem and show experimental evidence to support the observation (Callendar, 1938), it has gradually become accepted that the planet is warming due to the release of green-house gases such as CO_2, and that mankind's activities are responsible for this (IPCC, 2007). Figure 1.1 illustrates that global average surface temperatures have risen significantly in the recent past. Figure 1.2 illustrates that measured land temperatures in 2010 were the highest on record: on average 1.03°C warmer than the 20th century average (National Climate Data Center, 2010).

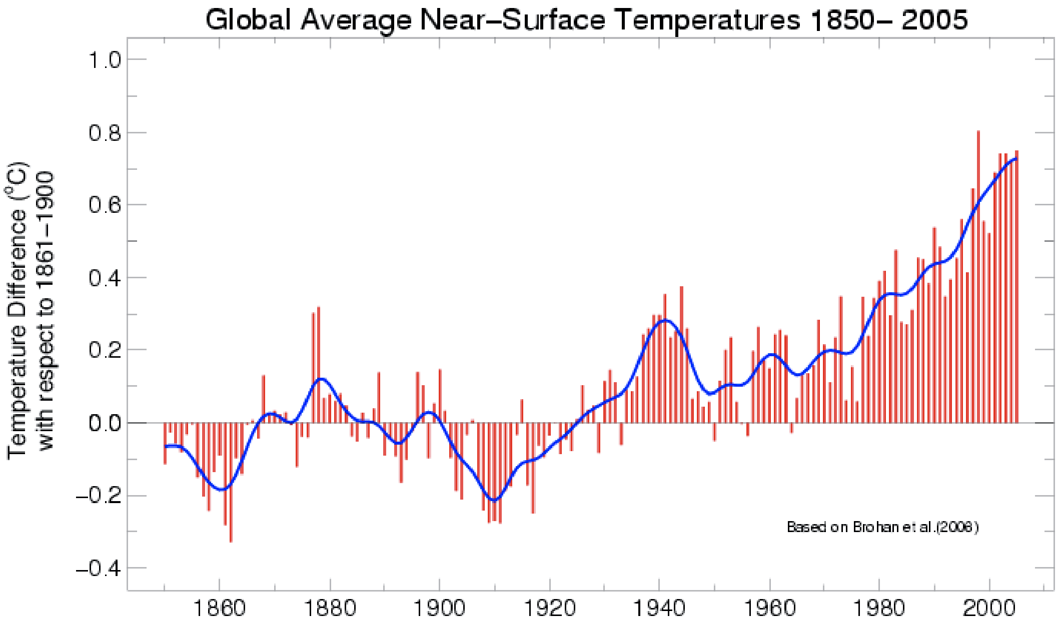

Figure 1.1: Global average near-surface temperature relative to 1861-1900 average (Brohan et al., 2006)

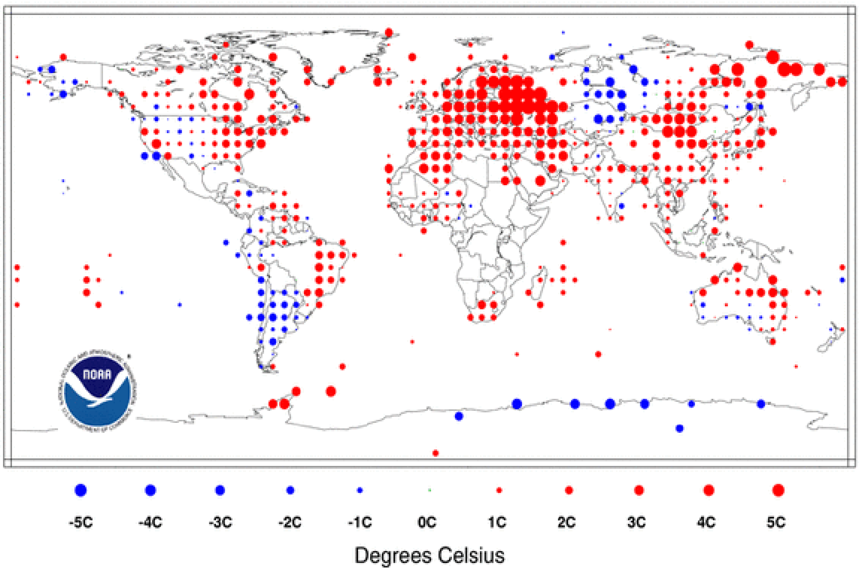

Figure 1.2: Land temperature anomalies in July 2010 (National Climate Data Center 2010)

There will be serious consequences as a result of climate change, in terms of water and food shortages, damage to ecosystems, and rising sea levels (IPCC, 2007). The effects of climate change on the global economy will be much more significant than the cost of acting now to stabilise levels of greenhouse gas in the atmosphere (Stern, 2006). Thus, it is essential that we reduce emissions in order to mitigate the damage caused by climate change. Unfortunately, the opposite is happening. Figure 1.3 illustrates that emissions have continued to rise.

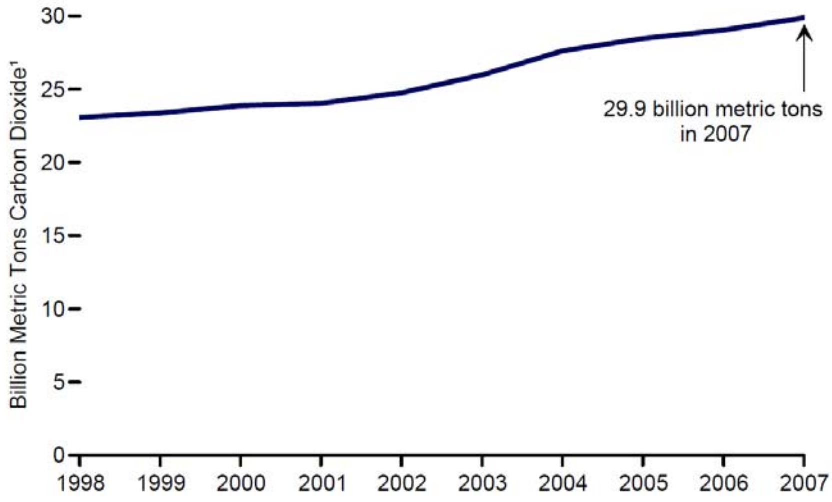

Figure 1.3: World CO_2 emissions from energy consumption (US EIA, 2009).

Many governments have now adopted emissions targets into legislation. For example, the EU has committed to reduce total greenhouse gas emissions by at least 20% by 2020 (EU, 2010). Similarly, an executive order in the United States has committed the federal government to reduce greenhouse gas emissions by 28% by 2020 (Obama, 2009). A two pronged approach is currently underway to meet these targets: energy efficiency and renewable power sources.

Although installed power capacities for many renewable energy technologies grew 10-60% from 2004 to 2009, these rapidly growing technologies are currently responsible for just 2.6% of total global energy requirements (Sawin and Martinot, 2010). Established renewable sources, such as traditional biomass and existing hydropower, are growing at rates that are comparable to growth rates in total energy demand. Thus, it is clear that significant improvements in energy efficiency are required in order to reduce greenhouse gas emissions in the immediate future.

1.3 Energy in buildings

1.3.1 Significance of the building sector

The most significant energy consumer worldwide is the buildings sector. In 1971 this sector was responsible for 39.0% of world primary energy, decreasing slightly to 38.5% in 2000 (Price et al., 2006). However, in absolute terms, it has increased dramatically, from 89EJ to 149EJ over the same period (Price et al., 2006). Similar percentages are reported at higher resolutions – buildings are responsible for approximately 40% of final energy consumption energy in the European Union (EU, 2002) and accounted for 35% of total energy demand in Ireland in 2006 (O'Leary et al., 2008). A recent article also paints a bleak picture, illustrating that energy consumption in buildings, particularly in the HVAC category, is increasing globally, and that there is very little statistical information available defining a significant portion of our total energy consumption (Perez-Lombard et al., 2008).

1.3.2 Inefficiency in the building sector

Unfortunately, the majority of buildings are inefficiently designed and operated. Estimates of how much of an improvement in energy efficiency can readily be achieved vary widely in the range of 10-45% (Herzog and Lavine, 1992; Claridge et al., 1996, 2000; Piette et al., 2001; Ardehali et al., 2003; Dix, 2003). Clearly this large range of estimates is based on what is considered a readily achievable improvement. In fact, a large survey of 'green' buildings suggests that opportunities for the reduction of energy use may be even larger for new construction. The average net energy use of highly rated 'green' buildings was found to be 44% less than an average building (USGBC, 2002). Thus, improved energy efficiency in buildings will clearly play an important role in order to meet the greenhouse gas emissions targets discussed in section 1.2. Governments around the world are acting on this through legislative approaches and funding initiatives (EU, 2002, 2006; COAG, 2009; US DOE, 2010d).

Although this inefficiency occurs at almost every level of the building life cycle (BLC) – design, construction, maintenance, operation and disposal – the majority of energy use occurs at the operational stage. Estimates for the ratio of the embodied energy in a specific building to the total energy measured over an assumed 50 year life span range from 12% (Szalay, 2007) upwards to 60% (Huberman and Pearlmutter, 2008). Such a wide variation is understandable when the large number of different materials used and different climates worldwide are taken into account. However, these papers, and others (Scheuer et al., 2003; The Royal Australian Institute of Architects, 2004) predict a more reasonable average to be approximately 20%. This clearly identifies that operational energy in buildings is the most significant energy consumer and therefore the most important area in which to seek improvements.

1.4 Prescriptive approaches

The traditional method of improving or making changes within industry has been through the use of a prescriptive approach in the form of standards and regulations, rather than a performance based approach. Prescriptive approaches consist of specifying the minimum level of performance for a specific item in order to be granted a pass or fail according to the standard. By nature of this, the standard must set the bar at the lowest acceptable level. This is clearly not an ideal situation. In fact, as prescriptive approaches such as standards usually become obsolete rapidly and are infrequently updated, they lag significantly behind industry practice and often hinder the use of novel improvements that are not covered or accepted by the standard (Wallace, 1995).

Prescriptive approaches have been used extensively to attempt to improve energy efficiency in buildings (Hui, 2002). Standards and guidelines such as ASHRAE 90.1 (ASHRAE, 2004a), California Title 24 (California Energy Commission, 2008), and CIBSE Guide F (CIBSE, 2004) are used, sometimes in a voluntary capacity, to improve energy efficiency in buildings. While there have been many successes, for example, increasing minimum R values for building envelopes in Ireland, regulated by the Building Regulations (Part L) (NSAI, 2007), there is still significant room for improvement due to the inherent inadequacies of this approach as discussed above. In fact, a recent article discusses an urgent need for an update to this specific regulation (Daly, 2008), further demonstrating the fact that prescriptive approaches lag behind best practice. These issues lead us to consider other approaches to the problem, such as one based on measurement of real performance. This need for a performance-based approach has recently been recognised by legislators and has resulted in the Building Energy Rating (BER) program, which is driven by the European Performance of Buildings Directive (EPBD) (EU, 2002).

1.5 Performance approaches

One of the many ways to improve the operational performance of any system is to give guidelines where none are available, so that an operator can compare their results to others in order to determine if they are reasonable. However, this does not currently exist for the operators, owners and occupants of buildings. There are two broad techniques that attempt to do so: benchmarking and rating systems.

1.5.1 Available benchmarking techniques

Currently available benchmarking methods, such as EUIs, EPIs, and the EnergyStar mark (US Environmental Protection Agency, 2009) are based on very low resolution measurements – at the utilities level (Perez-Lombard et al., 2009) – and hence do not take into account the fact that every building has different functions and operating characteristics. Utility level measurements also suffer from a myriad of other problems when used to measure energy performance. For example, typically readings are taken no more frequently than monthly and often at uneven intervals. Combined with the fact that the dates on which these measurements are taken usually vary between companies raises further problems with data-integrity as several different companies usually supply energy in some form to the building (Scofield et al., 2004). Furthermore, these utility level measurements do not take into account the local production of energy, which is becoming more relevant with the advent of small scale renewable energy systems, such as solar and CHP. Compounding the above mentioned issues with data based on utility level measurement is the fact that all of the comparisons are made against a sample of buildings that are understood to be inefficient (Claridge et al., 1996; Dix, 2003; Ardehali et al., 2003) and do not give recommended levels for these measurements.

1.5.2 Available rating systems

A rating system is defined as a method of comparing a building's performance to a standard. It supplies a means by which stakeholders can quickly ascertain a basic level of understanding about the building's energy performance when compared to others in the same framework. In the context of buildings, a rating system can mean many things - Some rating systems are based on similar benchmarking practices to those mentioned above, such as the 'performance rating' prescribed by the Building Energy Rating program (BER) (Casals, 2006), which is mandatory in the EU. This program proposes to rate energy performance when compared to the rest of the building stock at the utility level and to create labels that are displayed to the public. As each country in the EU implemented this in a different manner, in some countries an 'asset rating' based on design data is required, while in others a 'performance rating' based on measured utilities data is required.

Other currently available rating systems such as LEED (USGBC, 2002) and BREEAM (BRE Global Ltd., 2006) are more detailed and focus on an in depth point-by-point analysis of building sustainability. However, they are entirely voluntary and focus primarily on the design stage – hence they do not tackle the problem of operational energy use directly. Table 1.1 describes a selection of commonly used voluntary rating systems and the stages of the BLC at which they assess energy performance.

Table 1.1: Overview of Energy Performance Rating Systems

Is there an extensive, mandatory evaluation of energy performance?			
Stage of life cycle:	**Design**	**Commissioning**	**Operation**
Leadership in Energy and Environmental Design (USGBC, 2002)	Yes	Yes	No
Comprehensive Assessment System for Building Environmental Efficiency (JSBC, 2006)	Yes	No	No
Building Research Establishment's Environmental Assessment Method (BRE Global Ltd., 2006)	Yes	Yes	No
Green Globes (ECD Jones Lang LaSalle, 2010)	Yes	Yes	No

As can be seen above, these rating systems ascribe to the line of thought that if a building is designed well, it will operate well – however, there are problems with this approach. At least one recent journal paper describes increases in actual energy consumption over that which was expected from the design, often due to inaccurate assumptions made during the design process or poor construction and choice of equipment (Bordass et al., 2001). Without feedback from actual measured performance, how can we be certain that buildings are performing according to their designs?

1.6 The need for whole building energy simulation

"It is widely accepted that explicit performance appraisal by simulation defines a best practice approach to building design", (Clarke, 2001)

The construction sector is currently the only industry in which it is common practice to supply a product without fully testing the final product (Bazjanac, 2005). In general, buildings are handed over after commissioning without any feedback from measured operational performance (Bordass et al., 2001). Imagine if this was the case, for example, in the automotive industry - automobiles would be designed, simulated and built as usual, but there would be no feedback to the designers whether or not the vehicle performed as expected. If real improvements in actual performance are to occur, this situation is clearly untenable. Any means of designing a high quality product depends on the feedback of measured operational performance to designers and accurate predictions of performance at the design stage. The latter point is especially the case for the buildings sector as each building is unique – the only way to test performance prior to construction is using simulation.

Whole building energy simulation is a useful tool in estimating energy consumption in buildings, both at the design and operational stages of the building life cycle. The technique is becoming more common due to a number of reasons:

- As part of building rating systems such as LEED (USGBC, 2002) and BREEAM (BRE Global Ltd., 2006) discussed in the previous section;
- As part of local building regulations such as California Title 24 (California Energy Commission, 2008) and ASHRAE 90.1 (ASHRAE, 2004a);
- As part of energy auditing procedures such as the International Performance Measurement & Verification Protocol (Efficiency Valuation Organisation, 2007);
- Due to the design complexity of the innovative buildings that are required to reduce energy consumption.

1.6.1 Issues with whole building energy simulation.

Despite the need for performance assessment using whole building energy simulation, there are issues related to currently available tools and techniques. A recent investigation of 121 buildings found that although whole building energy models may predict energy consumption well as a population (with a correlation between measured and simulated annual consumption of 0.92), the results for specific buildings vary widely: individual projects had correlations ranging from 0.25 to 2.5 (Newsham et al., 2009). There are other studies which highlight this issue. For example, Figure 1.4 shows the actual measured savings of LEED buildings as percentages of the minimum prescribed by ASHRAE 90.1 - 2004 compared to the design model predictions. These studies, and others (Norford et al., 1994; Scofield, 2002; Torcellini et al., 2004; Kunz et al., 2009; Diamond et al., 2006), highlight the fact that design model estimates are typically significantly different compared to real measured performance.

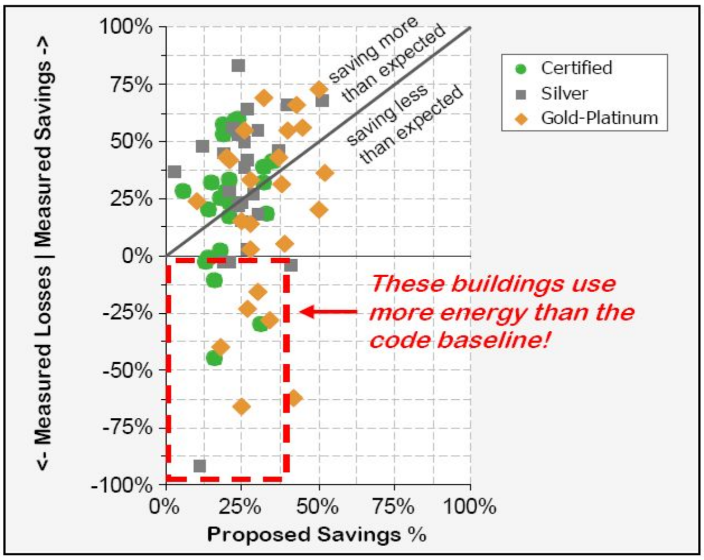

Figure 1.4: Measured vs. predicted energy performance of LEED - New Buildings (Turner and Frankel, 2008)

1.6.2 The need for calibration

Calibrated building energy simulation refers to reconciling the errors in the model to more closely represent the real building. The calibration process is key to improving energy efficiency at the operational stage of the BLC because once models are calibrated, they can be used:

- To analyse energy use in a building;
- To confirm an analysts knowledge of a building;
- To identify energy saving opportunities: Often, the very reason that it is difficult to calibrate the model is because there is something happening in the building that is not represented accurately by the input data (e.g., the Operation and Maintenance manuals (O&M), the as-built drawings, or the building operator's knowledge of the building is inaccurate) (Waltz, 1999);
- To analyse and provide support for investment grade Energy Conservation Measures (ECM);
- To provide a baseline for comparisons of ECMs that includes secondary effects (e.g. the model can estimate the reduced chiller loads or increased boiler loads associated with a lighting system retrofit).

- For Measurement and Verification (M&V) under a number of circumstances, described in M&V protocols (ASHRAE, 2002; Efficiency Valuation Organisation, 2007).

Aside from the operational stage benefits (above), from a research perspective, unless analysts investigate the measured performance of real buildings and compare this to their initial models or estimates, there is a lack of feedback in the model development process. Section 1.6.1 highlights issues with the prediction accuracy of whole building energy models. Without some sort of feedback, the accuracy of design stage models will not improve significantly. Thus, in a research context, the information gained during a calibration process is key, because it can be used to:

- Improve the accuracy of design stage models by supplying information regarding better modelling practices;
- Identify common assumptions made during the design stage that do not match real building operation;
- Identify gaps in knowledge and areas for further research;
- Further the development of simulation tools by identifying inaccuracies, bugs and missing capabilities.

1.7 Problem statement

Despite the need for calibrated simulation, there are issues with current methodologies. Chapter 2 describes a thorough literature review that identifies the properties of current calibrated simulation methodologies, summarised in Figure 1.5. Each of the reviewed methodologies contain at least one (and sometimes several) of the properties in this image.

Problem statement:

Current approaches to calibrated simulation are not explicitly evidence based and are insufficiently detailed.

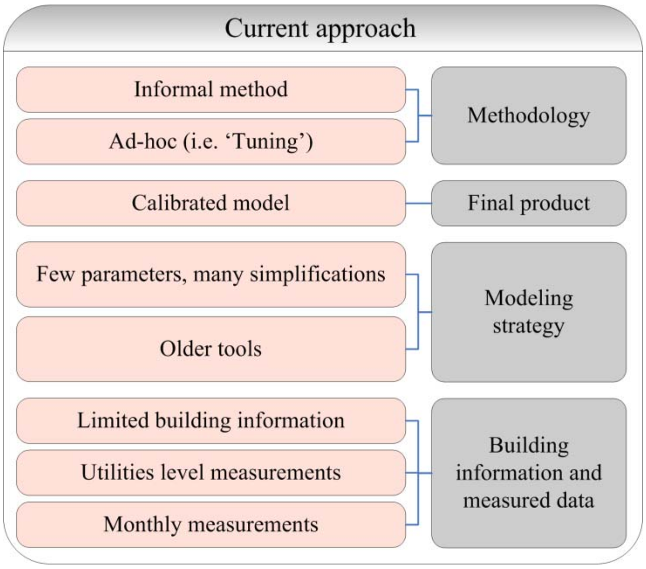

Figure 1.5: Properties of current approaches to calibrated simulation

1.8 Research question

How can a systematic, evidence-based approach and detailed measured data improve calibrated whole building energy simulation?

1.9 Overview of proposed solution

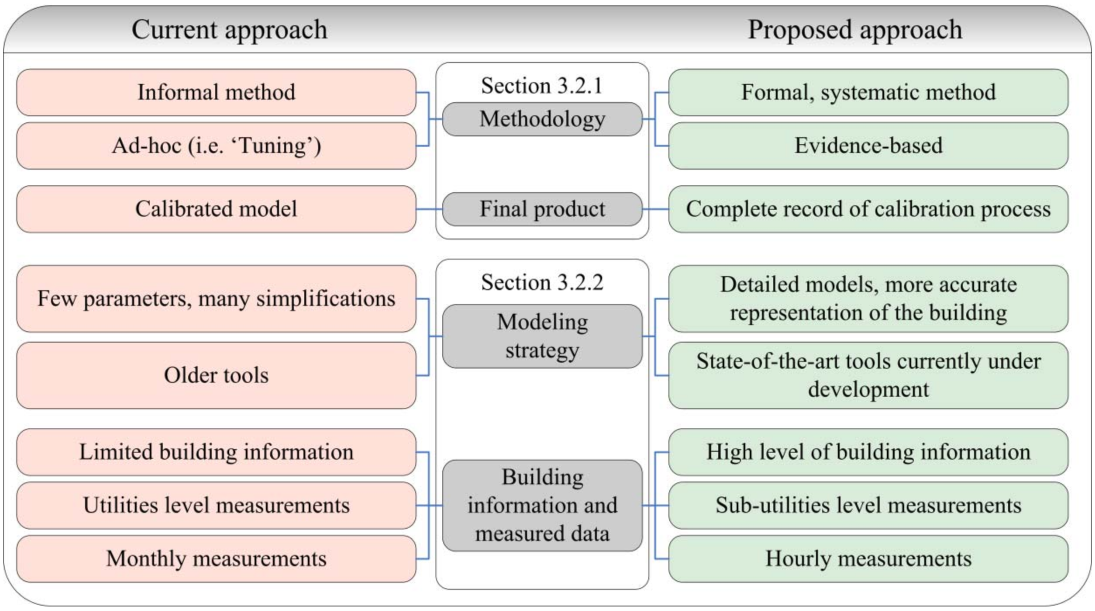

Figure 1.6: Contrasting the properties of current and proposed approaches to calibrated simulation.

This thesis proposes a novel, evidence-based approach described by the properties on the right hand side of Figure 1.6. Chapter 4 describes this methodology in detail.

1.10 Thesis structure

The remaining chapters of this thesis are as follows:

- Chapter 2 performs a detailed literature review of the existing research pertaining to calibrated whole building energy simulation;
- Chapter 3 defines the data and information requirements for calibrating whole building energy models and describes the selection of the demonstrator building from five case studies;
- Chapter 4 describes an evidence-based calibration methodology using version control techniques to store the 'history' of the whole process;
- Chapter 5 describes the application of the evidence-based methodology to the demonstrator building;
- Chapter 6 describes the results of the application of the evidence-based methodology to the demonstrator building.

Figure 1.7 illustrates the structure of this thesis and highlights the sections in which the key contributions to knowledge can be found.

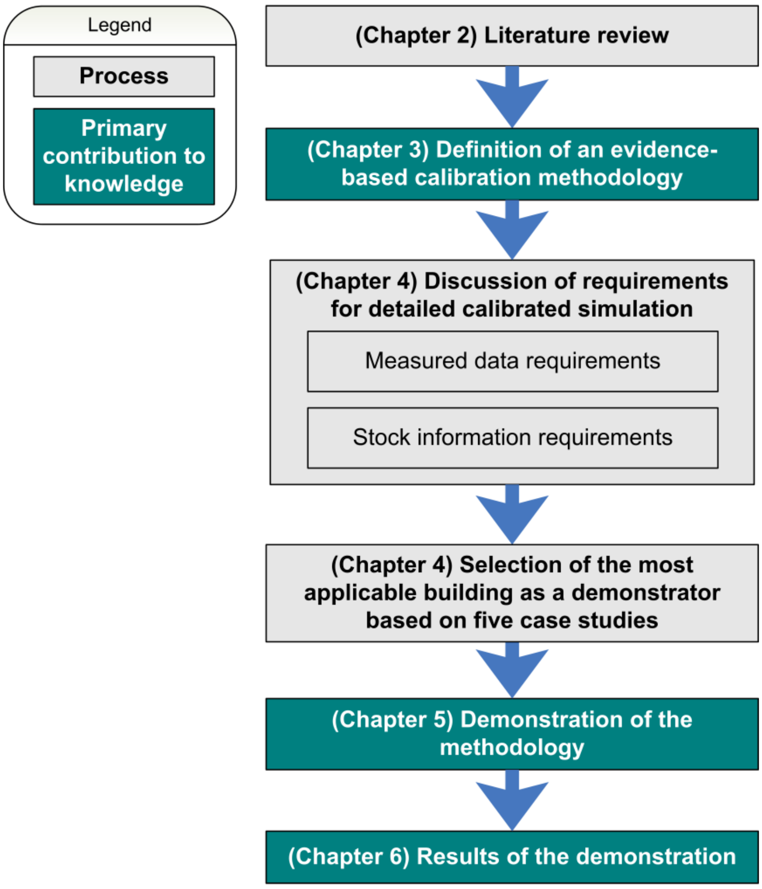

Figure 1.7: Thesis overview diagram

Chapter 2: Literature review

"Performance is more compelling than design awards"

- Michael G. Ivanovich

2.1 Chapter introduction

The primary aims of this chapter are to critically review existing research regarding:

- Building energy simulation tools;
- Methodologies for calibrating whole building energy models and case studies that incorporate calibrated models;
- Tools and techniques for visualising and analysing data relevant to building performance;
- Measurement and information in buildings;
- Environmental performance in buildings.

2.2 Building energy simulation tools

Building energy simulation tools are primarily used to assess the energy performance of buildings, either at the design or operational stages of the building life cycle. A key aspect of any building's function is its ability to maintain comfortable environmental conditions (see section 2.5) throughout the lifetime of the building. Thus, these simulation tools calculate the thermal conditions within the building, and the energy required to maintain these conditions, under the influence of a large number of external (such as weather) and internal parameters (such as occupancy profiles). The simulations typically run for a one year period: either a Typical Meteorological Year (TMY) for design studies or a historical weather-file for analysis during the operational phase of the building life cycle.

The requirements for building energy simulation tools are that they are fast enough for reasonable execution times on desktop computers, leading to many simplifications and assumptions within the software. A non-exhaustive list of examples are:

- One dimensional heat transfer is assumed at each surface;
- The thermal condition of a surface can be represented by a single node at the geometric centre of the surface;
- Zones are fully mixed and thus, properties of the zone can be represented by a single node;

- That a continuously operating building can be represented by a large number of discrete simulations separated by a fixed time-step (typically with intervals of an hour or less);
- Effects of real world control systems (e.g., PID control) are ignored, and control is assumed to be perfect.

Further information on simulation assumptions and simplifications can be found in software documentation (e.g., US DOE, 2009b) and in research (Maile, 2010).

Whole building energy simulation tools solve these simplified equations using forward finite difference methods. The conditions at a given node at the current time-step are calculated using current environmental and operational conditions and the previous state of the node. The simulation runs numerous times at each time-step until the solution reaches a specified convergence tolerance.

There are large differences between the various whole building energy simulation tools. These differences are discussed in a recent journal paper which contrasts the capabilities of currently available tools (Crawley et al., 2008). For example, older tools, such as DOE-2, simplify calculations by ignoring the conditions of the building when the HVAC systems are unable to meet the required heating and cooling loads, whereas more modern tools, such as EnergyPlus, do not.

EnergyPlus was selected as the primary tool for use in this research as it has been extensively validated (Henninger et al., 2004; US DOE, 2010a) and is the one of the most capable tools based on a extensive review (Crawley et al., 2008). The tool is used in a wide range of research in the field of the built environment (a non exhaustive list can be found in (US DOE, 2010b)). Furthermore, EnergyPlus is currently under active development. Thus, bugs can be fixed, missing capabilities can be added, and suggested improvements can be made to subsequent versions of the too.

However, EnergyPlus does not currently have a Graphical User Interface (GUI) that makes use of even a small proportion of the tool's capabilities. Currently available GUIs for EnergyPlus (e.g., DesignBuilder, 2010) focus almost entirely on geometry and constructions, with extremely limited ability to model the HVAC and plant aspects of a building. As the main aim of this research is to develop a detailed model of a real building, including the installed HVAC systems, it was essential to create an interface program that could utilise the capabilities of EnergyPlus more fully. This required a significant amount of programming effort, which yielded the EnergyPlus HVAC Generator software. This tool can be found in Appendix B.

2.3 Calibration of whole building energy models

2.3.1 Existing methods and case studies

Chapter 1 concludes by describing the need for calibrated whole building energy models by highlighting that large discrepancies between design model outputs and real measured energy consumption are common. However, there are issues with calibrated simulation today. A thorough literature review of calibrated whole building energy simulation case studies discussed these issues in detail (Reddy, 2006). All of the individual research papers identified by this literature review were reviewed by the author in order to gain an in depth knowledge of the current state-of-the-art in calibrated simulation. Several of the research papers in the existing literature review are discussed below to highlight key issues.

The sheer number of parameters involved in whole building energy modelling and a general lack of sufficient information about buildings yields a vast, under-determined parameter space. In other words, non-unique solutions may exist, even when simplifications are made to limit the number of parameters (Carroll and Hitchcock, 1993). Although there are standard criteria for determining when a model can be considered calibrated (ASHRAE, 2002; US DOE, 2008; Efficiency Valuation Organisation, 2007), these criteria focus on determining how well the model matches utility level annual data measured at monthly (or hourly) intervals and do not explicitly describe a method by which to calibrate a model. This lack of a formal methodology yields results that are “highly dependent on the personal judgment of the analyst doing the calibration” (Reddy, 2006). The methodology used is often not discussed in detail in many case studies. An approach in which the analyst tunes, or "fudges" (Troncoso, 1997), some of the myriad parameters until the model meets the acceptance criteria is commonly used. These ad-hoc, subjective approaches are not systematic and not explicitly evidence-based.

Aside from issues related to calibration methods, there is generally a lack of sufficient measured data in calibrated simulation studies. Most studies analyse model error using monthly utilities bills. However, monthly data analyses can easily miss significant errors at a daily or hourly resolution. Other studies combine monthly data analyses with further spot measurement over short periods on a daily (Yoon et al., 2003) or hourly (Soebarto, 1997; Pedrini et al., 2002) basis. Only one case study was found that analyses error using hourly data for a significant period of time (9 months) (Haberl and Bou-Sada, 1998).

Furthermore, many case studies do not describe the zoning strategy used in the model. There is a need to explicitly describe this as it can have a significant effect on the results. Typical zoning strategies use a core and four perimeter zone approach. This thesis discusses issues related to this approach and presents a new strategy that yields a more accurate representation of the building while stopping short of representing each thermal zone in the building by a zone in model (see section 3.3.3.1).

In addition to errors missed due to limited measured data, there can be significant inaccuracies in a model at a sub-utilities level. These inaccuracies can offset each other to yield results that match the measured data at a whole building level, but in reality, the model may be a poor representation of the actual building. Few studies report results for error analysis on a sub-utilities (or end-use) basis despite suggestions that this would aid significantly in improving simulation accuracy (Kaplan et al., 1990; Lunneberg, 1999).

Several case studies involving calibrated simulation were identified that are not included in the literature review (Reddy, 2006), all but one of these due to later publication dates.

Chimack et al. 2001 developed a DOE-2.1 model of a large, 101-year-old museum. The model was calibrated to measured monthly utility bill data using TMY weather data for the location. The calibration method is described briefly in an image, however changes to the model were not made on an evidence basis due to the age of the building and lack of sufficient building information. The final model had a Mean Bias Error (MBE) and Cumulative Variation of Root Mean Squared Error on a monthly basis ($CVRMSE_{(monthly)}$) of 5.7% and 14.6% for electricity consumption, and 2% and 15% for gas consumption respectively. These results almost meet industry acceptance criteria of 5% and 15% percent (ASHRAE, 2002) respectively.

Pan et al. 2007 developed a DOE-2 model of a large high-rise building in Shanghai using the core and 4 perimeter zoning strategy and calibrated it to monthly utility bill data. Hourly spot measurement over a 24-hour period was used to tune lighting and plug load schedules. The final model met FEMP (US DOE, 2008) acceptance criteria and was used to evaluate potential ECMs in the building. For example, the paper found that changing the water pumps from constant to variable speed would yield savings of 4.4% in annual electricity consumption.

Another case study (Iqbal and Al-Homoud, 2007) of a 6-storey office building in Saudi Arabia used a calibrated DOE-2 model to analyse various ECMs. The model was calibrated to monthly utility bill data without any further spot measurement by a method that is not discussed in detail. Various parameters were modified until the model met the acceptance criteria, for example, internal loads: "Schedules of people, lighting and equipment were adjusted and different infiltration rates were tried." The model was used to analyse eight ECMs and concluded that implementing these combined measures would reduce annual electrical energy consumption by 36%.

Eskin & Turkmen 2008 calibrated an EnergyPlus model of an office building in Istanbul to hourly cooling and heating load data measured during two three week periods during the summer and winter respectively. The calibration method is not described but the illustrated simulation results match the measured data quite well for the monitored periods. The model was then used to evaluate various low-energy design strategies for the same building across 4 climatic zones in Turkey. The results show that significant performance improvements can be obtained in Turkish office buildings using insulation on the inside of exterior walls, low-emissivity double-glazing, or light-coloured exterior paint.

Pereira & Ghisi 2009 simulated a naturally-ventilated house in Brazil using EnergyPlus. Indoor temperature was the primary focus of the model instead of energy consumption, and thus the model was calibrated to hourly temperature data measured during two one-week periods in the summer and winter. The calibration method employed explicitly describes the changes made at each stage of the calibration process. The mean and cumulative errors between the results of the final simulation and the measured data were both less than 0.5°C and 0.7°C respectively for each of the three zones in the model.

Tian & Love 2009 performed a case study of a novel radiant slab cooled building in Calgary by developing an EnergyPlus model and calibrating it to monthly energy consumption data. Spot measured indoor temperature data for a number of short periods was used to further verify the simulation outputs for zones conditioned by the radiant systems. The final model met FEMP acceptance criteria (US DOE, 2008). However, the calibration method was not described. The case study found the energy consumption of the building to be poorer than expected, especially when compared to a typical VAV system. The paper concludes with an analysis of three options for significantly improving the energy efficiency of the installed systems.

Aynur et al. 2009 took a novel approach to calibrating an EnergyPlus model in which a section of the building was modelled, instead of the entire building. The primary focus of this study was the power consumption of a Rooftop Unit (RTU) and the indoor temperatures for the zones which this RTU supplies. The model parameters were calibrated to information obtained from site surveys down to the individual zone component level. The simulated power consumption of the RTU was within ±15% of hourly measured data for 71.1% of the time during the cooling season. Simulated indoor temperatures were within 1.5°C of the measured data for 90.6% and 94.7% of the time for the 3rd and 4th floors respectively for the same period.

Rahman et al. 2010 developed a calibrated EnergyPlus model of a university campus building in Australia. The model was calibrated to monthly utility bill energy consumption additionally verified against indoor temperature, indoor humidity and total building electricity demand profiles for a typical winter and summer day. However, the methodology used to calibrate the model, or the zoning strategy used, were not described. The paper analyses various ECMs using the model and concludes that total savings of 41.87% are possible if all recommended changes were made.

Reddy et al. 2007a proposed a new method for calibrating whole building energy models to monthly measured data. An audit of the building is performed and a first-stage model of the building is created using input templates for the specific building and HVAC system type. A parametric optimisation analysis is then used to determine a number of calibrated models for the building. A measure of the uncertainty in the results is obtained by investigated ECMs using all of these proposed solutions. This methodology was then applied to two synthetic office buildings and one actual office building using monthly utilities level energy consumption data in a companion paper (Reddy et al., 2007b). The results showed that accurate conclusions can be drawn for ECMs that result in savings of more than 10% and that the method is robust enough to overcome the effects of noise in monthly utilities data.

Despite the numerous published case studies, there is still no widely accepted standard method of calibrating a simulation model. Many published studies do not explicitly describe the methods used to calibrate the model, or the zoning strategy used in the model. Based on the existing literature review (Reddy, 2006) and the other case studies to date, the current approach to calibrated simulation are at best based on an optimisation process used to identify multiple solutions within a parameter space that has been identified from a heuristic static knowledge-base of templates of influential parameters (Reddy et al., 2007a) and at worst based on an ad-hoc approach in which the analyst manually tunes the myriad parameters until a solution is obtained. The former approach is very useful in majority of cases in which only monthly utility bill data and limited resources for further measurement are available. It draws accurate conclusions for ECMs that yield savings of more than 10% of total energy consumption (Reddy et al., 2007b). However, it does not provide the analyst with a comparison between the measured and simulated building performance at a detailed level (e.g., energy consumption at a sub-utilities level). For example, when examining the performance of a HVAC system using an optimisation calibration technique and utility level measured data, parameters related to internal loads can overwhelm the results of the calibration effort. Thus, it is not an acceptable approach if the aim is to obtain detailed results to drive the development of simulation tools and best practice modelling techniques (as discussed in section 1.6.2). Furthermore, the approach uses heuristically defined templates of influential parameters based on building and HVAC system type. This is a significant simplification as all buildings are a unique combination of climate, location, geometry, constructions, overall function, and HVAC systems.

Each of the reviewed methodologies and case studies have at least one (and sometimes several) of the properties on the left of Figure 2.1.

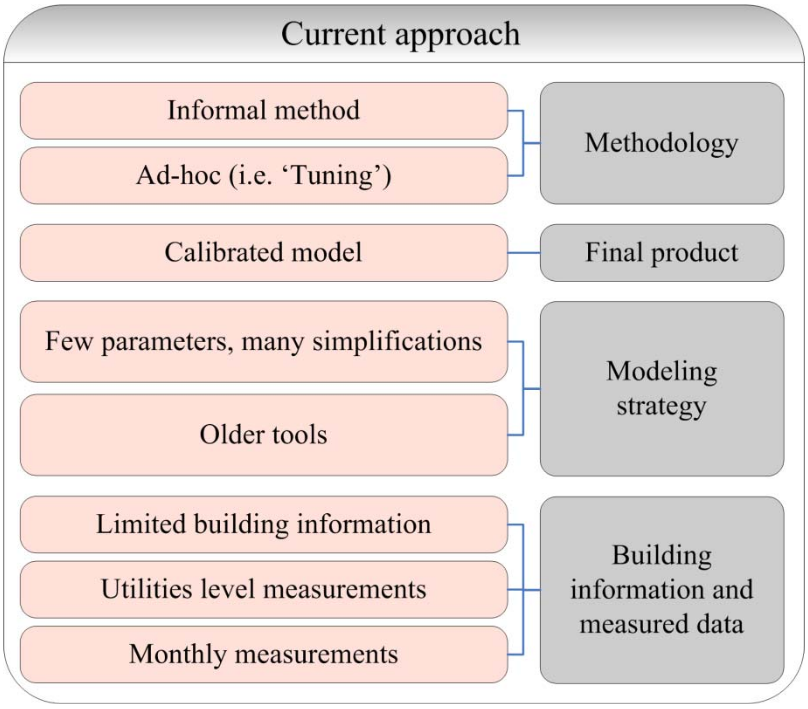

Figure 2.1: Properties of current approaches to calibrated simulation

This thesis presents a systematic, evidence-based approach to calibrated simulation in Chapter 3. This process yields a calibrated model that is based solely on referenced sources of information about the building. Although the process produces a single, deterministic model for an inherently stochastic process (building operation), such an approach can produce meaningful conclusions where sub-utilities hourly measured data, high levels of building information, and significant resources for further investigation and measurement are available.

The following sections of this chapter review published literature regarding data analysis techniques, measurement and information sources, and environmental performance requirements that are needed to underpin the calibration of building energy simulation models.

2.3.2 Data analysis techniques applicable to building performance data

2.3.2.1 Current acceptance criteria

It is essential to have clearly defined acceptance criteria in order to assess whether or not a model can be considered calibrated. To date, these criteria focus on analyses using utility level data, typically at monthly intervals.

Mean Bias Error (MBE) values describe how accurately the simulation model represents actual building consumption over a period. However, offsetting errors influence this calculation. In other words, MBEs do not capture effects where positive and negative errors cancel each other out. Hence, annual MBE remains the same regardless of data resolution (e.g., monthly, daily, hourly). Thus, an index that captures offsetting errors is necessary. This is the Cumulative Variation of Root Mean Squared Error (CV RMSE). This value will always increase (or remain equal to) with higher resolution calculations, because the higher resolution CVRMSEs will capture more offsetting errors. Thus, $CVRMSE_{month} \leq CVRMSE_{week} \leq CVRMSE_{day} \leq CVRMSE_{hour}$ for each case. Also, this value will always be greater than or equal to MBE. The formulae used to calculate these values are given below:

$$MBE = \frac{\sum_{i=1}^{N_p} (M_i - S_i)}{\sum_{i=1}^{N_p} (M_i)}$$

$$\overline{M_p} = \frac{\sum_{i=1}^{N_p} (M_i)}{N_p}$$

$$CVRMSE_{(p)} = \frac{\sqrt{\frac{\sum_{i=1}^{N_p} (M_i - S_i)^2}{N_p}}}{\overline{M_p}}$$

Where:

MBE = Mean Bias Error,

M_i = Measured data at instance i,

S_i = Simulated data at instance i,

P = Interval: monthly, weekly, daily & hourly,

$\overline{M_p}$ = Average of measured data,

$CVRMSE_p$ = Cumulative Variation of Root Mean Squared Error at interval p,

N_p = Number of data points at interval p. i.e., $N_{monthly}$ = 12, N_{hourly} = 8760,

Table 2.1 gives the currently available acceptance criteria for calibration to monthly and hourly measured data.

Table 2.1: Acceptance criteria for calibration to monthly and hourly data

	Monthly criteria		Hourly criteria	
Standard/Guideline	**MBE**	**$CVRMSE_{(monthly)}$**	**MBE**	**$CVRMSE_{(hourly)}$**
ASHRAE Guideline 14 (ASHRAE, 2002)	5%	15%	10%	30%
IPMVP[1] (US DOE, 2002)	20%	-	5%	20%
FEMP (US DOE, 2008)	5%	15%	10%	30%

2.3.2.2 Visualisation

Whole building energy simulation models and well-monitored buildings output significant amounts of data, typically at hourly intervals (or more frequently). This is 8,760 data-points per data-stream per annum. There are inherent difficulties in presenting this amount of data in a coherent and readily understandable manner. Fortunately, numerous visualization techniques can be applied, such as bar charts, time-series linear plots, and scatter plots. However, other key techniques have not been as widely adopted. This section highlights publications that describe these key techniques.

Several papers (Haberl et al., 1993; Bronson et al., 1992; Glaser and Ubbelohde, 2001; Haberl and Bou-Sada, 1998; McCray et al., 1995) describe the use of three-dimensional surface plots to visualize hourly annual energy consumption data. These surface plots are essential due to the sheer volume of information for display. However, peaks often obscure troughs in these images. This does not pose a significant problem in softcopy as users can often adjust viewing position using the visualization software. However, this is not possible in hardcopy. Surface plots using colour as the third dimension ('carpet' plots) provide a useful solution. Examples include (Baumann, 2004; Masoero et al., 2010).

Box-whisker-mean (BWM) plots are also a useful tool for providing statistical summaries of aggregate data beyond simple average values (Haberl and Abbas, 1998a). These plots efficiently present eight numbers per aggregate data point: 10^{th}, 25^{th}, 75^{th}, 90^{th} quartiles; maximum and minimum (or alternatively, outlier data points); median; and mean. BWM plots were combined with bin analysis in time of day and outdoor dry-bulb temperature bins (for all days, weekdays, and weekends) in the second part of this paper (Haberl and Abbas, 1998b).

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[1] These are suggested ranges rather than firmly defined criteria (US DOE 2002, pg 34). Furthermore, the later version of the protocol (Efficiency Valuation Organisation, 2007) does not state any acceptance criteria and instead references ASHRAE Guideline 14-2002.

2.4 Information sources relevant to calibrated simulation

2.4.1 Energy Monitoring Systems (EMS)

An Energy Monitoring System (EMS) is distinct from an Energy Management System, Energy Management Control System (EMCS), Building Automation System (BAS) and Building Management System (BMS) in that actuators are not part of this system. In the context of this thesis, an EMS is solely for *monitoring* building energy use (sub-metering), not for directly controlling systems in the building. Of course, EMCSs, BASs and BMSs often monitor energy usage and thus, this term applies to the monitoring aspects of these systems.

An EMS is a network of measurement devices that monitor energy use within a building. This network consists primarily of three phase electrical power meters attached to electrical panels and motor control centers (MCC) throughout the building. EMSs give higher resolution data about electrical energy use within a building (usually at 15-minute intervals) than can be obtained from utility bills. Such systems are essential if building energy performance is to be measured. There have been several case studies that quantify savings of between 5 - 15% associated with the ECMs identified using the data acquired after an EMS installation (Amundsen, 2000; Jones, 2006; Knight, 1995; Hirschfield et al., 2001; APPA, 2002; WBCSD, 2008).

Unfortunately, although many building stakeholders will state that their building has an EMS, there is no standard definition of what an EMS is, or what it consists of, and here-in lies the problem. EMSs are often installed in a piecemeal which drastically reduces their usefulness. Also, even in buildings where an EMS is part of the initial design, meters are often sub-optimally located – one meter may often monitor a variety of different loads, such as lighting loads, general plug loads, and HVAC loads. This impedes a user's ability to immediately identify the cause of an unexpected change in measured consumption (Raftery et al., 2009) and decreases the usefulness of the measured data, as further spot measurement is required to identify specific loads.

Another issue is that EMSs generally only monitor electrical consumption in buildings. Other sources of energy consumption, such as district heating and cooling supplies, gas, oil and solar thermal, are not included under the scope of the system. This seriously impedes a user's ability to monitor energy performance in the building, as significant energy consumption measurements are missing.

A final barrier arises from the fact that EMSs are costly and many owners consider the required investment prohibitive. Often, measurement devices are the first items to become 'value-engineered' out of a project that goes over-budget. The result of this is that buildings are constructed without sufficient measurement in place. However, costs are dropping, and will do so more rapidly in the future. Currently, up to 70% of the cost of an EMS is related to wiring (Jang et al., 2008), but with the advent of wireless sensor technologies, such as those being developed by the BuildWise project (BuildWise, 2007), this cost will dissipate. In fact, recent reviews of the current state of wireless technologies state that industry is already at a point where wireless sensors are becoming a cost-effective alternative in building control applications (Roth et al., 2008). Also, the cost of three phase electrical metering devices, a major component of any EMS, is also decreasing as new technologies and designs are produced (Sarkar and Sengupta, 2008).

Raftery et al. 2010 performed five EMS case studies and describes issues related to EMSs in more detail. The paper concludes with recommendations for avoiding these issues and references papers that include EMS design specifications (Gillespie et al., 2007; Jones, 2006).

2.4.2 Building Information Modelling (BIM) technology

A Building Information Model (BIM) is a central repository for all stock information related to a building. A complete model contains detailed information about the three-dimensional geometry of the building, the types and properties of the construction materials used and the electrical and mechanical systems and components installed. BIM supports interoperability between tools and serves as a means of storage for information about buildings that is usually lost between the design and operation phases of the BLC.

The most comprehensive BIM language to date is version 2x4 of the Industry Foundation Classes (IFC) (International Alliance for Interoperability, 2008). As opposed to other competing technologies, this language is open source, freely extensible, and is the only BIM technology that is currently an ISO standard (ISO, 2005a).

IFC based BIM technology supports interoperability as tools can now use the same model to exchange information related to their field, without the need for cumbersome third-party translating software. In fact, one of the main driving factors behind the continuing development of IFC is the cost of inadequate interoperability in the building industry, recently estimated to be almost $15.8 billion in the US in 2002 (Gallagher et al., 2004). This is due to a large number of factors, such as the time spent unnecessarily reproducing a building model in different programs (e.g., as is the case when developing a simulation model) and the cost of information lost between the design and operation phases.

Although BIM technology has been available for a number of years it has yet to reach a stage where it is the standard used worldwide (Ó Gallachóir et al., 2007). Although 48% of architect's offices in the US now use some sort of BIM technology there has not been a similar uptake among engineering firms (Schlueter and Thesseling, 2009). This is compounded by the fact that there is a general lack of tools that write and utilise BIM information in the HVAC and electrical domains - the majority of BIMs are currently geometry only. Only one tool was found that addressed all the aspects of a building in at least a basic manner – this was DDS-CAD (Data Design System, 2010), developed in Norway, where all newly constructed federal buildings require an IFC based BIM. Other tools, such as ArchiCAD 12 (Graphisoft, 2009), are focused primarily on architectural and structural details and though it can export high quality IFC BIMs, this is not the native format used in by the software.

In the context of this research, an IFC based BIM will serve as the source of stock information about the building related to geometry, constructions and material properties. IFC was chosen as the BIM language as it is non-proprietary, fully interoperable and extendable.

2.5 Environmental performance

It is clear that improvements in energy efficiency must not come at the expense of a reduced capacity of the building to fulfil its intended function. Unfortunately, this has occurred before. Following the oil embargo of 1973, the cost of energy drove developers and retrofitters to reduce the amount of ventilation in buildings. This caused large numbers of illnesses collectively known as Sick Building Syndrome (WHO, 1983). Occurrences such as this clearly illustrate the need to ensure that environmental performance criteria are met when improving building efficiency. A review of the science behind the thermal comfort and indoor air quality measurement was performed, along with modern standards and regulations related to these areas. The purpose of this section is to identify and understand the environmental performance requirements that drive energy use in buildings.

2.5.1 Thermal comfort

Most of the current methods of measurement are based on the work of Fanger who developed the predictive mean vote (pmv) and percentage people dissatisfied (ppd) method based on the experimental study of people's thermal comfort in environmental chambers. He developed equations to predict the comfort of occupants depending on parameters such as temperature, humidity, clothing level, metabolic rate and air speed (Fanger, 1970). This, and previous work, led to a large amount of further research that yielded the understanding of human thermal comfort that we have today. This understanding was crucial to the development of ranges of acceptable values in standards addressing thermal comfort. Such standards are ASHRAE 55 (ASHRAE, 2004b) and ISO 7730 (ISO, 2005b) in the USA States and the EU respectively. Both prescribe similar ranges of comfort criteria. The majority of buildings are designed to maintain an indoor temperature and humidity that will result in a comfortable indoor environment for occupied zones based on the Fanger equations. These measurements are some of the most widespread in buildings, as they are a key variable to control in order to maintain comfort criteria.

2.5.2 Internal Air Quality (IAQ)

The quality of indoor air is primarily dependent on two parameters, the fresh air rate supplied and the amount of pollutants. These pollutants can be from a number of sources, such as carbon dioxide released during respiration and volatile organic compounds (VOCs) released by paints and plastics (WHO, 1989). There are standards that govern the ventilation (fresh outdoor air) rates for buildings based on occupancy and floor area. These are ASHRAE 62 (ASHRAE, 2004b) and ISO 15251 (ISO, 2007) in the USA and the EU respectively. Both prescribe ventilation levels per person or per floor area, but vary widely in the suggested values and calculations – the EU standard recommends far higher ventilation rates.

The majority of buildings are designed to maintain a ventilation rate that results in a comfortable and healthy indoor environment. Unfortunately, once the building has been commissioned, few systems, excluding demand control ventilation (Sand, 2004), have measurement systems in place that monitor indoor air quality in even a partial manner.

2.5.3 Visual comfort

The efficient use of day-lighting is a key issue in buildings as it can yield significant improvements in energy performance and worker productivity. However, it is essential to maintain visual comfort and avoid issues in which glare affects the occupants. Numerous studies have shown significant energy savings and improvements to productivity (Abdou, 1997; Zain-Ahmed et al., 2002; Li et al., 2006; Li and Tsang, 2008; Ihm et al., 2009; Hua et al., 2011). Although there is no widely used standard that explicitly deals with day-lighting, some standards address the day-lighting and visual comfort issue as part of an overall strategy for the design of high performance buildings (ASHRAE, 2009).

2.6 Conclusion

Figure 2.1 gives a synopsis of the primary findings of the literature review presented in this chapter. The essential findings are that the majority of current calibration methodologies lack a formal evidence-based approach, use simplified modelling strategies, and lack sufficient building information and measured data. The following chapter describes a novel evidence-based approach that improves upon current approaches to calibrated building energy simulation.

Chapter 3: Methodology

"Engineers ... are not superhuman. They make mistakes in their assumptions, in their calculations, in their conclusions. That they make mistakes is forgivable; that they catch them is imperative. Thus it is the essence of modern engineering not only to be able to check one's own work but also to have one's work checked and to be able to check the work of others."
- Henry Petroski

3.1 Chapter introduction

This chapter describes a novel methodology for calibrating whole building energy models. This methodology addresses issues identified in the literature review by ensuring that the calibration process is entirely evidence-based. The chapter also presents a new zoning strategy that yields a more accurate description of the building than the typical core and four perimeter zone approach.

3.2 Concepts behind the methodology

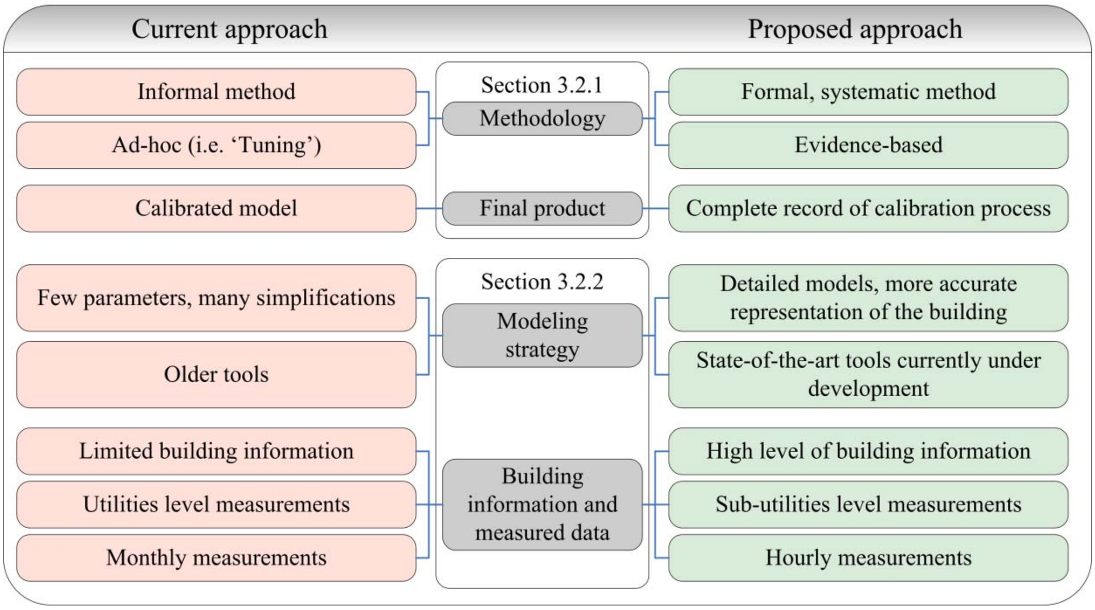


Figure 3.1: Contrasting the properties of current and proposed approaches to calibrated simulation.

Chapter 2 describes the numerous high-quality published papers to date that discuss calibrated simulation methods and case studies. However, each of these have at least one (and sometimes several) of the properties on the left of Figure 3.1. The methodology proposed in this chapter builds on the techniques in the reviewed literature and combines these with an evidence-based approach using version control techniques.

The proposed methodology describes a new approach that uses evidence-based decision making to improve the reproducibility and reliability of the calibration process, and uses detailed models to more accurately represent the operation of the actual building. The underpinning concepts behind this methodology are described in more detail below.

3.2.1 Evidence-based calibration

It is necessary to bring the principle of *evidence based decision-making* to the calibration process. To improve the reliability of calibrated models, changes to the input parameters should only be made according to available evidence in a clearly defined hierarchy of priorities. For example, information obtained by measurement is assumed to be a more reliable source of evidence than as-built documentation. Thus, a hierarchy of sources (hereafter referred to as *source hierarchy*) must be defined for each project. The order of the sources in the *source hierarchy* is indicative of the (assumed) reliability of the source of evidence. Changes should not be made unless the evidence comes from a more reliable source in the *source hierarchy*. Though the quality and availability of data and information sources will vary on a project by project basis, section 3.3.1.4 gives an example list of categories of evidence for the *source hierarchy*, and section 5.2.4.4 describes the *source hierarchy* for the demonstrator building.
In order to improve the reproducibility of the calibration process it is necessary to keep a history of the decisions made along with the evidence on which these decisions were based. The entire process should be available for review by future users of the calibrated model. This can be accomplished using version control techniques. Version control software issues a new version of the model whenever a modification is made and automatically stores all previous versions in a repository, allowing any user to review the calibration process at a later date. A description of the change is also stored with each successive version in a change log *along with the evidence on which the change was based.* This ensures that changes are not made on an ad-hoc basis and that the supporting evidence will be available to multiple analysts and future users. Version control techniques also serve to organise an analyst's approach to the calibration process. In addition, version control software can automatically and reliably identify changes between revisions or revert to a previous revision if there is an unexpected problem with the new model.

To follow through with the principles of the scientific method, published research should include a direct reference to the simulation model used for the research. For calibrated simulation case studies, access to the history of the calibration process via the version control techniques should also be included. This ensures that it can be a learning experience for all involved (both the author(s) and the readers) as it closes a feedback loop, ensuring that other researchers can reproduce or continue the work of the author(s). If errors are identified in the model, this can only be advantageous to the author(s). Also, an often ignored issue is that it is a valuable contribution to knowledge if it was not possible to calibrate the model due to a lack of information or software limitations. Without publishing these type of case studies, these limitations may never be addressed by the software developers.

3.2.2 Detailed models

Simulation tools represent continuous, stochastic processes in buildings by discrete time-step, deterministic model estimations. All simulation models make assumptions when representing real buildings. When using detailed high-resolution measured data (i.e., hourly, sub-utilities), it is essential to use detailed models that represent the building as closely as possible. Simplifications and approximations should be avoided where possible. For example, cancelling errors caused by aggregate zoning strategies should be minimised. The zone-typing method described later in this chapter provides a means of reducing these errors. Detailed models more closely represent the operation of the real building and allow ECMs to be investigated at finer resolution, using fewer assumptions. For example, an ECM that only affects a specific zone or group of zones (e.g. comms rooms, or conference rooms) can be evaluated quickly and easily in a detailed model without many of the assumptions that would be necessary when using a model with a core and 4 perimeter zoning strategy. Chapter 6 includes an example of using detailed models to investigate ECMs.
Furthermore, in order to represent the operation of the building as accurately as possible, the simulation tool that is currently most capable of simulating the building and HVAC systems should be chosen. In other words, the more capable, advanced, and well-documented simulation tools, such as EnergyPlus (US DOE, 2010c) or Esp-r (Energy Systems Research Unit, 2010), should be used to create the model intended for calibration. Also, to ensure that feedback from the research can be used to further improve upon the tool (proposed example discussed in section 6.5.3), a simulation tool actively under development should be chosen.

3.3 Calibration methodology

Figure 3.2 illustrates the methodology for calibrating a simulation model to measured data under the implementation of the evidence-based method discussed above.

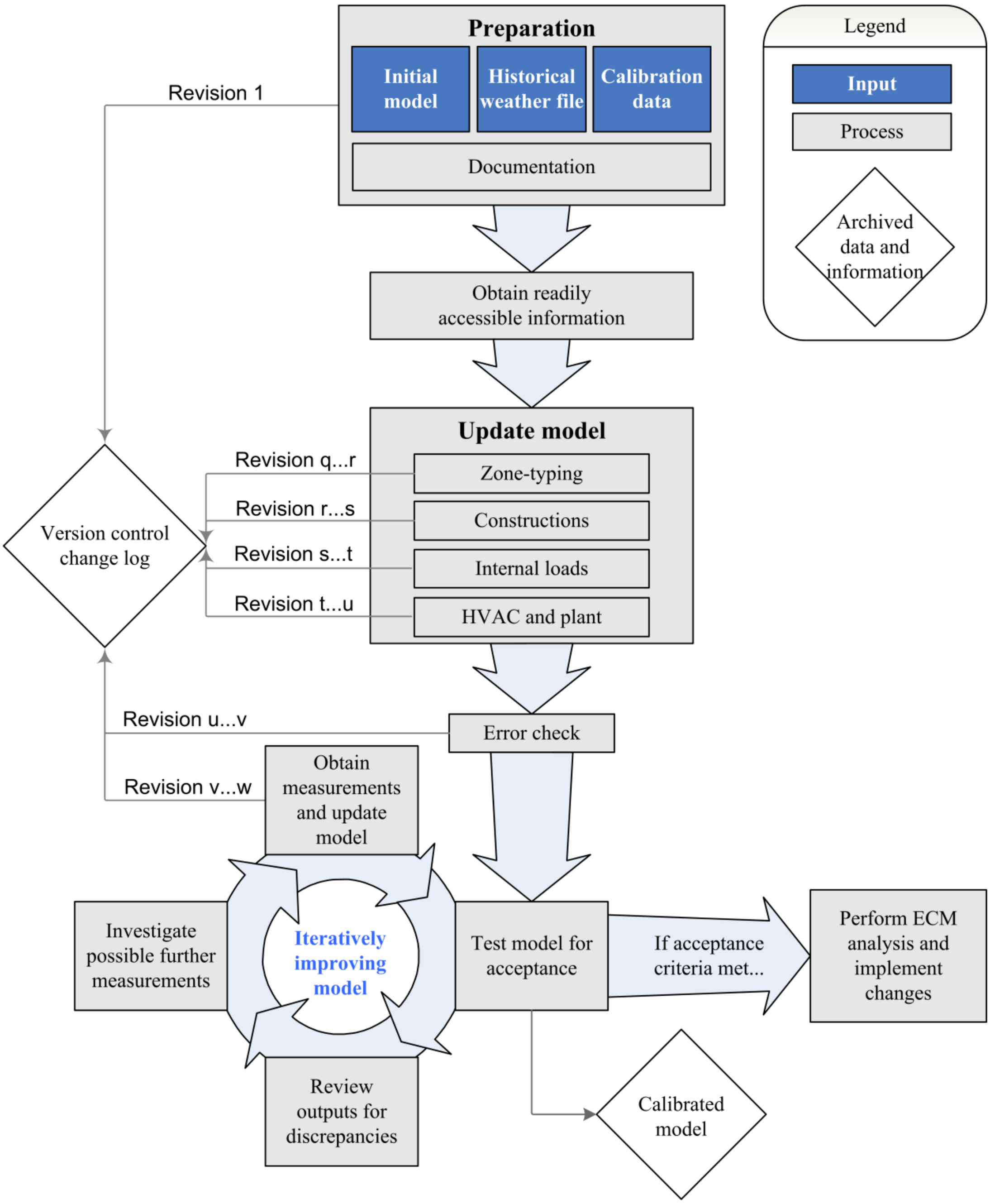


Figure 3.2: Flow chart of the calibration methodology

3.3.1 Preparation

The first step is to set up the version control software to track the revision history of the calibration project. Virtually any version control software can be used, however, there are several essential capabilities:

- Maintain a change log or revision history of the entire project;
- Force users to make an entry to the change log with each revision;
- Prohibit retro-active changes to revisions;
- No limitations on file sizes or file types;
- No limitation on total project size;
- Allow nested folders (to facilitate evidence storage);
- Remote access (to allow multiple analysts to work on the same project).

Once the version control software has been installed, this preparation stage becomes the first model revision. The first revision includes: the initial model; the historical weather file used for the simulation period; the measured energy consumption data for the building used to test the model for acceptance; and documentation templates.

3.3.1.1 Initial model

This methodology assumes that an initial whole building energy model was created at the design stage and is available as a starting point for the calibration process. However, the quality and complexity of this model may not match with detailed model requirements, and significant portions of this model, particularly those related to zoning strategy, may need to be recreated according to the zone-typing method described later in this chapter.

Whole building energy simulation is becoming more common with the increasing focus on energy efficient building design, and modelling requirements such as those driven by the LEED rating system (USGBC, 2002) and California Title 24 (California Energy Commission, 2008). However, it is common that no initial model is available. In this case, one can be created according to design information, standards and best-practice models (US DOE, 2010e).

3.3.1.2 Historical weather data

It is absolutely essential to use historical weather data when running the model in order to assess whether or not it is calibrated to the acceptance criteria. Weather data should include all of the necessary variables to create the weather-file and should be measured at the building itself where possible. However, in many cases this data is not available and other sources, such as national meteorological services and environmental agencies, local universities and research laboratories, must be pursued.

3.3.1.3 Calibration data

The calibration data used to evaluate whether the model meets the acceptance criteria should be collected and stored in the preparation stage. For the majority of guidelines and standards available at the time of writing, this data is monthly energy consumption. However, for research applications, it is preferable that more detailed measured data are used which focus on hourly, sub-utilities level measured data.

3.3.1.4 Documentation

In this section, the analyst defines which criteria to use in order to determine when the model is considered calibrated. These are the *acceptance criteria*. At the time of writing there are three standards or guidelines that apply: the IMPVP, FEMP and ASHRAE Guideline 14. The methodology outlined in this chapter applies regardless of the level of complexity of the chosen *acceptance criteria*.

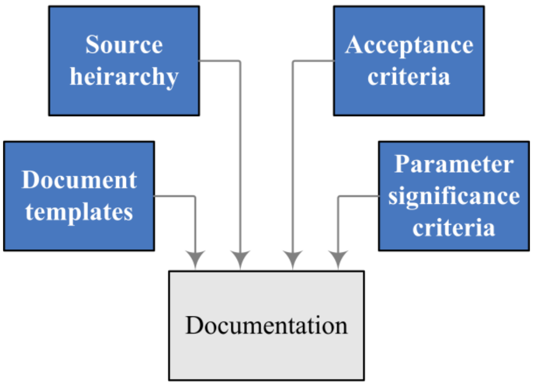


Figure 3.3: Necessary inputs for the documentation stage

Following this step, it is necessary to explicitly define the overall *source hierarchy* that will be used in order to maintain continuity throughout the calibration process. For example, sources based on direct observation should be the first priority, followed by data obtained from benchmark studies, then standards, and finally, information from the initial model. More recent peer-reviewed studies and standards supersede older ones. Changes to the model should not be made unless the evidence comes from a more reliable source in the *source hierarchy*. The list below describes the recommended categories for the *source hierarchy*:

- Data-logged measurements;
- Spot measurement (for relatively constant loads);
- Direct observation (site surveys);
- Operator and personnel interviews;
- Material data-sheets
- Operations & Maintenance (O&M);
- As-built documentation;
- Benchmark studies and best practice guides;
- Standards, specifications and guidelines;
- Information from the initial model.

Finally, it is necessary to explicitly define *significance criteria* for determining what is or what is not a significant effect within the iterative process discussed later in this chapter.

These criteria and the *source hierarchy* should be clearly outlined, and referenced where appropriate, in a simple an easy to understand format.

3.3.2 Obtain readily accessible data and information

At this stage of the process, the analyst(s) should obtain all readily accessible data and information about the building. A recommended, but by no means exhaustive, list of sources is given below:

- A Building Information Model (BIM);
- As-built drawings;
- Operation and Maintenance (O&M) manuals;
- Energy Monitoring Systems (EMS);
- Building Monitoring Systems (BMS);
- Surveys and interviews.

The availability of a high-quality BIM drastically reduces the time needed to create a simulation model as it inherently contains a large amount of the required information. In fact, the creation of models can become a semi-automated process through the use of translation middle-ware *if* building information is readily available and is organised in a systematic fashion. For example, IFC based BIMs can store all the geometry, construction, HVAC and electrical information needed to create a simulation model and are an invaluable resource to the analyst. Section 5.2.4.1 includes an example of the partially automated creation of an energy model using a BIM using a tool recently developed at the Lawrence Berkeley National Laboratory (Maile et al., 2007). Furthermore, recent developments have focused on including linking measured data from sensors to building information (Hitchcock, 2003; O'Donnell, 2009; Gokce et al., 2009). In the future, this will facilitate partially automated calibration of simulation models.

In the author's experience it is imperative that any information obtained from a document, such as 'as-built' drawings, should be verified by visible inspection and that *physical surveys* of the building are the most reliable and useful source of information. A detailed survey at the zone level is required to verify and identify such inputs as geometry, constructions and air supply methods. On a systems and plant level a physical survey and building operator interviews are needed to verify such inputs as nameplate manufacturer data, O&M information, control and operating schedules. Surveys during the night and other unoccupied periods can be an important source of information and are a highly recommended practice, as they can identify unexpected equipment operation.

3.3.3 Update model inputs

At this stage, the analyst updates the model based on the information that has been gathered to date. A key point to note here is that every time a change is made to the model, it is essential that a new version is created. The previous version, a brief description of the change made and the evidence on which it was based must be archived in the version control repository.

3.3.3.1 Zone-typing

It should now be possible to update the model external geometry to reflect changes to the building since the initial model was created, using the information obtained in the previous section. It is essential that the model geometry is verified by a physical survey of the building performed by the analyst.

However, a new approach is required for the process of defining the internal thermal zones within the building. The most common method for defining thermal zones for a simulation model follows a 5 zone per occupied floor approach – one core zone and 4 perimeter zones. This approach can be seen in benchmark and best practice models (US DOE, 2010e) as well as many published calibrated simulation case studies in which the zoning strategy used is described, e.g., (Pan et al., 2007; Tian and Love, 2009). Although it can be appropriate for buildings with small floor plans, it simplifies the model and moves away from accurately representing the actual thermal zones in the building. Agglomerating multiple actual thermal zones in the building into one large thermal zone in the model results in a less accurate representation of the building for several reasons:

- It does not accurately represent situations where opposing cooling and heating loads in individual zones counter-balance each other. This is a common occurrence in large office buildings, where unoccupied conference rooms are in heating mode to maintain zone temperatures while supplying minimum ventilation flow rates, and the remainder of the office space is in cooling mode to remove internal loads. If these two thermal zones are represented by one zone in the model, these effects are not captured.
- It does not allow for accurate representation of different occupancy profiles or internal loads (e.g., conference rooms, communications rooms), and different methods of conditioning (e.g., constant volume with exhaust for toilets, and VAV for open office space).
- It yields a simplified floor plan, which is not acceptable for buildings with large floor plans. A more detailed floor plan allows ECMs to be investigated at higher resolutions and with fewer assumptions.

Based on the above, it is clear that a detailed approach which more closely represents the operation of the real building is required, particularly for buildings with a large floor plan. The approach described in this thesis is known as zone-typing. Its objective is to separate thermal zones in such a way as to minimise the inaccuracies incurred by representing multiple actual thermal zones in a building with a single large zone in the model. Zone-typing is the process of deciding on the various types of thermal zones used in a model based on four major criteria: the function of the space, its position relative to the exterior, the measured data that is available, and the method used to condition the zone. These criteria capture the major differences between the thermal processes occurring in each zone, and defines how they appear in the model. Figure 3.4 describes these criteria and the reasoning behind their inclusion. There are guidelines (ASHRAE, 2004a; California Energy Commission, 2008) that define types of zones in buildings by space function. These serve as a useful starting point for identifying space functions and developing zone-types in the model. However, the zone-typing process is intended to be flexible, as each building is unique and must be analysed on a case-by-case basis.

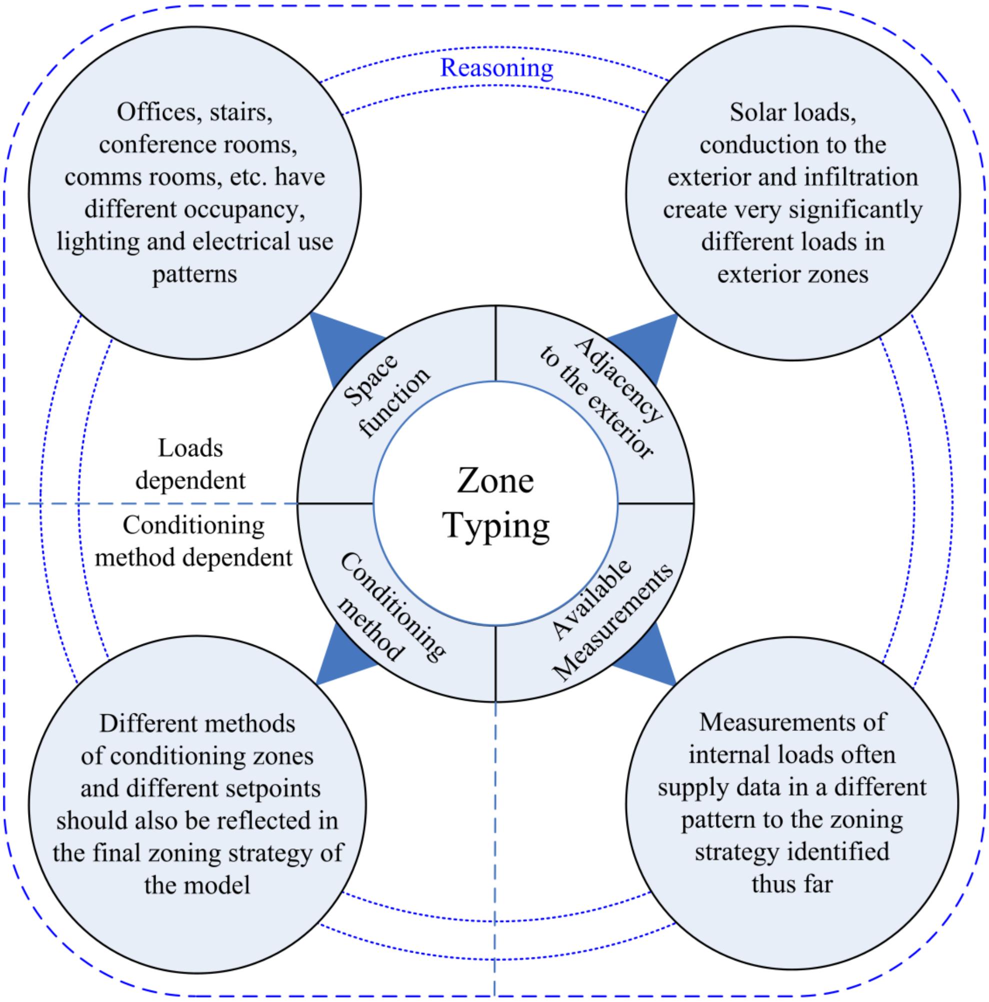


Figure 3.4: Zone-typing

Once the zone-types have been defined, these are applied to the model floor plan accordingly along with zone-type specific parameters, such as occupancy schedules, lighting loads, and conditioning methods. Actual thermal zones in the building may be agglomerated into a single thermal zone in the model if the following criteria are met:

- They are of the same zone-type;
- There is a significant inter-zone surface area with respect to total surface area of both zones;
- The resulting agglomerated zone would not be excessively large in any given dimension;
- The resulting agglomerated zone would not have an excessively large floor area.

The values used for the criteria above should be stored in the version control repository. This zone-typing process yields a more detailed floor plan than the traditional core-and-four-perimeter approach. Although the results of this method may not represent each individual thermal zone in the building by a thermal zone in the model, zones are only agglomerated when the inaccuracies incurred are minimal. Appendix A contains a detailed description of the zone-typing process as applied to the demonstrator building.

3.3.3.2 Constructions

The constructions used for all the surfaces in the model should be verified from commissioning as-built drawings or from a site survey. The source from which the material thermal properties were obtained should be clearly indicated *within the input file* for the simulation program. A complete list of sources should be included in the version control repository.

3.3.3.3 HVAC and Plant

System and plant information should be updated based on the readily available information obtained previously. All equipment characteristics should be verified by commissioning documentation, direct observation or measurement whenever possible. A non-exhaustive list of examples includes:

- Fans: Type, maximum airflow, pressure, operating efficiency, part load curve;
- Coils: Type, heating/cooling capacity, air/water on/off design temperatures, maximum air/water flow-rates, operating set-point(s);
- Motors: Type, maximum power, operating efficiency;
- Pumps: Type, maximum flow rate and head, part load curve, operating set-point(s);

- Boilers: Type, capacity, thermal efficiency, water flow rate and temperature, parasitic electrical consumption, part load curve, operating set-point(s);
- Chillers: Type, capacity, nominal coefficient of performance, design fluid temperature and flow rate conditions, capacity ratio curve, part load curve, operating set-point(s);
- Cooling towers: Type, capacity, fan power, design fluid temperature and flow rate conditions, part load curve (for variable speed cooling towers), operating set-point(s);

Special attention should be paid to ensure that equipment part load curves used in the simulation model are realistic and fully referenced, as this can have a major impact on simulated energy consumption.

It is also essential to update the characteristics of the equipment that conditions the building on a zone-by-zone basis. For example, equipment type (constant volume air supply, VAV box with reheat coil, baseboard heater, extract/exhaust fan, radiant slab, etc.), ventilation requirements, maximum and minimum air flow rates, nominal heating and cooling capacities, power consumption and operating set-point(s).

3.3.3.4 Internal Loads

At this stage, the internal loads should be updated. To ensure that this methodology can be applied to any calibration effort, this can be done in many ways. The most common approach, where only monthly utility bill data is available, is to estimate lighting, plug and occupant loads based on site surveys and spot measurements. However, this yields a model in which errors in HVAC parameters can be overwhelmed by errors in internal load parameters, as the current acceptance criteria for calibrated simulation focus only on whole building energy consumption. This drastically reduces the accuracy of the final calibrated model when it is used for estimating savings related to HVAC equipment, or for estimating savings due to a lighting retrofit, as each of these components are not individually assessed with acceptance criteria.

For research applications, and in the future for many new buildings, it should be possible to use real measured data from an EMS to accurately input the lighting and plug loads into the simulation model. This can be done in two ways: using a schedule in the model that contains the measured consumption data on a time-step basis for the complete year of simulation; or analyzing and categorizing the data into day-types using a day-typing analysis (Kaplan et al., 1990; Abushakra et al., 2001).

Unfortunately, it is very rare to have detailed measured data for occupancy, with some notable exceptions. For example, CO_2 sensor data for demand control ventilation (DCV) systems and meeting scheduling databases for conference rooms. There have also been several advancements in occupant tracking based on logging network access location with logon details or using RFID tags such as the Active Badge system (AT&T Laboratories Cambridge, 2002). However, such systems still have some significant hurdles to overcome in order to avoid an Orwellian working environment. Currently, detailed occupancy data will not be available in the vast majority of cases and occupancy schedules must be generated based on site surveys, benchmark studies, and Human Resources (HR) interviews. Also, it is rare to have detailed measured data for infiltration rates for large buildings. Thus, these values must be determined based on benchmark and best practice models, or from standards.

3.3.4 Error check

At this stage of the process, the analyst should run the current revision of the model and thoroughly review it to ensure that the information obtained to date has been modelled correctly and that the outputs are reasonable. Whole building energy simulation tools are extremely susceptible to the principle of Garbage In, Garbage Out (GIGO) and thus, the outputs cannot be blindly trusted without a thorough review. Evaluating the quality of the simulation results obtained is an essential process in whole building energy modelling, and analysts who are experienced with these tools typically develop a healthy scepticism in results. This step will continue to depend on the judgement of the analyst until detailed, explicit and robust acceptance criteria are developed. For example, future acceptance criteria could be based on an end-use matching technique (i.e. comparing measured and simulated fan consumption) rather than whole building level. However, significant improvements to typical approaches to measurement in buildings are required before this is feasible.

3.3.5 Iterative calibration process

3.3.5.1 Test model for acceptance

In this step, the results of the simulation are compared to utilities level measurements against the *acceptance criteria*. At the time of writing, only three standards or guidelines were available, and each consists of comparing the cumulative variation of root mean squared error (CV RMSE) and the mean bias error (MBE) of the simulated energy consumption on a monthly basis (or hourly if the data is available) to utilities level measurements. As the currently available standards only contain criteria for analysis at the whole building energy level, it is hoped that in the future, with the advent of more detailed measured data, an accepted standard will be published that contains improved *acceptance criteria*. Of course, the analyst is the most informed in regard to the quality of the model, and thus the iterative process continues until the *acceptance criteria* are met *and* the analyst is satisfied that the model is an accurate representation of the building.

Generally, the first simulation run will not agree well with the measured data, and further investigation will be necessary through the iterative process defined below. Also, it should be noted that the results of each simulation run associated with each iteration and the comparison to the *acceptance criteria* must be stored in the version control repository.

3.3.5.2 Review outputs using visualisation techniques

This section focuses on problem identification and solution in order to improve the accuracy of the model. As there is an overwhelmingly large amount of data generated by simulation programs and measurement systems it is essential to employ numerous visualisation techniques, as discussed in the literature review (Chapter 2), such as:

- Linear time-series plots;
- Scatter plots and matrices of dependent scatter plots;
- Three dimensional carpet or surface plots(Baumann, 2004)(Baumann, 2004)(Baumann, 2004);
- Box whisker mean (BWM) plots;
- Three-dimensional carpet plots of binned variables (section 6.3).

3.3.5.3 Investigate possible further sources of information

Figure 3.5 describes how further changes to the model are made. Each of the letters in brackets in this section refers to a path in the figure. Assuming that the discrepancy identified in the previous step is not due to a clear modelling error (A), changes to input parameter(s) related to the source of the discrepancy should be preliminarily investigated. If no clear discrepancy source is identified, the sources of information should be reviewed (B). Starting at the lowest level in the *source hierarchy*, parameter(s) are identified for which more reliable information or further measurement is possible. By this stage of the calibration process there will typically be a small number of parameters for which further information or measurement is possible. However, if there are many opportunities for further measurement, a sensitivity analysis applicable to building energy simulation (Lomas and Eppdl, 1992; Lam and Hui, 1996; Heiselberg et al., 2009) could be performed on the parameters in order to identify the most significant.

The analyst then moves through the remaining steps assuming that the identified parameter(s) is the cause of discrepancy in the model. Where there is a more reliable source of information in the *source hierarchy* which is easy to obtain and related to the parameter(s) it can be done immediately (C). For example, replacing a parameter value from the initial model with one from a standard.

However, changes that require significant further resources (such as spot measurement, or additional site visits) should be investigated in a manner similar to sensitivity analysis. Parameter values should be modified within reasonable limits and the sensitivity of the model to this parameter is investigated. This identifies which changes are minor or trivial and thus reduces the total number of measurements that must be obtained. If the *significance criteria* are met (D), the further information must be obtained and the model updated. If a parameter does not meet the *significance criteria*, the analyst can decide at their own discretion whether it is necessary (E) or not (F) to obtain the information. However, currently there is no standard for *significance criteria*. In order to maintain reproducibility and the principle of evidence-based decision-making the criteria used *must be consistent throughout the calibration effort* and for this reason, it must be defined in the documentation in the first revision. A synopsis of the results of each investigation are also stored with each version of the iterative process.

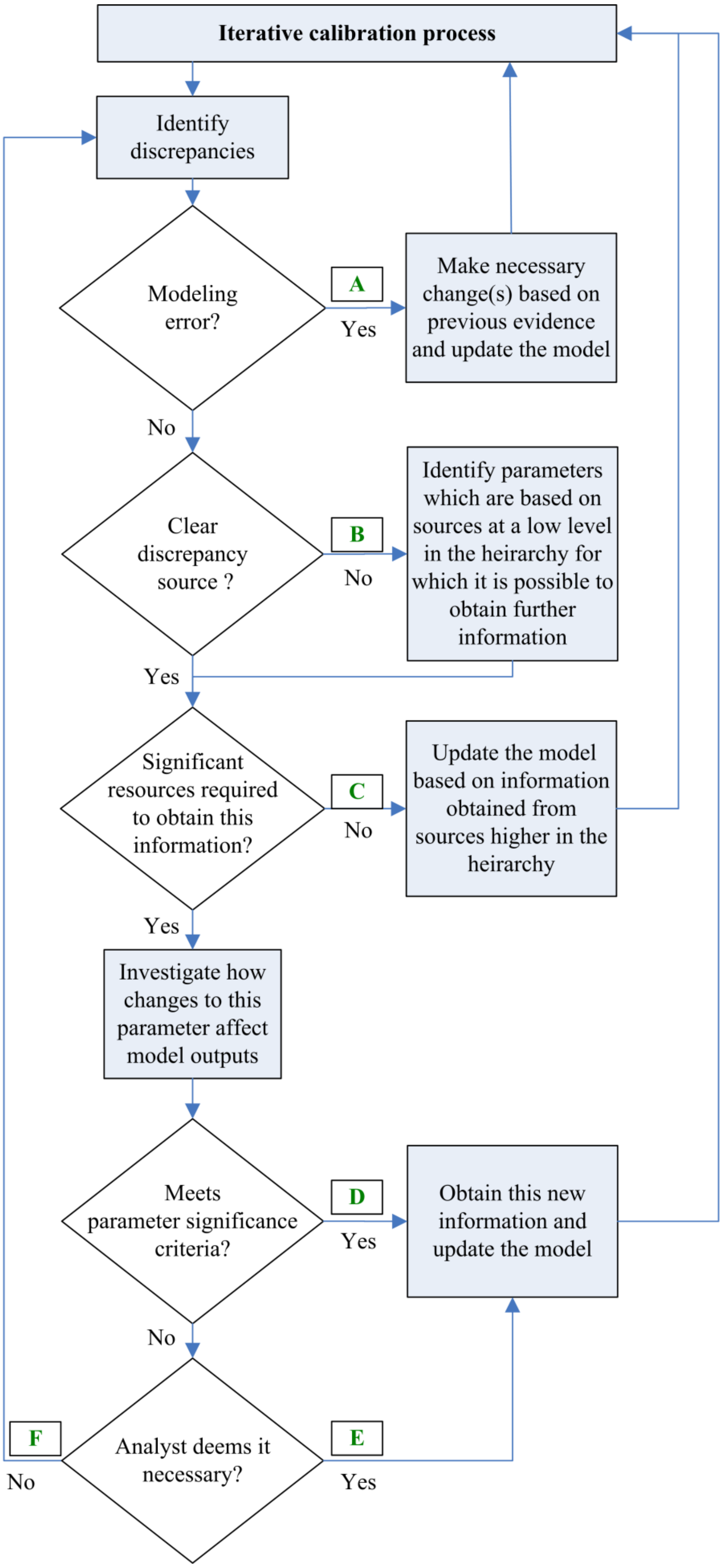


Figure 3.5: Investigation of further measurement

3.3.5.4 Update model

At this stage, information from more reliable sources in the *source hierarchy*, or measurements that have been identified as significant in the previous stage, are obtained and the model is updated accordingly. The overall process of the previous four steps should be repeated in order to iteratively improve the model until the simulation outputs match the acceptance criteria and the analyst is satisfied that the model is a reasonable representation of the building. Above all, the documentation of changes to the model must be kept updated, and the evidence upon which decisions were made must be stored along with the each change to the model. Without working in this manner, the calibration process is not reproducible.

3.3.6 Perform Energy Conservation Measure analysis

The nature of the calibration process implies that the analyst will identify numerous areas for improvement. This is because the analyst can only include in the model what is explicitly known about the building. Discrepancies between simulated and measured data are often due to problems with the real building and may offer opportunities to improve energy performance. Furthermore, it is likely that the building will never before have been studied in such detail at the operational stage of the Building life Cycle (BLC).

Once the model has been calibrated to a chosen standard using the above methodology it can be used to investigate the viability of ECMs according to a recognised protocol, such as the IPMVP (Efficiency Valuation Organisation, 2007). A variety of methods can be used to estimate ECM savings such as the test/reference method, the before/after method and the measure removal method (Schuldt and Romberger, 1998).

3.4 Conclusions

This chapter proposes a novel methodology for calibrating whole building energy models using a systematic, evidence-based approach. The methodology prescribes the use of version control techniques in the calibration process to organise and structure an analysts approach to the calibration process. The version control repository stores a complete record of the calibration process, including the evidence on which each change to the model was based.

This methodology also describes a new zoning process that more accurately represents the real building. The zone-typing strategy models many of the effects that are not captured by the traditional core and 4 perimeter zone strategy, while stopping short of representing each thermal zone in the building with an individual zone in the model. This is particularly applicable to deep floor plan buildings.

This methodology has the following advantages:

- Improved model reliability and credibility when compared to 'tuning' approaches: Only verifiable information about the building is used to make changes to the model.
- Improved reproducibility in the calibration process: Any change, and the evidence on which is based can be reviewed by future users. Future users will be able to review the decisions made throughout the calibration process, both improving their understanding of assumptions made and reducing the likelihood of analysts tuning input parameters without supporting evidence.
- A systematic approach to the calibration process: Version control techniques help to organise and structure an analysts approach to the calibration process. Version control software allows users to reliably review the changes between versions and revert to previous versions of the model if an error is discovered.
- An improved zoning strategy: The zone-typing strategy will yield a more accurate representation of buildings when compared to a typical core-and-four-perimeter zoning strategy.

Though the methodology is intended to apply to detailed calibration studies with high resolution measured data and detailed levels of building information, the primary aspects of the methodology (evidence-based approach, version control techniques, and zone-typing) are independent of the available measured data and information, and could be used in any calibration effort.

The following chapter focuses on the selection of a demonstrator building with which to implement and evaluate this methodology.

Chapter 4: Demonstrator selection

"If you cannot measure it, you cannot improve it."

- Lord Kelvin

4.1 Chapter introduction

The aims of this chapter are to:

- Outline the data and information requirements for the calibration of detailed whole building energy models;
- Describe five preliminary candidate buildings (i.e., case studies) for the demonstrator;
- Describe the selection process of the most appropriate building to demonstrate the methodology described in Chapter 3.

4.2 Measurement and information requirements

4.2.1 Measured data requirements

In the context of detailed whole building energy modelling, measured data consists of information about the building which is dynamic in nature. For example, total building electrical consumption. This data is used to verify that the model is an accurate virtual representation of the real building.

Monthly utility bills are typically the only source of measured data regarding the energy consumption of most buildings. However, calibrating models to monthly utility bill data is insufficient for many reasons. Two of the most significant are that:

- Large errors on a daily or hourly basis cannot be identified when using data that is measured at monthly time-steps. Section 6.5.1 includes an example that demonstrates this issue in detail;
- Using utility level data ensures that factors which drive the energy consumption of HVAC systems (such as lighting and equipment loads), cannot be separated from total energy consumption. Internal loads are typically more than half of total building electrical energy consumption (US EIA, 2003). Thus, errors in how internal loads are modelled can easily offset errors in HVAC consumption. Furthermore, measurement by end-use (i.e., sub-utilities levels) aids the analyst in identifying where errors and discrepancies lie between the model and the real building. Section 6.5.1 includes an example that demonstrates this issue in detail.

It is unlikely that it will ever be possible to calibrate a model to match the real building precisely at all resolutions due to: issues with measured data; simplifications inherent in the simulation tool; and the fact that the number of variables creates a vast parameter space that has multiple unique solutions (Reddy, 2006). However, if higher-resolution measured data and tighter acceptance criteria are used, the model will *more closely* represent reality, as shown in Chapter 6. Thus, there is a need for hourly, sub-utilities measurement of energy consumption, which much of the building stock does not currently employ. Fortunately however, the level of measurement in newer buildings is improving, and they often include dedicated EMSs. Furthermore, EMSs can be added to existing buildings at relatively low cost. As discussed in section 2.4.1, this initial cost is typically recovered due to Energy Conservation Measures that are identified using the resulting data. Thus EMS retrofits are also becoming more common-place in existing buildings. The approach described in this thesis focuses primarily on applications in which hourly EMS data measured at sub-utilities level is available.

4.2.1.1 Energy consumption measurement requirements

To perform any model calibration it is clearly essential to have measured data regarding energy consumption. Energy consumption in buildings can be broken down into four categories:

- Electricity from utilities and/or electricity generated from renewable sources onsite;
- Fuel consumption (e.g., gas, oil, etc.,);
- District hot and chilled water consumption.

A number of different sensors measure energy consumption under the above categories, such as:

- Power sensors (current transducers with a voltage reference);
- Flow sensors , gas meters, or level sensors;
- Heat sensors (flow and temperature sensors connected to a data-logging device).

When connected via a wired or wireless network, this network of meters is known as an Energy Monitoring System. For the reasons stated in the previous section, the data acquired by EMSs should be archived over at least one year (preferably more) at hourly intervals (or more frequently) and measured at a sub-utilities level, separated by end-use where circuit layouts allow. The list below describes end-uses in typical buildings:

- Electrical:
    - HVAC;
    - Lights;
    - Plug and general loads;
    - Process (e.g., manufacturing processes, cooking, etc.,);
    - People movers (e.g., elevator, escalator, walkway);
    - Onsite generation (e.g., solar, micro-hydro, CHP).
- Fuel consumption and district water supply:
    - Space heating load;
    - Space cooling load;
    - Process (gas consumption from cooking, domestic hot water, etc.,)

An often-overlooked key issue is that EMSs should measure *all* energy consumption in a building. Further discussion of the value of these systems, issues surrounding their implementation, and recommendations to address these issues can be found in Raftery et al., 2010.

4.2.1.2 Weather measurement requirements

Weather data is used to run the model in the same outdoor conditions experienced by the building during the period under investigation. Ideally, weather conditions should be measured at the building itself. However, this is rare in the current building stock and thus, some concessions must be made. Where onsite measurement is not available, data from local weather stations that are no more than 10km away, without a significant change in elevation, can be used. These weather stations should maintain a historical record of the following variables measured in hourly intervals (or more frequently) over at least one year (with desired accuracy in parentheses):

- Dry-bulb temperature ($\pm$ 0.1°C);
- Wet-bulb temperature ($\pm$ 0.1°C) or relative humidity ($\pm$ 2%);
- Wind speed ($\pm 0.1 ms^{-1}$ ($0.5 – 10 ms^{-1}$); $\pm$ 1% ($10 - 50 ms^{-1}$); $\pm$ 2% (> $50 ms^{-1}$));
- Wind direction ($\pm$ 5°);

- Global solar irradiance (± 2.5%);
- Barometric pressure (± 50Pa).

There are other potentially useful variables to measure, depending on the climate and type of systems installed in the building. For example:

- Rainfall;
- Snow presence and depth;
- Diffuse solar irradiance;
- Direct solar irradiance.

4.2.1.3 Other desirable measured data

Other measured data is useful during the calibration process aside from measured energy consumption and weather conditions. For example, a Building Management Systems (BMS) often stores data regarding set-points (such as coil air temperature set-points, supply air temperature set-points) and measured performance of equipment (such as variable frequency drive percentages, actual supply and return air temperatures). This information can be very helpful during the calibration process to identify discrepancies between the model and the real building. However, these systems are typically not designed for long term storage of data and short archive lengths are common. Thus, the data may be of limited use to an analyst working on calibrating the model to annual data. Also, it should be noted that some of this data may overlap with, or further verify, the stock information described in the next section. For example, supply air set-points could also taken from the O&M manuals, operator interviews, site surveys or spot measurement.

4.2.1.4 Data quality

Data quality is a significant issue and all databases examined over the course of this research included some errors. Thus, data must be carefully reviewed and repaired through interpolation before use in the calibration process. To avoid these issues, data logging devices should ideally be capable of:

- High frequency data-logging (e.g. 1 minute values), as the data can easily be collated to other frequencies if necessary;
- Long term archiving (>3 years);

- Maintaining a regular sampling period and accurate timestamps (no drift in timestamp values);
- Capturing all values/timestamps (no missing data);
- Removing spurious outlier values (rudimentary error checking of data).

4.2.2 Stock information

Stock information consists of all the information about the building that is static in nature. This information is used to update the model so that it matches the actual building as closely as possible. The following information is required:

- The geometry of the building;
- Wall constructions, material types and the thermal properties of these materials;
- Occupancy, lighting and plug characteristics, loads, and schedules;
- HVAC equipment at both a system (e.g. a coil in an AHU) and a zone level (e.g., a VAV box):
  - Equipment types;
  - Maximum capacities;
  - Maximum and minimum flow rates;
  - Performance curves;
  - Modes of operation and control strategy;
  - Set-points.

In addition to this, knowledge of the design conditions for the building (e.g., summer and winter design days, fresh air requirements) can be very helpful for determining an estimate for a parameter value when no other information regarding the parameter is available.

4.2.2.1 Sources of stock information

Typically, stock information about a building can be obtained from many sources, such as:

- As-built drawings;
- As-built panel schedules;

- Commissioning documents;
- O&Ms;
- Equipment nameplates;
- Day and night site surveys;
- Human Resources interviews and personnel estimates;
- Building operator and technician interviews;
- Spot measurement.

Thus, access to the building, the resources for surveys and spot measurement, and the quality of documentation regarding the building are extremely important issues when considering the calibration of a whole building energy model.

However, the quantity and quality of stock information is typically quite poor in buildings. Small organisations rarely undertake a systematic approach to construction documentation, and older buildings typically have very little information available, particularly regarding installed mechanical systems. Even in cases where a structured approach is used (e.g., large organisations, buildings with critical systems, etc.) there are often many pieces of information which are necessary for a whole building energy model but are missing in the documentation. Furthermore, even in cases where the information is available, it is not structured in a standardized manner and usually takes the form of as-built (2-dimensional) drawings and manufacturer datasheets. These formats require significant manual effort before the information can be added to a whole building energy model.

Building Information Modelling (BIM) technology, as discussed in section 2.4.2, has emerged because the current situation regarding stock information in buildings is unacceptable. A significant amount of valuable information is lost at each transition stage of the Building Life Cycle (BLC): from design to commissioning and from commissioning to operation. BIM technology can capture this information in an organised manner. Thus, a Building Information Model (BIM) is by far the best source of stock information.

Furthermore, in the context of calibrated whole building energy modelling, a significant amount of effort is expended in manually updating the model to match the actual building during the calibration process. This process can be partially automated if a systematic source of information related to the building is available, such as a BIM. The procedures and tools to do this for an entire building model are not yet available, particularly when focusing on HVAC components. However, there are already a number of tools available to automatically translate geometries and constructions from an architect's BIM directly into a whole building energy model (Maile et al., 2007). Section 5.2.4.1 contains an example in which this tool was used to translate a partial BIM into geometry, constructions, and materials input for a whole building energy model. However, complete, high-quality BIMs are not available for the vast majority of buildings today. Thus, the required stock information must be obtained from other sources, such as those described at the beginning of this section.

4.3 Selection of the demonstrator building

Each of the buildings described later in this chapter was reviewed as a possible demonstrator for the methodology described in Chapter 3. None of the buildings fit the requirements perfectly. However, currently very few real buildings will meet all of these requirements. Thus, any calibration methodology must allow for some flexibility when measured data or information is simply unavailable.

The list below describes the relative importance given to various criteria during the selection process:

- Availability of high quality hourly measured energy consumption data at a sub-utilities level (EMS data) for at least one full year;
- Availability of historical weather data for the above year;
- Quality of stock information, such as as-built drawings and O&Ms;
- Ease of access for site visits and resources for further measurement.
- Availability of high quality BMS data;

Other considerations included:

- Ease of occupant load estimation;
- Existence of an initial model;
- Difficulties and inaccuracies arising from:

- Modelling the HVAC systems;
- Modelling the geometry;
- The size of building;
- The age of building.

The final section of this chapter describes the results of the selection process including comparison tables describing each building under a number of categories (Table 4.1 to Table 4.5).

4.4 Case studies

Each of the five case studies in this section are described below under four headings:

- Overview: an overall description of the building, including the building function and primary aim of the investigation;
- Geometry and constructions: describes difficulties related to modelling the geometry of the building in a whole building energy simulation tool;
- HVAC systems: describes the HVAC systems in place and modelling difficulties associated with these systems;
- Stock information and measured data: describes the quantity and quality of information available about the building.

4.4.1 Environmental Research Institute (ERI)

4.4.1.1 Overview

The Environmental Research Institute is a research building in Cork, Ireland (University College Cork, 2007). The 3-storey building contains offices, laboratories and a clean room. It has a floor area of 3,000m^2 and was completed at the end of 2005. The building is primarily a daytime office, occupied from 8am-6pm, Monday to Friday. However, the building is conditioned 24 hours per day in order to maintain space temperatures for laboratory and clean room areas, and to allow access to staff outside of office hours if necessary. The building was designed as an ongoing experiment in green building technology with a particular emphasis on an increased knowledge of downstream performance from green design. The building is currently under investigation as part of a number of projects such as whole building energy simulation, Fault Detection & Diagnosis (FDD), wireless sensor networks and building performance metrics.

Figure 4.1: Photograph of the ERI (Courtesy of Andrea Costa)

4.4.1.2 Geometry and constructions

The external column features of this building add to the difficulty of accurately representing this geometry in a building energy simulation tool because the columns both shade and conduct heat into zones in which they are not contained.

4.4.1.3 HVAC systems

The HVAC systems conditioning this building are highly unusual. The primary conditioning system is an aquifer fed electric heat-pump. This heat pump supplies hot water to an underfloor heating system. However, depending on the current operating strategy, a solar water heater located on the roof may preheat the water coming from the aquifer and a gas boiler may boost the hot water temperature after the heat pump. An AHU with a heat recovery wheel conditions the clean room. The remainder of the building is ventilated and cooled via natural ventilation using automated windows.

The automated natural ventilation, underfloor heating, and cleanroom AHU systems can be modelled by a whole building energy simulation tools such as EnergyPlus. However, currently it is not possible to model the complexity of the hot water plant loop, which includes integrated equipment on both sides of the heat pump (see Figure 4.2 below)

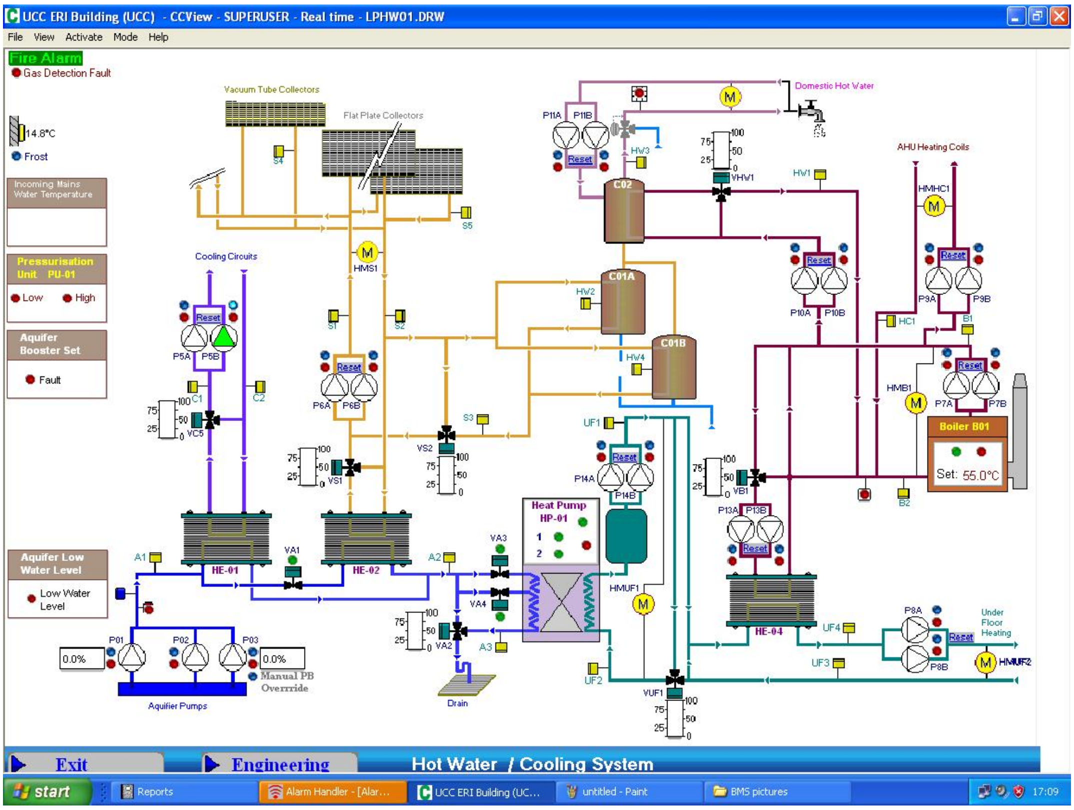


Figure 4.2: BMS screenshot of the ERI plant loops

4.4.1.4 Stock information and measured data

A state of the art BMS was specified at design for this building. However, much of this was not installed. The building came into focus at a later stage as part of several research projects and many further sensors were added to the BMS. However, the quality of the data obtained by this system is quite low. There are numerous instances of missing data-points, erroneous time-stamps and spurious outliers.

EMS data is also measured by the BMS, and thus these data quality problems also affect this data. Also, several of the EMS sensors required for calibrating whole building energy models are not installed, such as meters for the electrical consumption of internal loads. Furthermore, some of the EMS sensors which are installed, such as the 'heat meters' (i.e., flow and temperature sensors) on the hot water loops, are either incorrectly sized or not calibrated.

Aside from these issues, the quality of stock information about the building is quite high. As-built drawings are available and of relatively high quality, and detailed information is available on materials and constructions. In addition, O&M manuals are available which describe much of the HVAC equipment.

4.4.2 Intel IR6

4.4.2.1 Overview

Intel Ireland manufacture microprocessors at a production site in Leixlip, Co. Kildare, Ireland. The four-storey Intel IR6 office building supports the manufacturing facilities and was completed at the end of 2003. It has a gross floor area of 30,000m^2 and an aspect ratio of 2.1:1. The ground floor contains a clean-room gowning area, a control room, a kitchen, a canteen, and a facilities area; the first and second floors consist of open office space and conference rooms; and the third floor is currently unoccupied. The building is primarily a daytime office, occupied from 8am-6pm, Monday to Friday. However, the Intel facility operates on a 24-hour basis and there are a significant number of staff who are directly involved in the operation of these production facilities. Thus, the building is at least partially occupied at all times. Typical night occupancy is approximately 10% of the peak day occupancy.

The goals of the project were to develop a whole building energy model; to perform an energy audit; and to analyse possible Energy Conservation Measures (ECMs). Two zones were excluded from the model and analysis by Intel request: the clean-room gowning area and control room.

Figure 4.3: Photograph of the IR6 building (Courtesy of Luke Fenner)

4.4.2.2 Geometry and constructions

Two minor features of this building add to the difficulty of accurately representing this geometry in a building energy model:

- The second floor overhangs the first floor by 2m in three sections of the building. This is highlighted in red in Figure 4.4.
- The three stairwells on the south face have a ground to roof wall that is semicircular in plan. As the currently available simulation tools model 1-dimensional heat transfer through a single plane, these walls were modelled as flat surfaces at angles of 30°. This is highlighted in green in Figure 4.4.

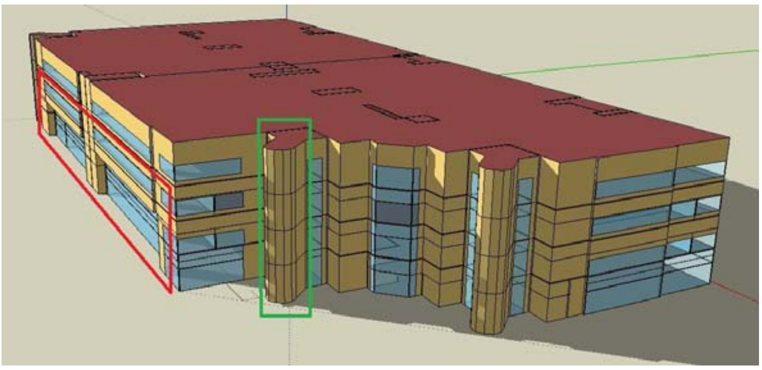


Figure 4.4: Screenshot of the EnergyPlus geometry in Google SketchUp for IR6.

4.4.2.3 HVAC systems

There are 10 large Air Handling Units (AHUs) on the roof of this building. Three identical AHUs supply a riser which serves the east of the building, one of which is un-commissioned additional capacity for the currently unoccupied third floor. Each AHU has variable air volume (VAV) supply and return centrifugal fans on Variable Frequency Drives (VFD), an outside air dry-bulb economiser, a cooling coil, a preheating coil and a reheat coil. The west of the building is conditioned by 3 systems which are identical to those in the east.

A dedicated outside air system (DOAS) with two speed supply and exhaust fans and a heating coil conditions the kitchen area. A dedicated outside air system (DOAS) with variable air volume (VAV) supply and exhaust fans, a preheating coil, cooling coil, and reheat coil conditions the canteen area. Two make-up AHUs, each with two redundant VAV supply and return fans, condition the cleanroom. Preheat, cooling and reheat coils control the clean room to within tight temperature and humidity ranges. Fan-coil units within the building also serve this area.

The control room was retrofitted into the building after the initial construction phase. Due to high internal loads in this zone, additional cooling capacity was required and direct exchange (DX) refrigeration units were added as a retrofit on the ground floor.

A single AHU with a constant speed supply fan, outside air enthalpy economizer, heating coil and cooling coil supplies the mechanical, electrical and battery rooms, and is located in the mechanical room on the ground floor.

On a zone level, a range of VAV terminal boxes, constant volume terminals, fan-powered terminals, with and without reheat coils, condition the individual thermal zones within the building. Hot water convective baseboards (radiators) heat the stairwells.

On a plant level, district hot water and chilled water systems supply all the heating and cooling coils in the building.

These HVAC systems do not present any significant difficulties to whole building energy simulation tools, such as EnergyPlus. Furthermore, the size and deep floor plan nature of the building will minimize the effects on calibration of variables that are typically difficult to quantify. For example, the effects of infiltration, direct solar irradiance and three-dimensional ground heat transfer will be reduced when compared to smaller buildings.

4.4.2.4 Stock information and measured data

The Intel site has extremely high quality measurement systems when compared to the other case studies. The BMS measures supply and return air temperature and relative humidity; coil and damper percentage open signals; VFD speed percentages; and Proportional Integral Derivative (PID) controller process values for all AHUs. A dedicated EMS monitors electrical power consumption at every major electrical panel or Motor Control Centers (MCC). The panels are generally organised into the following categories: lighting, general equipment, emergency power, uninterruptible power, and MCCs. An onsite weather station measures outdoor dry-bulb temperature, dew point temperature, relative humidity, barometric pressure, daily rainfall, wind speed and wind direction. Furthermore, the archived datasets are of extraordinarily high quality when compared to other case studies (Raftery et al., 2010). Data-points are typically logged at 15 minutes for EMS data and the data is maintained in full for at least 5 years. Very few missing data-points or irregular logging periods were found in any of the data, and no spurious outliers were present.

However, zone level measurement, such as zone air temperatures, are not logged by the BMS. Also, although the EMS data is extensive and the panels are organised well, a more detailed look at the panel schedules show discrepancies that complicate the use of this data in calibrated building energy models. For example, although HVAC equipment is mostly supplied from MCCs, some HVAC equipment are supplied from emergency power panels (clean room fans), and general equipment (unit heaters and air curtains) panels.

Also, 'heat' meters (flow-rate and temperature sensors) for hot and chilled water consumption were not in the original design and were added as a retrofit in 2010. Thus, it was not possible to calibrate the HW and ChW consumption for the building for the selected year of the project (2007).

The quality of stock information about the building is very high due to its recent construction and to the systematic approach to construction documentation that Intel undertakes. High quality as-built drawings and detailed information on materials and constructions are available. In addition, detailed design information and O&M information is available for most HVAC equipment.

4.4.3 Philips Research

4.4.3.1 Overview

Philips perform research and manufacturing at a site in Briarcliff, Newark, New Jersey, USA. The building in question is appended to the main manufacturing and research facility. It has a floor area of 2,500m^2 and 2 floors (with one penthouse floor that houses the HVAC equipment). The building was completed in 1965 and has undergone numerous retrofits since then. The building consists of open office space, private offices and a lobby reception area. Its primary function is as a daytime office, occupied from 8am-6pm, Monday to Friday. However, staff members sometimes remain in the office outside these hours and thus, the HVAC system conditions the building on a 24-hour basis. Dr. Vladimir Bazjanac and the author jointly completed the goals of this project: to perform an energy audit and develop a complete model of the building in EnergyPlus.

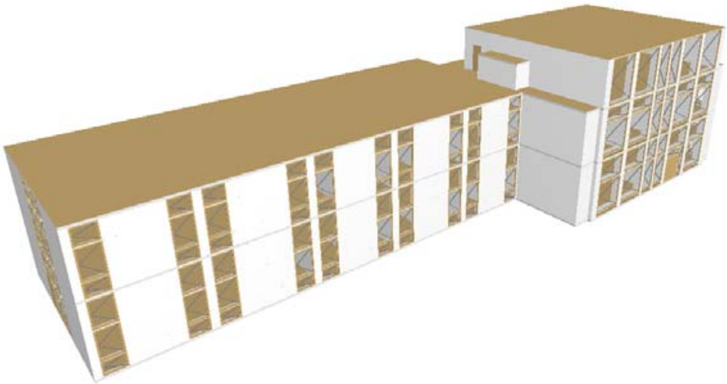


Figure 4.5: ArchiCAD screenshot of the Philips building

4.4.3.2 Geometry and constructions

There was one relatively uncommon feature of this building that significantly added to the difficulty of accurately representing this geometry in a building energy simulation tool. The exterior walls are constructed of 60cm thick concrete columns which protrude from the building. Thin insulated panels and windows followed by a composite of concrete block and brick separate the columns. This construction is quite difficult to model accurately in whole building energy models.

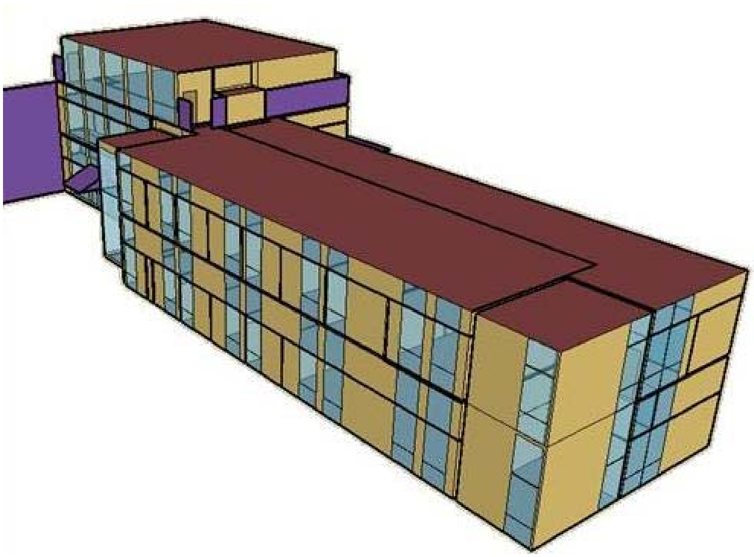


Figure 4.6: Google SketchUp screenshot of the EnergyPlus geometry for the Philips building.

4.4.3.3 HVAC systems

Three AHUs in the penthouse condition the building. A large exhaust fan and hot water unit heater are also present in this room. The AHUs have constant speed fans, dry-bulb outside air economisers, heating coils and cooling coils. Convective hot water baseboard heaters also condition the building and are the primary heating equipment during the winter. All equipment is pneumatically controlled. Hot and chilled water is supplied by a district system from the central plant for the site.

There have been multiple zone level retrofits since the date of construction, many of which are difficult to model. For example, approximately half of the supply terminals were retrofitted with VAV boxes, while other are constant volume supplies. However, the central fans are still constant speed. Thus, when the VAV dampers close due to reduced cooling load, the pressure in the supply duct increases, and consequently, more air will flow out of the constant volume supplies. This then affects reheat consumption and cannot be modelled easily by currently available simulation tools.

Furthermore, the size and age of this building significantly increases the effect that variables related to the external environment have on energy consumption. For example, due to the age of the building and construction of the windows, infiltration is likely to be significant, but this would be very difficult to quantify without an air leakage test.

4.4.3.4 Stock information and measured data

Both EMS data and BMS data were unavailable for this site due to the age of the building and the installed pneumatically controlled HVAC systems. Furthermore, there was no local historical weather data available. TMY data from a site 10 miles away was used for the weather-file for the model. Furthermore, very little stock information is available due to the age of the building and numerous retrofits since construction. For example, there was no accurate information concerning the geometry and thus, this was verified by site survey. Also, many assumptions had to be made regarding thermal properties of the constructions due to a lack of information. No O&Ms were available and thus, only name-plate information could be used for parameters relating to HVAC equipment. In some cases, even nameplate information was unavailable.

4.4.4 The David Brower Center

4.4.4.1 Overview

The David Brower Center is a newly constructed office building in Berkeley, California, USA (The David Brower Center, 2008). The 4-storey building contains a gallery, restaurant and auditorium on the ground floor, with tenant-occupied office space on the other three floors. It has a floor area of 5,000m^2 and was completed in 2009. The building is primarily a daytime office, occupied from 8am-6pm, Monday to Friday.

However, the building is often occupied later in the day due to events held in the gallery and auditorium. The building includes many novel features and is currently a focus of research in areas such as whole building energy simulation of UFAD and radiant hydronic slab systems and energy performance of integrated HVAC systems.

Figure 4.7: Rendered image of the Brower Center (Courtesy of Solomon E.T.C.)

4.4.4.2 Geometry and constructions

There are no aspects of the geometry which would be significantly difficult to model in whole building energy simulation tools, such as EnergyPlus. However, the solar shading devices on south facing walls do increase model complexity.

4.4.4.3 HVAC systems

The HVAC systems conditioning this building are highly unusual: a novel combination of Underfloor Air Distribution (UFAD) and radiant hydronic slab systems. Investigations of this novel hybrid HVAC system have been performed in EnergyPlus (Raftery et al., 2010). The hydronic slab system is the primary means of maintaining space temperatures in the building and the air systems use carbon dioxide sensors in each zone to ensure sufficient fresh air is provided to the occupants (Demand Controlled Ventilation). Furthermore, natural ventilation via operable windows allow occupants control over their environment.

A condensing boiler supplies low temperature hot water and a cooling tower supplies chilled water directly to the hydronic slabs and air handlers. Both the slab and air systems can operate in pre-cooling mode during the night, which removes the need for a chiller. Additional building features include solar photo-voltaic panels on the roof and a rain-water collection system.

4.4.4.4 Stock information and measured data

The BMS monitors a significant number of points in this building. However, the data is not yet archived for a sufficient period to be of use in annual calibration of whole building energy models.

A very well designed EMS was part of the original specification for this building. The design included an explicit separation of electricity consumption by end-use (e.g. HVAC, lighting and plug loads). However, this was value-engineered out of the project due to cost over-runs. These sensors were later installed in the building in 2010 as part of an investigation by researchers at the Center for the Built Environment, University of California, Berkeley.

The quality of stock information about the building is very high due to its recent construction. High quality as-built drawings and detailed information on materials and constructions are available. In addition, O&M information is available for the HVAC equipment and detailed design criteria would also be available.

4.4.5 Nursing Library

4.4.5.1 Overview

The Nursing Library is a newly constructed building at the National University of Ireland, Galway located in Galway, Ireland. The 3-storey building contains a library and study areas, as well as a computer room on the ground floor. It has a gross floor area of 700m^2 and was completed in 2009. The building is conditioned 24 hours per day.

The building is currently a focus of research in areas such as whole building energy simulation, energy performance of earth tube systems, and calibrated CFD modelling of natural ventilated spaces.

Figure 4.8: Photograph of the Nursing Library (Courtesy of Magdalena Hajdukiewicz)

4.4.5.2 Geometry and constructions

Significant portions of the ground floor are below grade. Thus, three-dimensional ground heat transfer will have a significant effect on the results of any HVAC energy performance analysis. This is difficult to model in currently available simulation tools. Also, the solar shading devices on south- and west-facing walls increase model complexity.

4.4.5.3 HVAC systems

This mixed mode building has a dedicated outside air system for ventilation and automatic (or manually operated) windows for natural ventilation in most areas. The dedicated outside air system draws air through an earth tube system to temper the air in the winter and summer months. Stand-alone direct exchange units cool the computer rooms. Convective hot water baseboard heaters maintain indoor temperatures outside of the summer months. Campus-wide district hot water supplies all of the heating systems in the building.

It is possible to simulate all of these HVAC systems in whole building energy simulation tools such as EnergyPlus. However, it is expected that a naturally ventilated building would be quite difficult to calibrate to a reasonable level of accuracy due to the variability of parameters on which energy consumption is highly dependent, such as wind driven infiltration through windows. Furthermore, the building's size and the zones that are partially below grade increase the impact of 2- and 3-dimensional heat transfer effects on energy consumption when compared to larger buildings.

4.4.5.4 Stock information and measured data

The BMS monitors a significant number of points in this building. However, initially the data was not archived for a sufficient period to be of use in annual calibration of whole building energy models. The BMS was modified to archive this data in April 2010. Measured EMS data for the district hot water heating system is available, however the electrical sensors have not yet been installed. The panels explicitly separate electricity consumption by end-use (e.g. HVAC, lighting and plug loads). Also, it should be noted that the location of the building ensures easy access for site surveys and further measurement.

The quality of stock information about the building is very high due to its recent construction, and the attention paid to the building during commissioning by researchers at the National University of Ireland, Galway. High quality as-built drawings and detailed information on materials and constructions are available. In addition, O&M information and detailed design criteria is available for all the HVAC equipment.

4.5 Results of the selection process

Tables 4.1 to 4.5 compare the buildings under a number of categories, ordered by date of initial investigation. The '+', 'o', and '-', values correspond to high, medium and low respectively. As can clearly be seen from this comparison, although not an ideal candidate, the Intel IR6 building was the best candidate to evaluate the methodology described in Chapter 3.

Table 4.1: Comparison of general modelling parameters for the five case studies

	ERI	IR6	Philips	Brower Center	Nursing Library
Location	Cork, Ireland	Leixlip, Ireland	New Jersey, USA	California, USA	Galway, Ireland
Date of initial investigation	Dec 2007	Apr 2008	Oct 2008	Feb 2009	May 2009
Date of construction	2005	2003	1965	2008	2008
Gross floor area	3,000m^2	30,000m^2	2,500m^2	5,000m^2	700m^2
Number of floors	3	4	2	4	3
Existing whole building energy model?	No	No	No	No	No
Ease of modelling geometry	o	+	o	o	o
Ease of modelling air systems	o	+	+	-	o
Ease of modelling plant equipment	-	+	+	o	+

Table 4.2: Comparison of stock information for the five case studies

	ERI	IR6	Philips	Brower Center	Nursing Library
Ease of access for site visits and surveys	o	o	-	o	+
Onsite personnel and equipment resources	-	+	o	o	o
Quality of as-built drawings and panel schedules	+	+	-	+	+
Quality of material datasheets	o	+	N/A	o	o
Quality of O&M manuals	o	+	N/A	+	o
Ease of estimating occupant loads	-	o	-	-	-

Table 4.3: Comparison of energy consumption data for the five case studies

	ERI	IR6	Philips	Brower Center	Nursing Library
EMS data	Yes	Yes	No	Not at time of selection	Not at time of selection
EMS monitors all electrical energy consumption?	No	Yes	N/A	N/A	N/A
EMS monitors all other energy consumption?	No	No	N/A	N/A	N/A
Complete sub utilities level measurement?	No	Yes	N/A	N/A	N/A
Panel separation by end-use	o	+	-	+	+
Data quality	o	+	N/A	N/A	N/A
Sufficient archive length	Yes	Yes	N/A	N/A	N/A

Table 4.4: Comparison of BMS data for the five case studies

	ERI	IR6	Philips	Brower Center	Nursing Library
BMS data	Yes	Yes	No	Yes	Yes
Detail of measurement	o	+	N/A	+	+
Data quality	o	+	N/A	+	+
Sufficient archive length?	Yes	Yes	N/A	Not at time of selection	Not at time of selection

Table 4.5: Comparison of weather data for the five case studies

	ERI	IR6	Philips	Brower Center	Nursing Library
Historical weather data available?	Yes	Yes	No	Yes	Yes
Dry-bulb temperature	Yes	Yes	N/A	Yes	Yes
Wet-bulb temperature or relative humidity	Yes	Yes	N/A	Yes	Yes
Wind speed	Yes	Yes	N/A	Yes	Yes
Wind direction	Yes	Yes	N/A	Yes	Yes
Global solar irradiance	Yes	No	N/A	No	Yes
Direct solar irradiance	No	No	N/A	No	No
Barometric pressures	Yes	Yes	N/A	Yes	Yes
Data quality	o	+	N/A	+	+
Sufficient archive length?	Yes	Yes	N/A	Yes	Yes

4.6 Conclusion

This chapter describes measured data and stock information requirements for the calibration of whole building energy models to detailed measured data. The chapter discusses five preliminary case study buildings and the reasons for the selection of the Intel IR6 building as the demonstrator for the methodology described in Chapter 3. The following chapter describes the application of the methodology to the IR6 building.

Chapter 5: Demonstrator

"A good system shortens the road to the goal."

- Orison Swett Marde

5.1 Chapter introduction

The purpose of this chapter is to demonstrate the application of the methodology on a step-by-step basis. This chapter contains several contributions to knowledge, that:

- Demonstrates the evidence-based approach to calibrating whole building energy models described in chapter 3;
- Presents the entire history of a calibrated model. This can be reviewed by future users, along with the reasoning behind decisions made during the calibration process and the evidence on which the model is based.

5.2 Demonstration of the calibration methodology

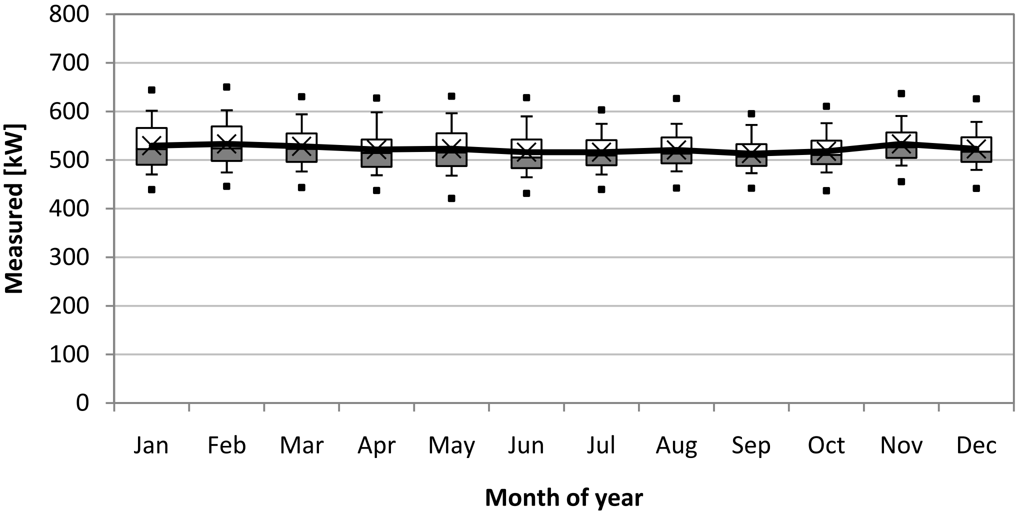
5.2.1 Demonstrator aims

The primary aim of this demonstrator is to validate the methodology described in Chapter 3. That is, to calibrate a whole building energy simulation model to an accepted standard using the methodology. Chapter 4 describes the selected demonstrator building – the 4-storey, 30,000m^2, Intel IR6 office building.

Figure 5.1 presents an overview of measured total energy consumption for the building. These Box Whisker Mean (BWM) plots illustrate 25th, 50th and 75th percentiles using two boxes; 10th and 90th percentiles using error bars (or 'whiskers'); minimum and maximum using high and low data-points; and the mean of the data using a linear plot.

Although the model includes the entire building geometry, two zones were excluded from the calibration process at the request of Intel: the clean-room gowning area and control room (combined floor area of 1,500m^2). Measured data is available in sufficient detail to separate the energy consumption of these zones from the rest of the building because separate emergency power systems serve these critical systems. Thus, the calibration focuses on energy consumption in the remaining zones - these comprise 95% of the total building floor area. Eight large Air Handling Units (AHUs) on the roof and one AHU on the ground floor condition these zones.

The secondary aim of this demonstrator was to develop a list of proposed HVAC related Energy Conservation Measures (ECMs) for consideration by the building operator based on the thorough review of the building that the calibration process ensures. Chapter 6 contains a list of these ECMs.



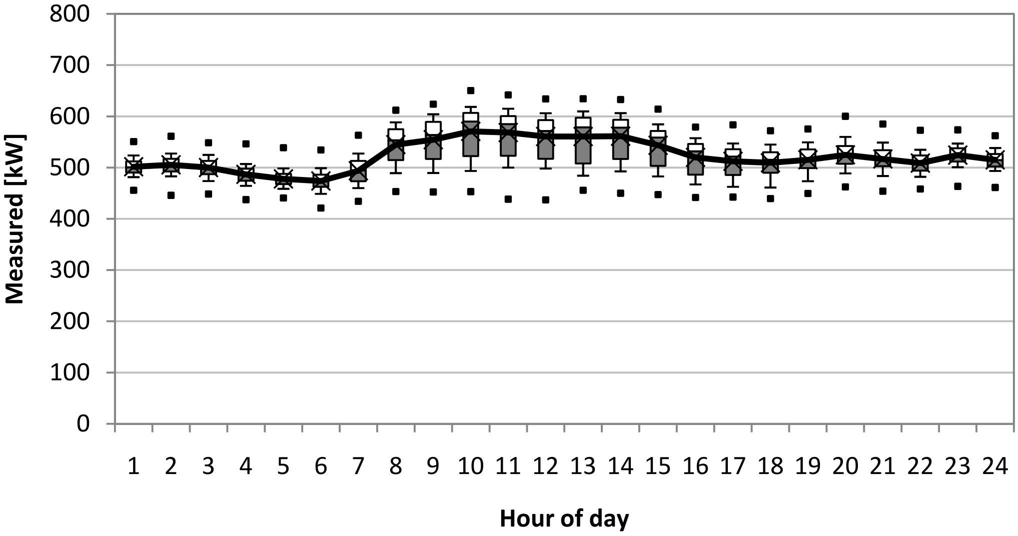


Figure 5.1: Monthly and hourly BWM plots of total building electrical power in 2007.

5.2.2 Overview of calibration process

This remainder of this chapter is broken down into 5 major sections (outlined in green in the image below) to guide the reader through the calibration process:

- Version control;
- Preparation;
- Update model;
- Error check;
- Iterative process.

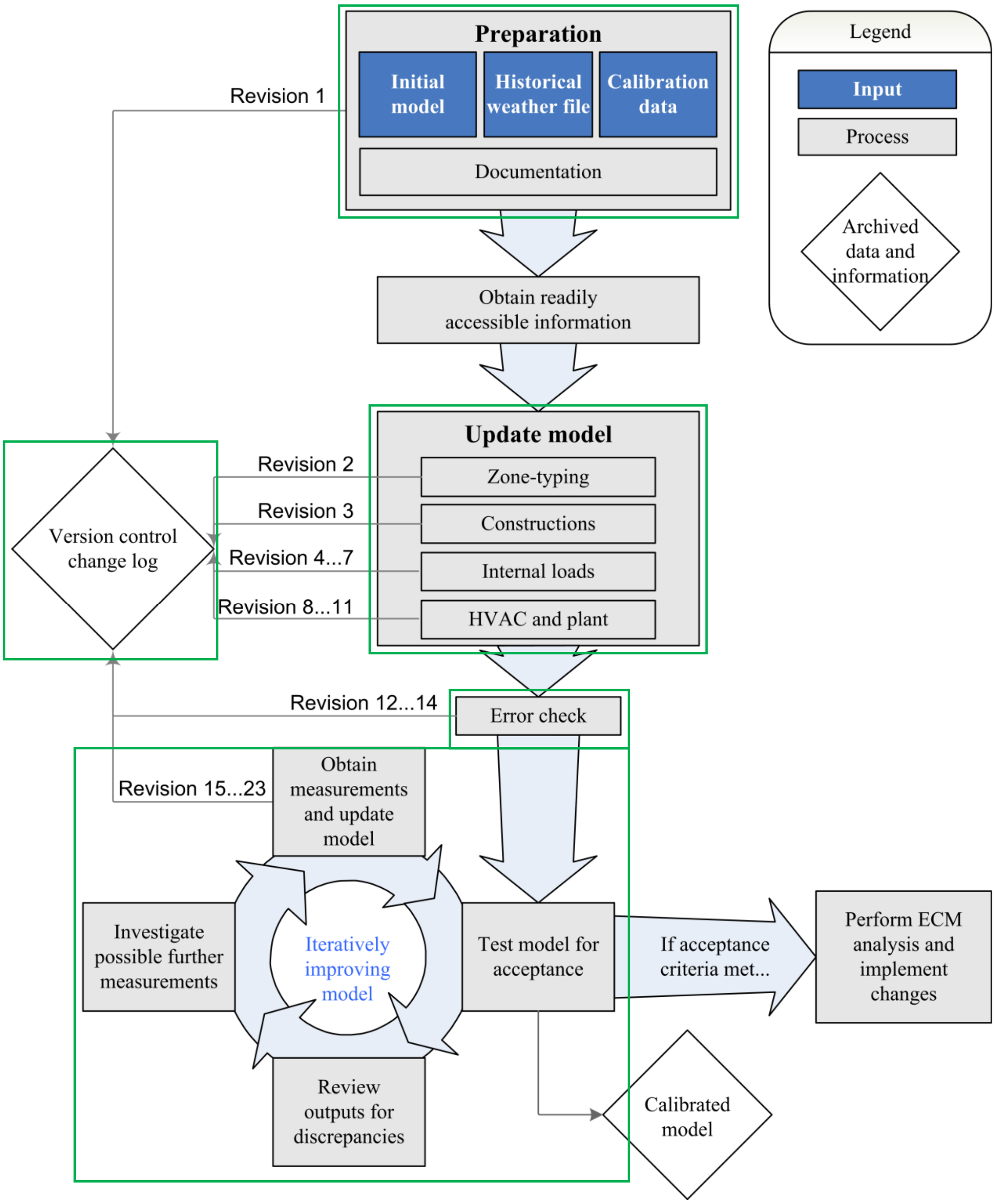


Figure 5.2: Demonstration of the methodology

5.2.3 Version control

TortoiseSVN (CollabNet, 2010), an open-source version control software tool, was used create a version control repository of the calibration process. This repository stores each version of the model, a description of modifications made between versions and the evidence based on which the changes were made. The use of version control technology underpins the evidence-based approach described in Chapter 3.

This improves the reproducibility and reliability of the calibration process by allowing future users of the model to review the entire history of the calibration process and the evidence on which the current version is based. Appendix C contains a softcopy of the entire repository and instructions on how to access it. Thus, the model itself, and the evidence that supports it, can be reviewed at any stage of the calibration process.

5.2.4 Preparation

5.2.4.1 Initial model

As building energy simulation is still a relatively rare practice in Ireland, no initial model was available and hence one was created for this research project. The initial model was created according to program defaults and design documentation such as the scope document and Architectural/Mechanical drawings. A standard core and 4 perimeter zone strategy was applied to each floor. These zones were defined at a higher resolution where multiple air conditioning systems served zones on the same floor.

EnergyPlus v3.1 (US DOE, 2010c) was chosen as the simulation tool based on a comprehensive literature review of program capabilities (Crawley et al., 2008). Furthermore, EnergyPlus input files are in human-readable text format. This allows for the use of version control software capabilities to immediately highlight differences between two versions of the same file. The EnergyPlus program has been validated against experimental measurements and through comparative testing with the BESTEST suite (Henninger et al., 2004).

An Industry Foundation Class (IFC) based Building Information Model (BIM) of the geometry and constructions was created using as-built drawings. This was further verified by a physical site survey. An EnergyPlus input data file (IDF) containing the model geometry was created from the BIM automatically using GST/IDF Generator; a newly developed data transformation tool from the Lawrence Berkeley National

Laboratory (Maile et al., 2007). This is an example of partial automation in the calibration process through the use of BIM technology, as mentioned in Chapter 3.

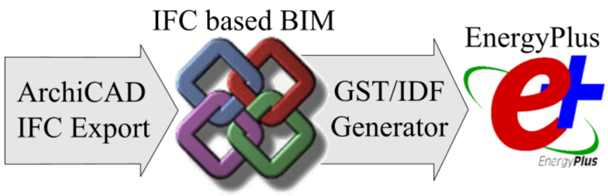


Figure 5.3: Geometry & constructions translation

The HVAC systems and miscellaneous other objects were added to this IDF file using a separate interface tool developed by the author – EnergyPlus HVAC Generator. This tool was written in Visual Basic and EnergyPlus Macro language in a manner that facilitates application to any building. The tool makes use of the filtering capabilities in Microsoft Excel. This allows a user to quickly and reliably change parameter values for multiple zones based on a filtered variable (e.g., zone-type).The tool takes into consideration the need for future expansion to account for additional features that may be required for other projects. EnergyPlus HVAC Generator also includes some automated error checking by issuing a warning if the user has entered an unreasonable value for a parameter. For example, the program issues a warning for fan efficiencies of greater than 90% or less than 30%.

The latest version of the tool, v1.11 at the time of writing, can be found in Appendix B, along with a description of capabilities.

5.2.4.2 Historical weather file

A historical weather file was created from measured data obtained by the on-site weather station. Typical Mean Year 2 (TMY2) data for Dublin was used for solar irradiance values as this was not measured by the weather station. This does incur a certain (unavoidable) amount of error. However, this is not significant due to the buildings' deep floor plan, highly insulated exterior constructions and low-emissivity double-glazed windows. In addition, none of the lighting systems are light dependent.

5.2.4.3 Calibration data

Hourly measured EMS data was obtained for the building and was selected as the target for calibration. As discussed above, measured data for district chilled and hot water energy consumption was unavailable, and thus the calibration criteria focus only on electrical energy consumption.

5.2.4.4 Documentation

Chapter 4 defines the need for *acceptance criteria* and *significance criteria* in the calibration process. ASHRAE Guideline 14 -2002 defines the *acceptance criteria* for hourly data calibration as within ±10% MBE and <30% $CVRMSE_{(hourly)}$. These were selected as the *acceptance criteria* for the demonstrator.

In the absence of guidelines for *significance criteria,* for the purpose of this demonstrator any modification to the model that results in a change of greater than 1% MBE, 1% $CVRMSE_{(monthly)}$, or 2% $CVRMSE_{(hourly)}$ was considered significant.

The *source hierarchy* was defined according to the recommendations in Chapter 3. As required by the methodology, a complete record of all the sources of information used in the model was kept at every stage of the calibration, starting at the preparation stage (revision 1). Table 5.1 illustrates the *source hierarchy* for the final revision under a number of categories as described in Chapter 3. It is used in conjunction with Table 5.2, which illustrates which sections of the model are affected by each source of information. These two tables are populated as follows:

- A new source of information is reviewed for use in the model and this source of information is added the relevant category in Table 5.1 (i.e., electrical panel measurements are added to Category 2: Spot measurement);
- The sections of the model affected by this new source are added to Table 5.2.

Table 5.2 also highlights an occurrence where a source of information overrides one that is lower down in the *source hierarchy*. In this case, power consumption per light fixture was updated based on as-built electrical panel schedules at revision 15 (entry 29). However, this parameter was updated again based on spot-measured data as soon as it was available (entry 32) as this source is further up in the *source hierarchy* and is expected to be a more reliable estimate for this parameter.A detailed change log was kept as required by the methodology. Table 5.3 illustrates the section of the log related to the light fitting change (above) as an example. Further information about any given change can be found in the evidence files stored with the respective revision.

The version control repository (Appendix C) contains the documents themselves as they appeared at each stage of the calibration process.

Table 5.1: List of all sources of information used in the final model (revision 23) and the *source hierarchy* used for this demonstrator.

Category	Source type	Unique reference	Description	Associated file(s) or folder(s)	Revision
1	**Logged measured data**	**o**	EMS lighting and general equipment electrical load data	EMS Light & Equip Data 2007.xlsx	6
		p	EMS emergency power electrical load data	EMS Emerg Data 2007.xlsx	7
2	**Spot measured data**	**h**	Conference room bookings (5 weeks of 2007 data)	Conference Room Calcs.xls	4
		v	Spot measured electrical data (2009 data)	553LP6.xlsx	16
		w	Spot measured electrical data (2009 data)	554LP3.xlsx	17
		aa	Spot airflow (hood) measurements from commissioning phase	also stored in ADU O&Ms: /ADU O&Ms	21
		ae	Spot check of air setpoints at numerous VAV boxes	/VAV Box Setpoints	23
3	**Surveys and physical verification**	**a**	Geometry verified by physical inspection	N/A	2
		i	Office occupancy counts (4 surveys - 3 day, 1 night)	Office_Occupancy.xls	4
		x	Photographic evidence	Return air light fixture.jpg	18
		y	Site visit and walk through	Walkthru notes.txt	18
		z	Photographic evidence	/Photos	19
4	**Interviews**	**j**	HR Interviews	HR Interview Notes.txt; ir6-1-sections.ppt	4
		s	Building operator interview	Operator Interview Notes.txt	11,22
5	**Material data-sheets**	**d**	Material properties - Kingspan KS1000 and TR26 datasheets	Kingspan Material Properties.zip	3
6	**Operation & Maintenance manuals**	**r**	Air Handling Unit Operation & Maintenance manuals	/AHU O&Ms	9,10
		ab	Air distribution unit Operatuion & Maintenance manuals	/ADU O&Ms	21
7	**As-built documentation**	**b**	Architectural and mechanical as-built drawings	/As-builts	2,14
		c	Architectural elevation as-built drawings	/As-builts	3
		g	Summary of wall materials taken from as-built drawings	IR6 -WallMaterials.xls	3
		k	Official IR6 project scope document	SCOPE.doc	4,8
		m	Electrical as-built drawings	/As-builts	6,7,9
		n	Electrical panel schedules	Electrical Panel Schedules.pdf	6,15,16,21
		q	Mechanical as-built drawings	/As-builts	9
		ac	As-built VAV box design data	VVboxIR6 22-09-03.xls	21
8	**Benchmark or best practice models**	**f**	Glass properties - Window 6 datasets	N/A	3
		e	Material properties - ASHRAE Handbook of fundamentals	N/A	3
		l	DOE Benchmark models	/DOE Benchmark Models; http://www1.eere.energy.gov/buildings/commercial_initiative/new_construction.html;	5,11
9	**Standards**	**t**	EnergyPlus Input/Output Reference v3.1	InputOutputReference.pdf	13
		u	ASHRAE 2005 Handbook of Fundamentals	N/A	14
		ad	Advanced Variable Air Volume System Design Guide	Advanced VAV System Design Guide.pdf	22
10	**Initial model**				

Table 5.2: Sections of the model affected by each source of information

Number of entry	Section of model	Subsection or system	Other identifier	Category	Unique reference	Description	Change made at revision	Overwrites entry number
20	HVAC and plant	Systems	All AHUs	7	q	Updated AHU type, coil arrangements and supply & return paths based on mechanical drawings.	9	N/A
21	HVAC and plant	Zones and systems	All fans	6	r	Updated fan power, fan pressure, fan airflow, fan efficiency, economiser, motor power, & motor efficiency based on as-built electrical drawings and O&M manuals.	9	N/A
22	HVAC and plant	Zones and systems	All fans	7	m		9	N/A
23	HVAC and plant	Systems	All AHU Coils	6	r	Updated all AHU hot and chilled water coil characteristics (design air/water on/off temperatures, flowrates and nominal capacities) based on O&M manuals.	10	N/A
~~24~~	~~HVAC and plant~~	~~Systems~~	~~AHU fan curves~~	~~8~~	~~l~~	~~Updated fan part load curves to VSD based on curves found in DOE benchmark models~~	~~11~~	~~N/A~~
25	HVAC and plant	Systems	AHU setpoints	4	s	Updated AHU cooling, heating and preheat coil and mixing box setpoints based on operator interview	11	N/A
26	Error Check	Zones	All ground floor zones	9	t	Added ground surface temperatures based on EnergyPlus v3.1. InputOutput Reference recommendations	13	N/A
27	Geometry	Zones	All zones	9	u	Added internal mass objects to represent furniture as per ASHRAE 2005 Handbook of Fundamentals	14	N/A
28	Geometry	Zones	All zones	7	b	Updated building orientation based on survey information in as-built architectural drawings	14	N/A
~~29~~	~~Internal loads~~	~~Emergency lighting~~	~~All zones~~	~~7~~	~~n~~	~~Addition of constant emergency lighting load was based on as built panel schedules for each zone~~	~~15~~	~~N/A~~
30	Exterior lighting	Lighting panel power consumption	N/A	2	v	Added exterior lighting loads based on spot measured panel data.	16	N/A
31	Exterior lighting	Emergency power panel	N/A	7	n	Added exterior lighting based on EMS data analysis, panel schedules and comparisons with spot measured data for a similarly loaded panel	16	N/A
32	Internal loads	Emergency lighting	All zones	2	w	Addition of constant emergency lighting load was based on spot measurement for wattage/light fitting	17	29
33	Internal loads	Light fixture types	All zones	3	x	Light fixtures were updated to return air type based on photographic evidence and site walkthrough.	18	N/A
34	Internal loads	Light fixture types	All zones	3	y		18	N/A

Table 5.3: Excerpt from detailed change log

Stage of calibration process	Section of model impacted	Sub-section of model	Description of Change	Revision Number	Source(s)	Route through iterative process
HVAC and plant	Zones and systems	All fans	Updated AHU type, coil arrangements and supply & return paths based on mechanical drawings. Updated fan power, fan pressure, fan airflow, fan efficiency, economiser, motor power, & motor efficiency based on as-built electrical drawings and O&M manuals.	9	Operation & Maintenance manuals; As-built mechanical & electrical drawings	N/A
HVAC and plant	Zones and systems	All coils	Updated AHU coil characteristics (design air/water on/off temperatures, flowrates and nominal capacities) based on O&M manuals.	10	Operation & Maintenance manuals;	N/A
HVAC and plant	Systems	AHU fans & setpoints	Updated fan part load curves to variable frequency drive curves based on DOE Benchmark models. Updated AHU coil and mixing box setpoints based on operator interview. Capabilities were added to EnergyPlus HVAC Generator (now version 1.08) to allow for variable AHU coil & mixing box setpoints.	11	DOE Benchmark Models; Building operator interview;	N/A
Error Check	Zones	All zones with VAV RH boxes	Corrected an incorrect IMF entry in EnergyPlus HVAC Generator v1.08 for the VAV_HOTWATER_RH object - due to this, the minimum airflow fraction for all VAV RH boxes was zero, despite the fact that the value was entered as 0.3.	12	N/A	N/A
Error Check	Zones	All ground floor zones, misc other zones	Added misc surfaces which were erroneously deleted by GST/IDFGenerator. These surfaces were identified by a thorough visual inspection of the geometry using GoogleSketchup OpenStudio Plugin. Screenshots are included in the evidence forlder for this revision that highlight the missing surfaces. Corrected EnergyPlus warning by adding missing Ground Temperatures based on EnergyPlus InputOutput Reference recommendations.	13	InputOutputReference.pdf	N/A
Error Check	Building, Zones	Site, All Zones	Corrected building orientation based on as-built drawing survey information. Added infiltration for missed exterior zonetypes (Uncond & Stairs). Corrected location data: Latitude, Longitude, Elevation. Added internal mass objects to represent furnishings as per ASHRAE Handbook of Fundamentals 2005	14	As built drawings; DOE Benchmark models; ASHRAE Handbook of Fundamentals 2005	N/A
Iteration 1	Emergency power loads	All zones	Identified a clear modelling error - simulated lighting consumption greater than installed lighting power. Corrected an incorrect assumption in emergency power distribution - based on electrical panel schedules.	15	Electrical as built drawings; Logged EMS Data, Electrical panel schedules	A
Iteration 2	Exterior Lighting	N/A	Identified exterior lighting in panel schedules. Heat generated by these will not affect HVAC consumption. Analysis showed that the parameter did not meet significance criteria but the analyst deemed it necessary. Thus, further measurement was required to identify the load profile of these lights and remove them from the existing EMS data used to assign loads within the building.	16	Spot measured data;	E
Iteration 3	Emergency power loads	Constant emergency lighting	Identified a discrepancy between spot measured data for wattage/light fitting and current model value (based on as-built electrical panel schedules). The model was updated based on the values obtained by these spot measurements.	17	Spot measured data;	C

5.2.5 Update model

Figure 5.2 comprises the processes that are required to update the model based on the information available at this stage of the calibration process. The number of revisions (Rev 2 -11) relates to the building that was selected as the demonstrator. A higher or lower number of revisions could be required in other projects depending on the complexity of the modelled systems and the amount of information available at this stage of the calibration process.

5.2.5.1 Zone-typing

Section 3.3.3.1 discusses issues related to traditional zoning strategies and defines the zone-typing process. This section gives a brief description of the zone-typing process as applied to the demonstrator. Figure 5.5 is a screenshot of the floor plan of the initial model, described in section 5.2.4.1 . This model uses the traditional zoning strategy in which a core zone and a zone at each perimeter face of the building represent the actual thermal zones in the building. Note however, that in this case the floor plan is additionally split in two halves (East and West) because separate conditioning systems supply either side of the building. This yields 8 zones per floor (1 core zone and 3 perimeter zones per conditioning system) instead of the usual 5 (1 core zone and 4 perimeter zones). This model also includes the assumption that all zones are separated by a physical internal partition (in this case, an un-insulated gypsum plasterboard construction), even where the analyst is modelling open office spaces where there is no actual physical separation between zones. This practice is a result of limitations in older simulation tools, such as DOE-2.1, in which it is not possible to couple long-wave radiation between zones. The zone-typed model couples long-wave radiation between zones that are not separated by a physical wall using Material:InfraRedTransparent objects in EnergyPlus (US DOE, 2009c).

Figure 5.4: Legend for zone-types in figure 5.6.

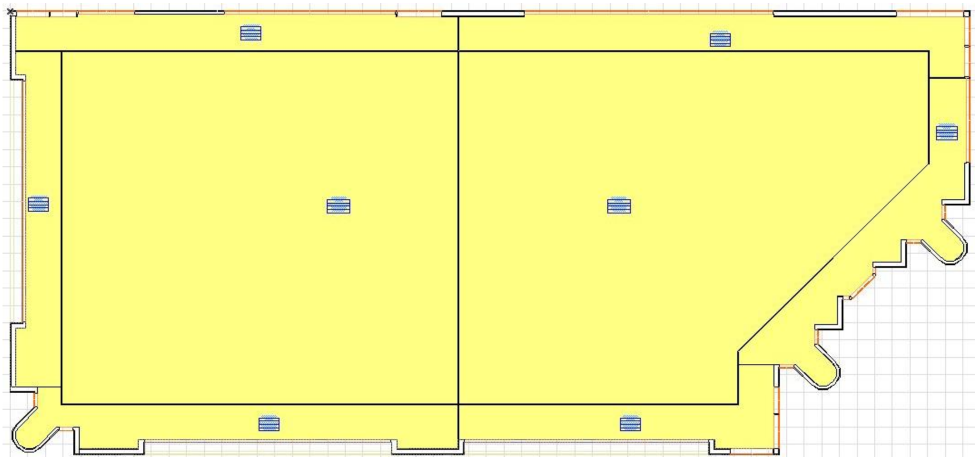


Figure 5.5: Typical zoning strategy - first floor plan from the initial model (revision 1)

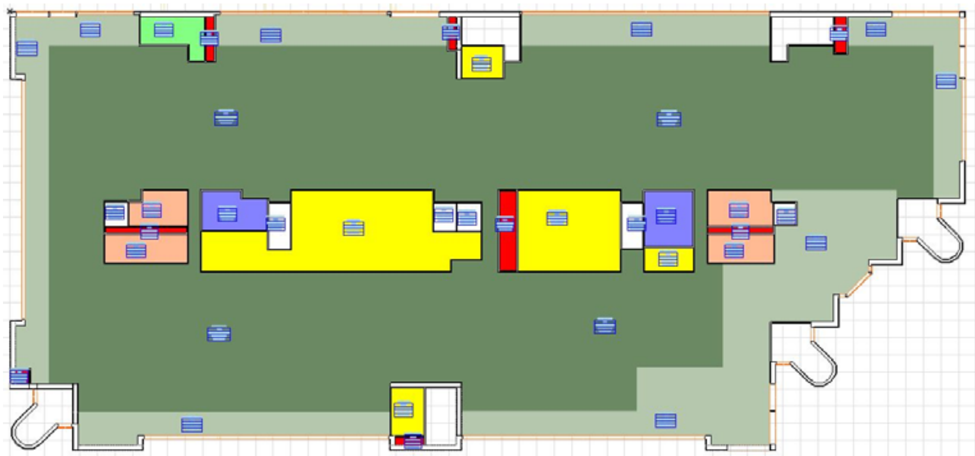


Figure 5.6: First floor plan from the zone-typed model (revision 2)

Figure 5.6 illustrates the thermal zones in the model after the zone-typing process has been completed. Zone-types were defined based on the criteria discussed in Chapter 3. For example, the final zone-typed model:

- Describes communications rooms, conference rooms, stairwells and toilets as separate zone-types because these zones will have significantly different internal load profiles and conditioning methods (e.g., variable air volume terminal boxes with return air plenum, constant air volume with exhaust air, hot water baseboard heaters, etc.).
- Describes large ducts (e.g., 'risers') as separate zone-types in order to ensure accurate floor areas for other zones and so that the simulation can estimate heat transfer between these ducts and other zones in the building.

- Describes return plenums as individual zones instead of incorporating them into floor constructions as an increased thermal resistance (e.g., as an 'air gap' under the slab).

Actual zones in the building of the same zone-type were agglomerated (i.e., represented as a single zone in the model) when:

- The inter-zone surface-length to perimeter ratio was greater than .05%;
- The resultant agglomerated zone had a maximum distance in any dimension of 75m and a maximum floor area of 1,500m^2.

The zone-typing process yielded a model containing 106 zones and 2,494 surfaces, compared to 27 zones and 955 surfaces in the initial model. Although the zone-typed model is a more accurate representation of the actual building, it has an associated cost both in terms of the additional time required to create the detailed model and in model run-time. For the demonstrator project, changing from the initial model strategy to the zone-typing strategy increased run-time 370%, from 2792 seconds (46 minutes) to 13,122 seconds (3 hours, 38 minutes)[2]. Appendix A contains a more comprehensive discussion of the zone-typing process. Both the initial and zone-typed model are available in the version control repository (Appendix C).

5.2.5.2 Constructions

Wall constructions and materials properties were updated in revision 3 based on commissioned as-built material datasheets (Table 5.1, Category 5). Standards or benchmark models were used where these were unavailable (Table 5.1, Categories 8 and 9). The sources of the information used can also be found as comments under the name of each individual material in the input file for the EnergyPlus model.

5.2.5.3 Internal loads

The internal loads were first updated in revisions 4 to 7. Occupancy data for each zone-type was updated based on human resources interviews, personnel counts, and multiple day and night occupancy surveys (Table 5.1, Category 3). Furthermore, a room booking database was used to determine conference room occupancy (Table 5.1, Category 2).

[2] These run-times were obtained with models that use a 15 minute zone time-step and a 1 minute system time-step for HVAC and plant calculations. Decreasing the zone time-step has very little effect on the energy consumption results (e.g. using a 5 minute time-step affects MBE and CVRMSE(hourly) by less than 0.005%).

Infiltration loads were added to the model based on best practice models (Table 5.1, Category 8) as no measured source of information was available related to this parameter.

Measured data from the EMS was used to update lighting and equipment loads at revisions 6 and 7 (Table 5.1, Category 1). Average values were used for measurement streams that were constant within a maximum error band of ±5% over any given hour. The remaining data-streams were analysed in order to identify patterns and to apply these loads to the model using schedules (e.g., day-typing (Kaplan et al., 1990; Abushakra et al., 2001)). However, much of the data did not conform to a day of week pattern for each month within ±5% error.

Modelling of the lighting and general plug loads using typical schedules could have been employed. However, this introduces error into the simulation. This is unnecessary if complete annual measured data is available and the simulation tool is capable of using this data directly. Thus, instead of day-typed schedules, the *actual measured values* for these loads were used in the model *at each hour of the simulation*. Each of the individual EMS data-streams (measured at nine panels across the building) were added to the model *on a floor-area-weighted basis*. This was deemed a better approach because the primary purpose of calibrated models is to investigate changes in HVAC consumption due to a proposed ECM, not to explicitly model lighting and plug loads. This is especially the case when this would incur significant (>5%) unnecessary error in the hourly results. Plug loads are typically occupant controlled and building operators do not have a significant amount of control over these aspects of building consumption. Furthermore, cost effectiveness analyses of retrofit options related to lighting can be performed easily when measured data is available. Thus, there is no need to model these aspects of building consumption using schedules when accurate measured data is available for these variables. However, lighting and plug load consumption data was measured at a multiple zone level. Therefore, assumptions were made in order to assign these loads to specific zones, such as:

- As-built electrical drawings and panel schedules were used to allocate these loads on a floor area weighted basis.
- Additional spot measurement, as-built panel schedules and as-built electrical drawings (Table 5.1, Categories 2 and 7) were used to further refine the floor

area weighting of this measured data at later stages of the calibration process (revisions 15 to 17).

- Large constant loads were assigned to the specific zone in which the equipment is located and exterior equipment (external lighting) was added to the model.

The version control repository (Appendix C) contains a record of these assumptions including the measured data and spreadsheet calculations on which they are based.

5.2.5.4 HVAC and plant

The model inputs relating to HVAC and plant were updated from revision 8 to 11 based on the readily available information: the official design scoping document, commissioned as-built mechanical drawings, operator interviews and O&M manuals including spot air hood measurements (Table 5.1, Categories 4, 6 and 7). Further refinements were made at later stages of the calibration process. For example:

- Pump characteristics were verified on-site at revision 19 (Table 5.1, Category 3);
- Air Distribution Units O&Ms (including commissioning spot measurements) were obtained and used to update the maximum airflows and heating coil capacities on a zone by zone basis at revision 21 (Table 5.1, Category 2);
- Fan part load curves were updated to reflect operating static pressure set-points at revision 22 (Table 5.1, Category 4);
- Manual spot checks of VAV box set-points were used to update the model at revision 23 (Table 5.1, Category 2).

All HVAC characteristics in the final model were either updated or verified based on information at a higher level in the *source hierarchy* than the initial model. For example,

- Fans type, maximum airflow, pressure & operating efficiency were updated based on the O&M manuals (Table 5.1, Category 6). Part load curves were selected from the Advanced Variable Air Volume Systems Design Guide (Hydeman et al., 2003) based on fan static pressure set-points (Table 5.1, Category 8);
- Coils types; air and water on and off design temperatures; maximum air and water flow-rates; and heating/cooling capacity were updated based on heating and cooling coil O&M manuals (Table 5.1, Category 6).

5.2.6 Error check

There is a need to evaluate whether the model is performing as expected. As discussed in Chapter 3, the tools to do this automatically are not yet available and thus, this step relies on the analyst.

Several inconsistencies were identified and corrected at this stage of the calibration process. Revision 12 demonstrates a case in which the outputs from the simulation are clearly unreasonable. The minimum airflow through the VAV Air Distribution Units (ADUs) was zero, despite an entered value of 0.3. This was due to a bug in EnergyPlus HVAC Generator v1.08 where two lines of code were reversed, causing the entry for the minimum airflow parameter to be blank (i.e., zero). Revision 14 illustrates an instance where previously obtained information was added to the model incorrectly: infiltration was accidentally omitted for Unconditioned and Stairs zone-types and the building orientation was incorrect.

5.2.7 Iterative process

The model met the defined acceptance criteria (ASHRAE 2002) for calibration to hourly data at the first iteration (revision 15). However, even though the revision 15 models meets the acceptance criteria, model error was still quite dependent on outdoor dry-bulb temperature (Chapter 6 discusses this in detail). Thus, the analyst continued the calibration in order to improve the model and to thoroughly demonstrate all stages of the iterative process. Figure 5.7 illustrates all paths through the iterative process for each revision using letters A to F. Table 5.4 gives a detailed description of the changes at one revision for each step (A to F) through the iterative process. As can be seen in Table 5.4, Revision 16 describes a case where it was possible to obtain new information but significant resources were required: spot measurement of electrical panels. Thus, a significance test was performed and two runs were made to evaluate the significance criteria as described in Chapter 3. The parameter in question (exterior lighting) was modified between estimated maximum and minimum values based on commissioned as-built panel schedules. The results described in Table 5.5 indicate that this parameter did not meet the significance criteria.

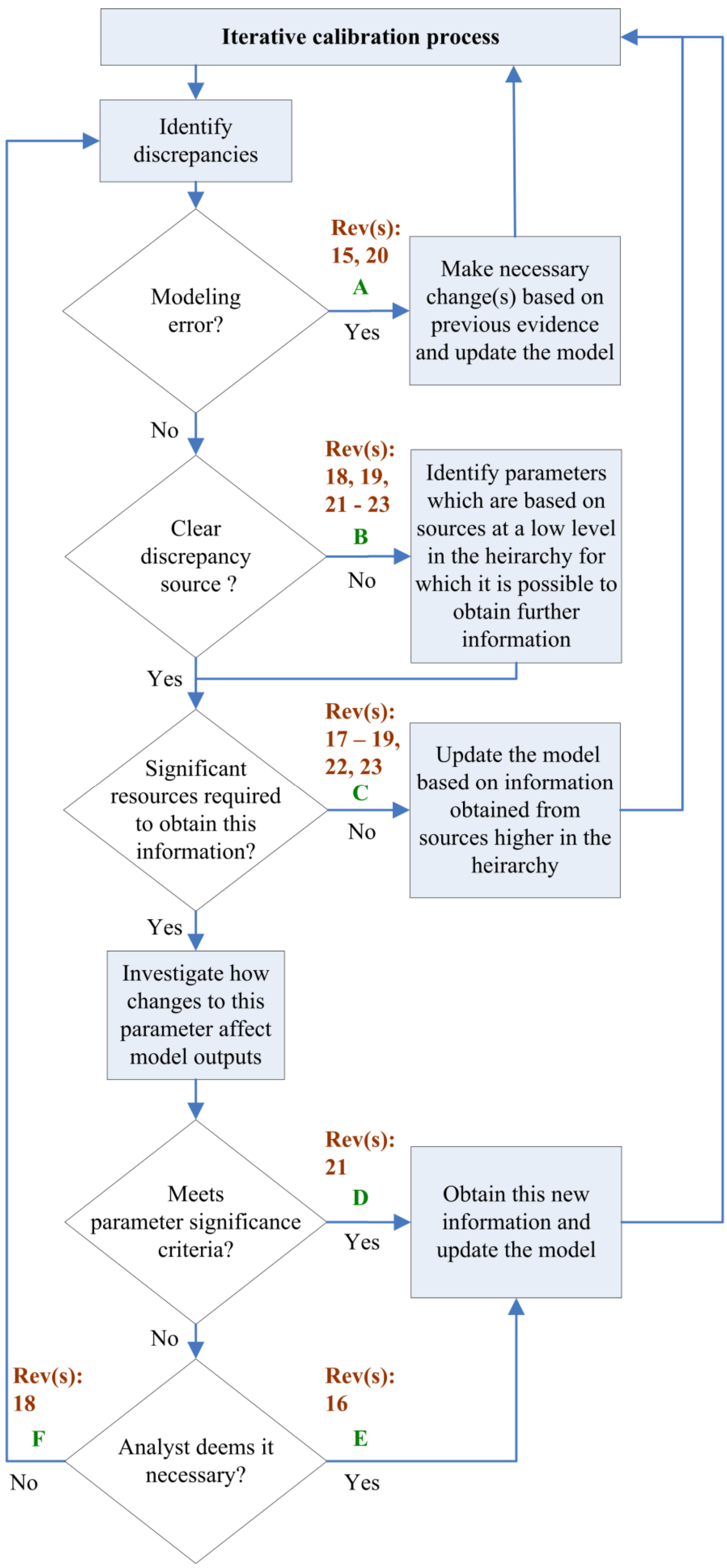


Figure 5.7: Overview of the path through the iterative process as occurred in this demonstrator

Table 5.4: Examples of each stage of the iterative process

Example of point in Figure 5.7	Revision	Description
A	15	The simulated lighting consumption was greater than the installed lighting power in some zones – a clear modelling error. It was discovered that the consumption of several high load devices was spread out across many zones in the building. This flawed assumption in emergency power distribution was remedied, and a new approach was taken based on an as-built electrical panel schedules document.
B	19	There were no clear discrepancy sources in the model. Starting at the lowest level in the *source hierarchy*, parameter(s) were identified for which more reliable information or further measurement was possible. It was discovered that parameters related to the pumps were based on the initial model and that further information was available. It was discovered that secondary pumps supply the ChW and HW loops from outside the building and that the tertiary pumps within the building are not yet connected.
C	18	A discrepancy was identified between spot measured data for wattage/light fitting and previous revision value (which was based on as-built electrical panel schedules). There were little further resources required as an Intel technician had previously measured that panel. Thus, no significance test was required.
D	21	Maximum air flows and heating coil max capacities related to some of the air distribution units (VAV boxes) were based on the initial model and it was possible to obtain further information. However, significant resources were required to obtain this information and enter it into the model. A significance test was performed and the parameter met the criteria. Thus the information was obtained and the model updated accordingly.
E	16	Exterior lighting fed from internal lighting panels was discovered through an in-depth review of the as-built panel schedules. The heat generated by these lights does not affect HVAC consumption in the real building, but due to the floor area weighting of EMS data, simulated HVAC consumption was affected. Analysis showed that the parameter did not meet significance criteria, but the analyst deemed it necessary. Thus, spot measured data was obtained to identify the power consumption of these lights and the floor area weighting of the EMS data was corrected to account for these loads.
F	18	The floor area weighting of the EMS data from one the equipment panels did not account for a relatively high load contained in one zone on the ground floor (vending machines). However, the parameter did not meet the significance criteria required to justify additional spot measurement.

Table 5.5: Results of significance test at revision 16

	MBE	CVRMSE (monthly)	CVRMSE (hourly)
Run 1: Constant maximum design load	7.80%	7.85%	8.14%
Run 2: Photocell operation at 75% of design load	8.50%	8.55%	8.96%
Significance criteria	1.00%	1.00%	2.00%
Difference between the two runs	0.70%	0.70%	0.82%

5.3 Conclusion

This chapter describes the application of the calibration methodology (defined in Chapter 3) to a comprehensive case study. The use of this methodology yields an systematic, evidence-based approach to the entire calibration process. The version control repository (Appendix C) stores a complete history of the calibration process and the evidence on which each change is based. Furthermore, it was found that because EnergyPlus input syntax is human-readable, the version control software makes it simple to identify changes between revisions. Changes can be quickly and easily reviewed against the evidence on which they are based, making it less likely that unexpected accidental errors or changes are included in the new revision.

This chapter also describes the zone-typing process as applied to the IR6 building. The process yields a more accurate representation of the building than the typical core-and-4-perimeter zoning strategy. Appendix A describes this in further detail.

Chapter 6: Results

"Things should be made as simple as possible, but not any simpler."

- Albert Einstein

6.1 Chapter introduction

This chapter describes the results of the demonstration contained in Chapter 5. The first section of this chapter describes the data analysis and visualisation techniques used to present the results. Later sections discuss the results and findings of the demonstrator, including a list of proposed ECMs for the IR6 building.

6.2 Data analysis techniques

This research presents results under three consumption categories: total building electrical consumption (Total), HVAC electrical consumption (HVAC) and lighting, plug load and emergency power consumption (LPE). MBE and CVRMSE values were calculated for each of these consumption categories using the formulae section 2.3.2.1 . Several other data analysis techniques were used in this research and require definition here. For example, biased percentage error was calculated by the following formula:

$$\text{Biased Percentage Error} = \frac{\mathrm{M_i} - \mathrm{S_i}}{\mathrm{M_i}}$$

Where $\mathrm{M_i}$ and S_i refer to the measured and simulated value at any instance i respectively. Thus, positive values illustrate periods when the model under predicts actual consumption, and vice-versa. However, average calculations using this value will not account for offsetting errors. Thus, absolute percentage error is an important variable:

$$\text{Absolute Percentage Error} = \sqrt{\left(\frac{\mathrm{M_i} - \mathrm{S_i}}{\mathrm{M_i}}\right)^2}$$

Furthermore, characteristics of subsets of the data provide immediate insight into the circumstances under which the model least accurately represents the building. This powerful analysis technique, commonly known as ‘bin’ analysis, consists of collating data into subsets (or bins) based on the value of another variable. Typical variables on which consumption is likely to be dependent are: hour of day; day of week; month of year; outdoor dry-bulb temperature; outdoor wet-bulb temperature; and global solar radiation. Solar radiation and wet-bulb temperature bins were not used in this demonstrator because energy consumption is not highly dependent on these variables. This is due to the deep floor plan nature of the building and district chilled water supply respectively.

The general form of this formula to calculate the average value ($\beta_{h,v}$) of a variable (v) for a specific hour of the day (h) over all the days in the year (d) is:

$$\beta_{h,v} = \frac{\sum_{d=1}^{N_d} v_{h,d}}{N_d}$$

Where $v_{h,d}$ is the value of the variable at a specific hour of the day (h) on a specific day of the year (d), and N_d is the number of days in the year. A specific example of bin use could be to determine the average error in total building electrical consumption between the simulated and measured data. Thus, $\beta_{5,AbsErr(total)}$ is the absolute error for total building electrical consumption averaged every day at 5a.m. throughout the annual simulation period.

The results of this research are presented using the above formulae for both Biased Percentage Error and Absolute Percentage Error for three levels of electrical measurement: Total building electrical consumption (Total), HVAC electrical consumption (HVAC) and internal load electrical consumption (lights, plug and emergency power - LPE). Bin analysis was conducted using hour-of-day, day-of-week, month-of-year, and outdoor air temperature bins.

Furthermore, Table 6.1 to Table 6.3 also present the standard deviation of each average biased error bin for every revision. When compared against each other, these standard deviations are a means of highlighting on which variable the error is most dependent. The following two formulae describe the calculations of the standard deviation of an hourly bin for a specific variable, v.

$$\overline{\beta_v} = \frac{\sum_{h=1}^{N_h} \beta_{h,v}}{N_h}$$

$$\sigma_{\beta_{h,v}} = \sqrt{\frac{1}{N_h}\sum_{h=1}^{N_h}\left(\beta_{h,v} - \overline{\beta_v}\right)^2}$$

6.3 Visualisation

As discussed in the literature review (section 2.3.2.2), there are inherent difficulties in presenting the amount of data output by whole building energy models in a coherent and readily understandable manner. Three-dimensional plots are essential, as they significantly increase the number of data-points that can be visualised when compared to two-dimensional graphing techniques. However, three-dimensional plots can often obscure data, and do not lend themselves well to printed media. Figure 6.1 and Figure 6.2 represent identical data. However, it is clear that the carpet plot represents a more easily understandable method for visualisation, which does not obscure data. Furthermore, the carpet plot is more spatially efficient. Both plots use identical text sizes, yet Figure 6.2 has a smaller graphing area even though the overall image is 20% larger (due to the increased white space that is required to display the rotated 3-dimensional image). Thus, carpet plots are used throughout this thesis.

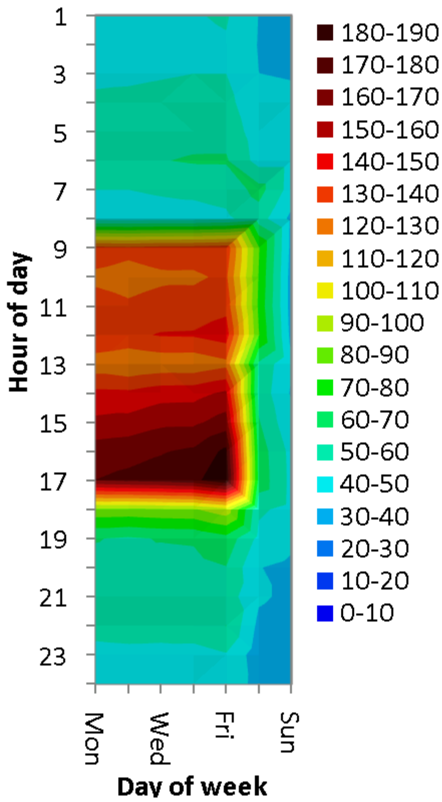


Figure 6.1: Carpet plot visualisations of initial model average absolute percentage error for Total electricity consumption.

Furthermore, even if three-dimensional plots are used, the sheer number of data points in an annual simulation makes it difficult to quickly visualise the data in a meaningful manner. Consider that the output from an annual simulation (8,760 data points or more) plotted hourly would require a carpet plot 365 data-points long and only 24 wide. Such 'tapestry' plots take significant time to review and comprehend. However, during the course of this demonstrator, it occurred to the author that carpet plots could be combined with bin analysis to better visualize these large data-sets. This technique has not been published to date. It should be noted that only independent variables are plotted on any given carpet plot. For example, outdoor dry-bulb temperature is plotted with respect to day of week (of which temperature should be relatively independent) instead of hour of day or month of year (of which temperature is dependent).

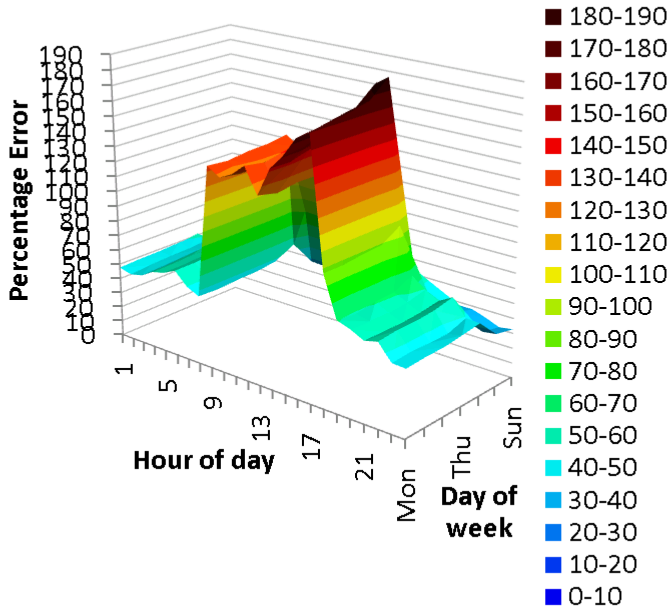


Figure 6.2: Surface plot visualisation of initial model average absolute percentage error for Total electricity consumption.

Also, it should be noted that given the fixed total number of colours (20), the smallest possible integer step size is used for each image (e.g. 1%, 2%, 3% etc.). This illustrates each image to the highest level of detail while maintaining integer step sizes, with the disadvantage of making it more difficult to quickly compare images that use different colour ranges.

Figure 6.4 in the next section illustrates model error for the initial model using carpet plots by bin for hour of day, day of week, month of year and outdoor dry-bulb air temperature rounded to intervals of 2°C. The Max and Min values correspond to the maximum and minimum data-point in the plot directly above. In the image, it is immediately apparent that the illustrated model revision (the initial model) is:

- More inaccurate during weekdays than weekends (Figure 6.4, first plot);
- More inaccurate during the summer than the winter (Figure 6.4, first and second plots);
- More inaccurate from 9am to 5pm (with peak inaccuracies occurring later in the day) than at other times of the day (Figure 6.4, second and third plots);
- Most inaccurate at high outdoor air temperatures, with maximum absolute error of over 210% (Figure 6.4, fourth plot). The white areas of this plot correspond to data-points which do not occur in the simulated year. In other words, it was

never below -2°C on a Thursday or above 24°C on a Wednesday in 2007 at the weather station at Intel.

This method of analysis allows an analyst to rapidly assess how well the simulation predicts actual energy consumption, and the patterns that are presents in the model error, on just a single page. Thus, this new approach was used to view model error at each revision of the demonstrator.

Although it is a minor issue, due to software limitations it was not possible to interpolate colours around the edges of carpet plots for continuous variables, such as day of week and hour of day. In other words, it was not possible to interpolate the colours outside of the plot area between Sunday and Monday and between midnight and 1am.

The advantages of using carpet plots of binned variables to visualize simulation data can be seen by comparing the scatter plot below (Figure 6.3) with the fourth plot of Figure 6.8. It is more clearly visible in the carpet plot that there is still a certain amount of outdoor air temperature dependent error in the model, and the carpet plot also requires significantly less space to visualize the same information.

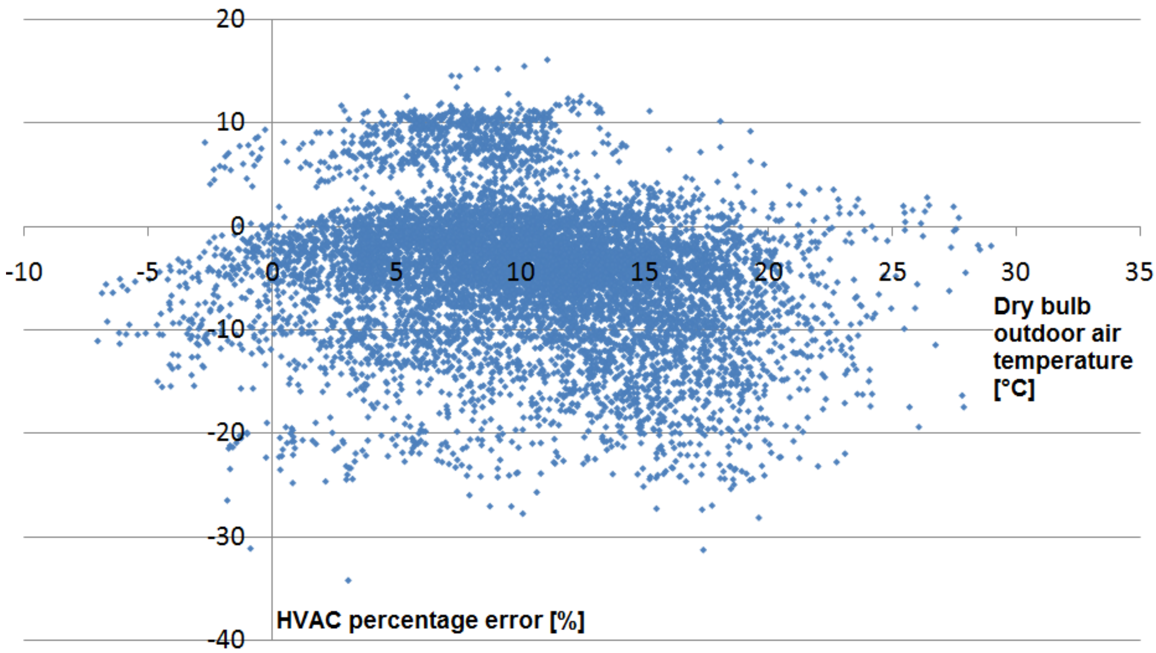


Figure 6.3: Scatter plot of final model (revision 23) HVAC percentage error against outdoor dry-bulb temperature.

6.4 Results

6.4.1 Comparison of the initial and final models

Section 5.2.5.3 describes that lighting, plug, equipment, and emergency (LPE) power load data are used by the model on an hourly basis, with assumptions and modifications made to assign this data on a floor-area-weighted basis. Further details of all the assumptions are contained in the version control repository at revisions during which changes were made to lighting, plug and emergency loads (see Appendix C). Thus, the MBE for this consumption (LPE) for the final model is zero and the CVRMSE is very low (0.02%) and the visualisation plot is not needed. The use of internal load data in this manner means that the error in total building electrical consumption (Total) is effectively a diluted version of the HVAC consumption error (as Total consumption is equal to the sum of HVAC and LPE consumption). However, it should be noted that the model would meet the acceptance criteria even if they were also applied to HVAC energy consumption.

This section compares the initial and final model results with the measured consumption data for 2007 using techniques described section 6.3. As can be seen from the following six images, there was a large improvement in how well the model fit the measured data. The MBE for total building electrical consumption drops from -78.89% to -1.00% between the initial model and final calibrated model respectively. Likewise, $CVRMSE_{(hourly)}$ drops from 95.02% to 1.87% between the initial model and final calibrated model respectively (Figure 6.4 and Figure 6.7). HVAC MBE and $CVRMSE_{(hourly)}$ drop from -342.48% to -4.16% and 349.1% to 7.8% respectively (Figure 6.5 and Figure 6.8). Also, Figure 6.6 indicates the significant amount of error between the internal loads in the initial model and the real building.

6.4.1.1 Initial model results

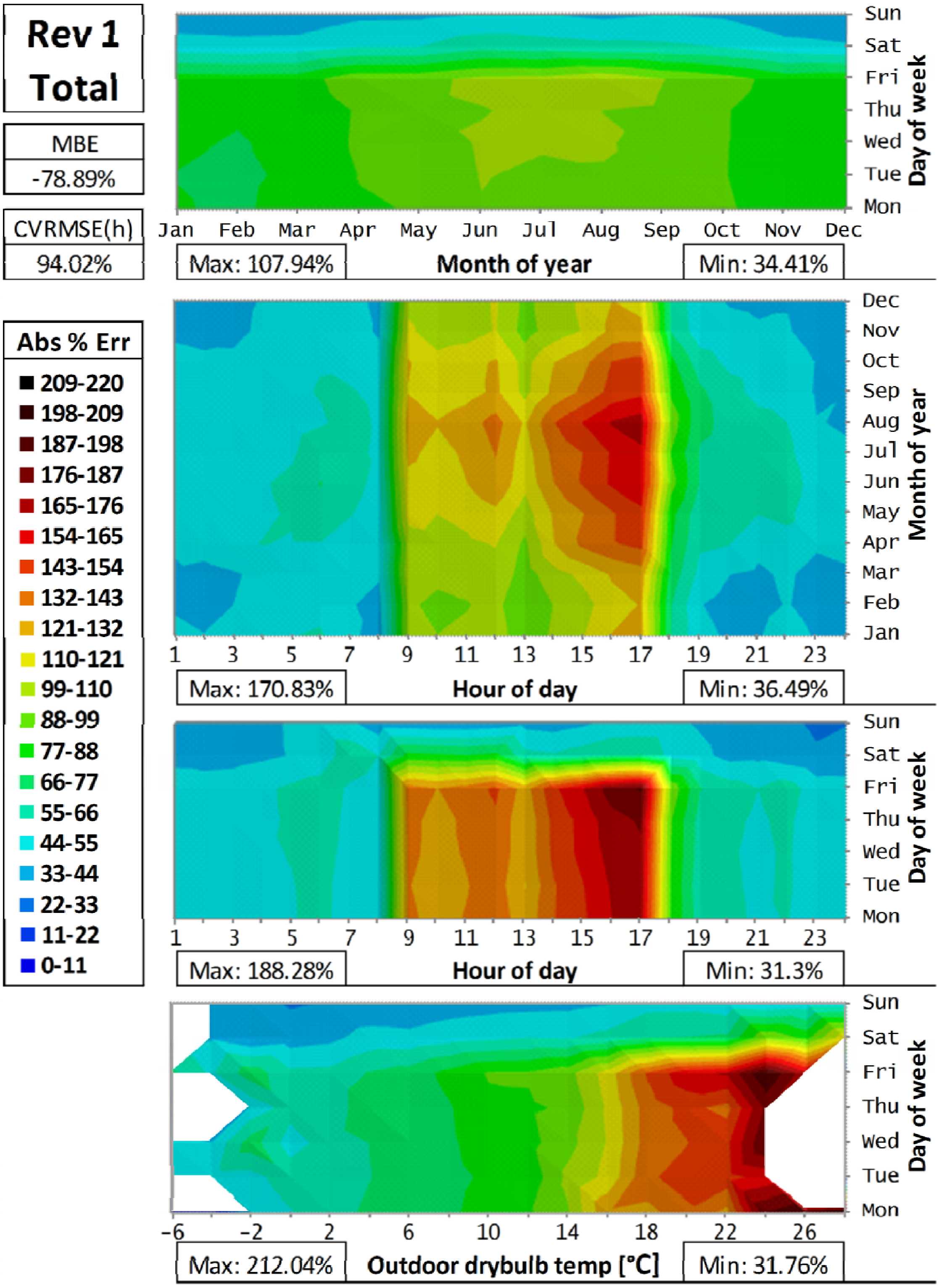


Figure 6.4: Initial model (revision 1) average absolute percentage error for Total electricity consumption.

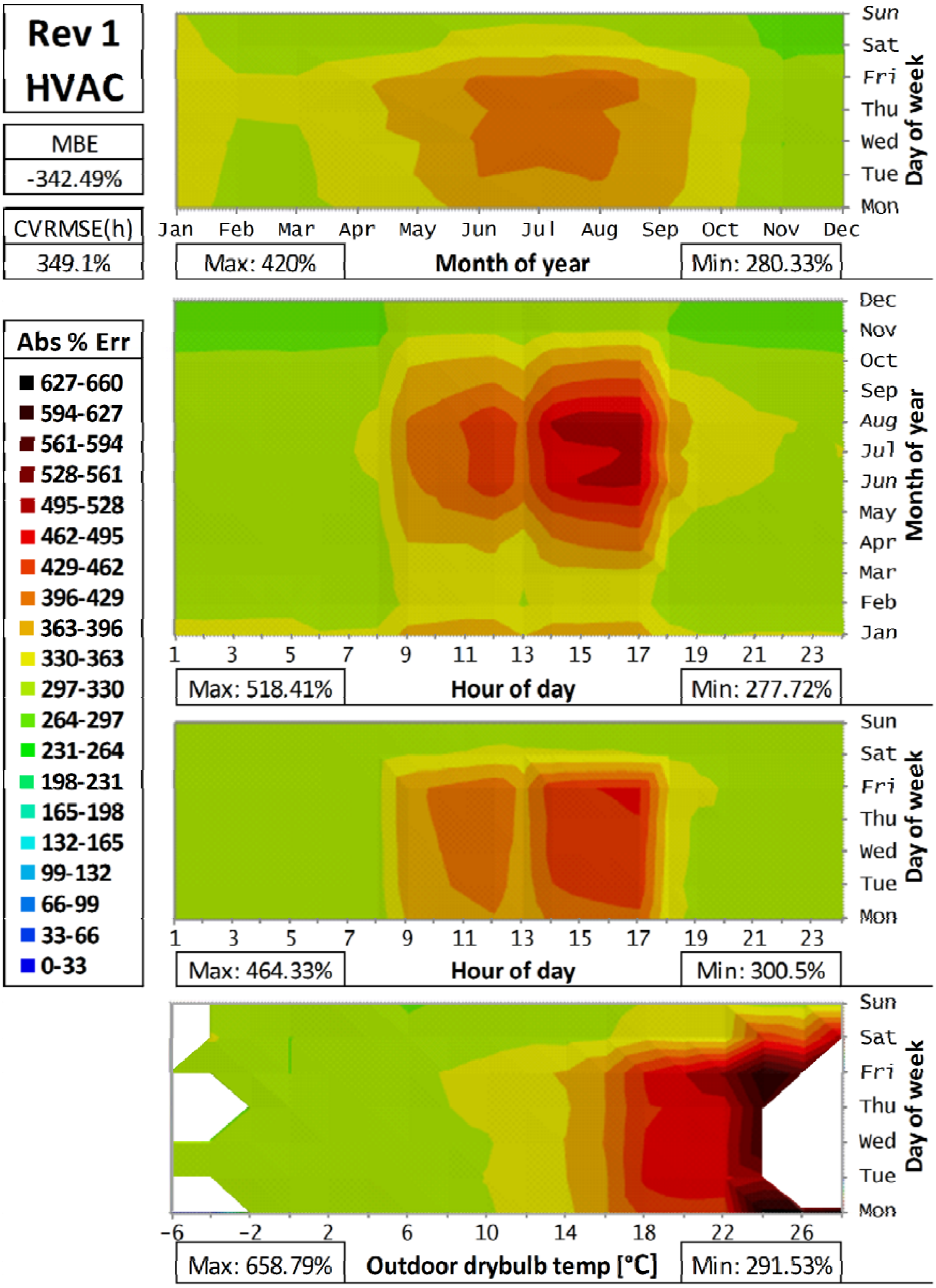


Figure 6.5: Initial model (revision 1) average absolute percentage error for HVAC electricity consumption.

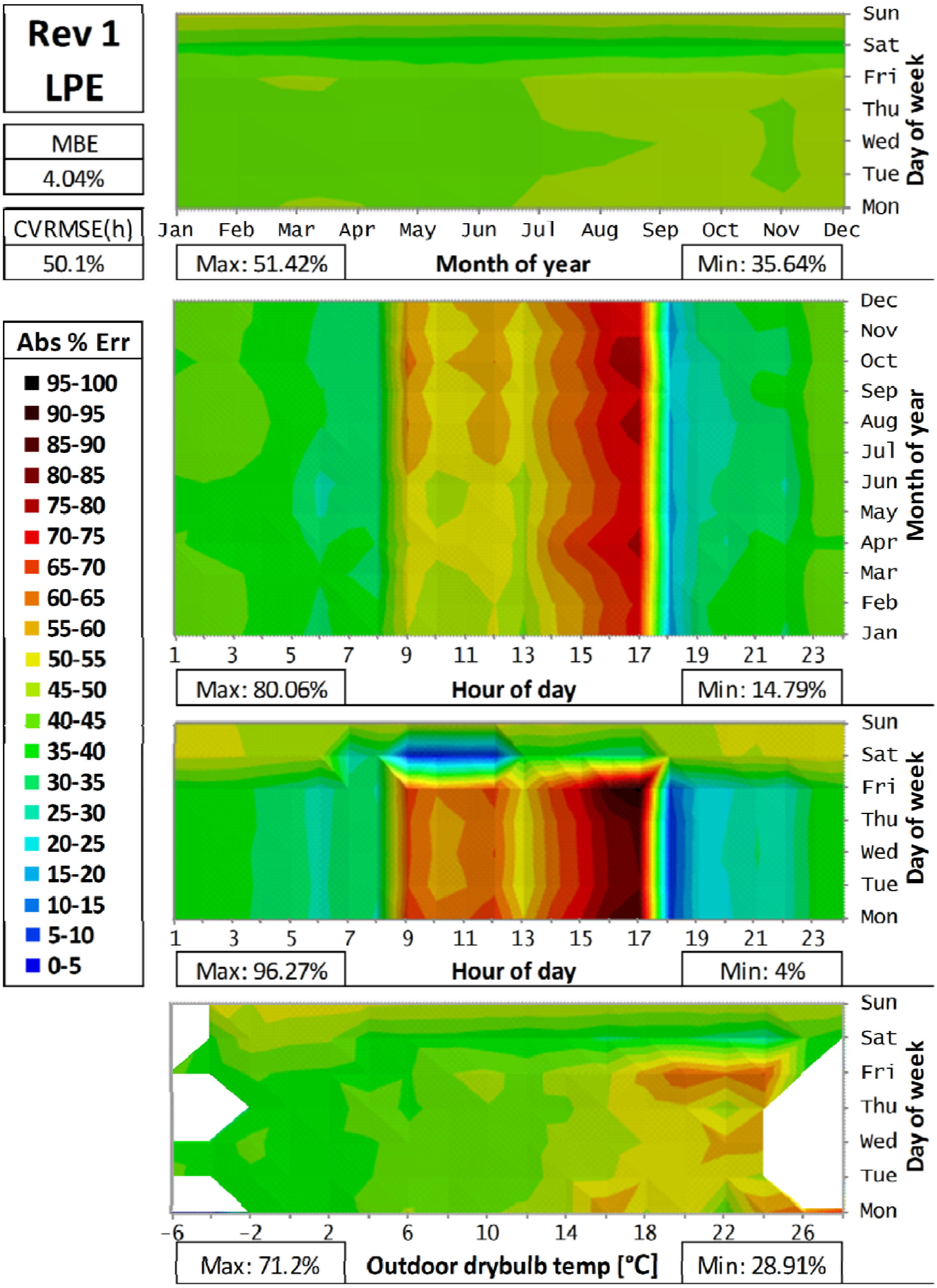


Figure 6.6: Initial model (revision 1) average absolute percentage error for LPE electricity consumption.

6.4.1.2 Final model results

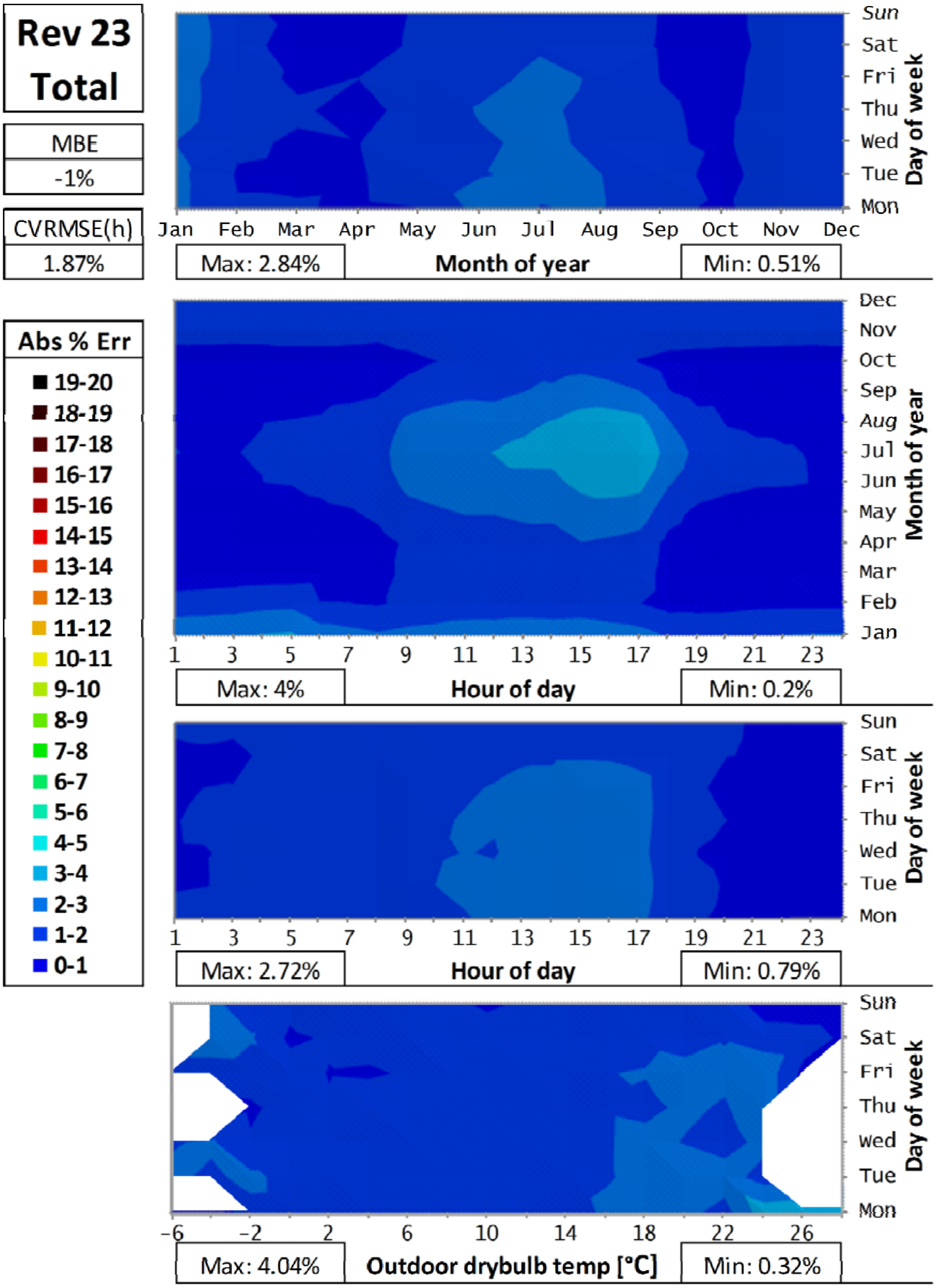


Figure 6.7: Final model (revision 23) average absolute percentage error for Total electricity consumption.

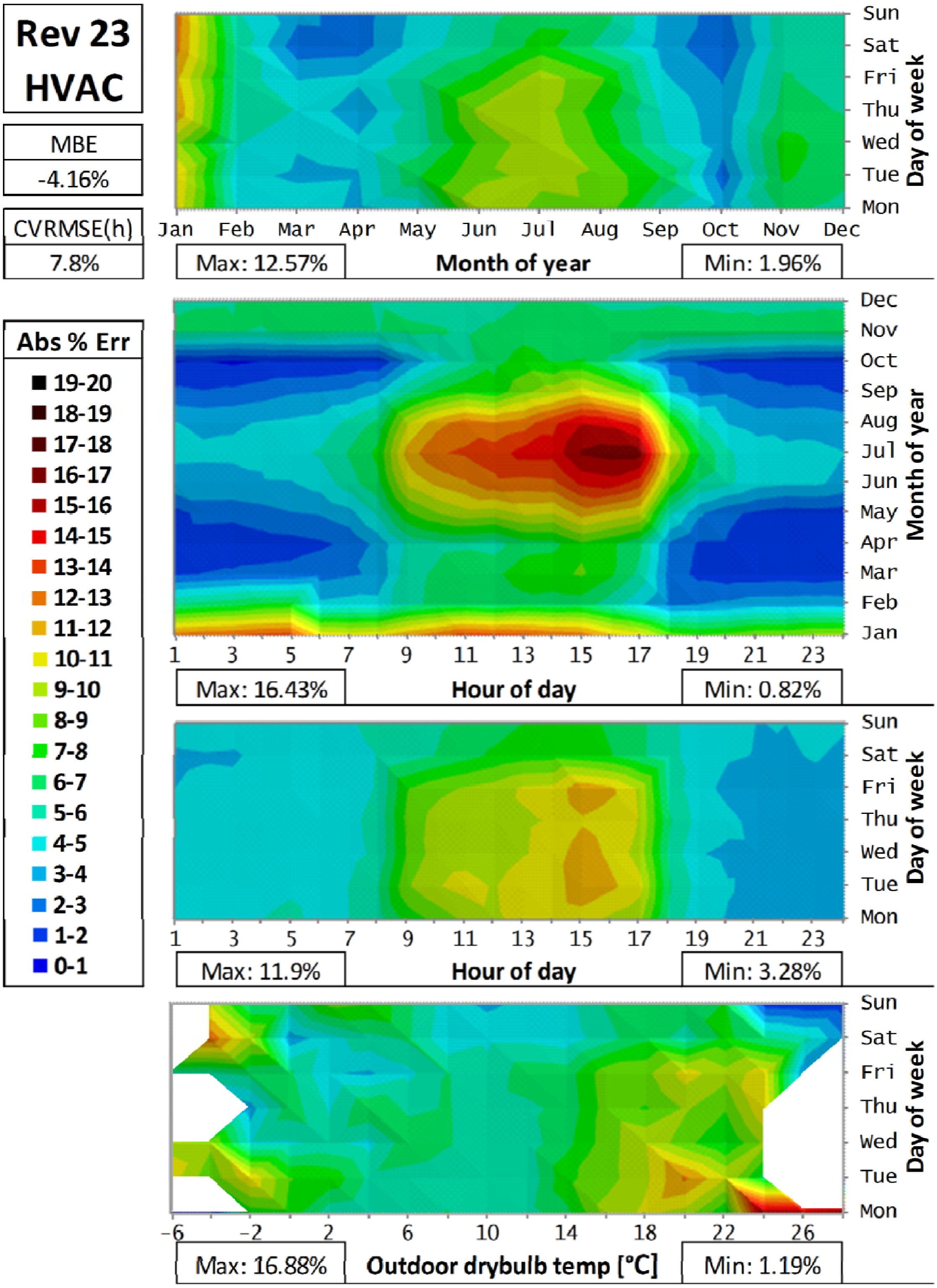


Figure 6.8: Final model (revision 23) average absolute percentage error for HVAC electricity consumption.

6.4.2 Results over the entire history of the calibration process

Table 6.1 to Table 6.3 on the following pages illustrate the accuracy of the model at each revision of the project for total building electrical consumption (Total), HVAC electrical consumption (HVAC) and internal loads electrical consumption (LPE). The status of the model with regard to the most stringent hourly and monthly acceptance criteria currently available (ASHRAE Guideline 14 - 2002) is also calculated. Maximum and minimum model error at any hour over the entire annual run is also given, along with the standard deviation of biased percentage error for each of the data bins discussed earlier in this chapter.

It should be noted that the significant decrease in error between the initial model (revision 1) and revision 2 is due primarily to an upgrade from EnergyPlus HVAC Generator v1.0 to v1.07. This later version included automated error checking of many parameter values. This feature identified an unreasonably low value for AHU fan efficiency and corrected it to a default value. As expected, when the zone-typing change is examined in isolation (i.e., using the same version of EnergyPlus HVAC Generator as the initial model) it yields a smaller effect on model error: MBE, $CVRMSE_{(monthly)}$ and $CVRMSE_{(hourly)}$ improve by +7.63%, -7.73%, and -6.94% respectively.

As can be seen from the tables, the acceptance criteria for this project are met at each stage of the iterative process (from revision 15 onwards). Monthly acceptance criteria are met from revision 19 onwards due to more stringent requirements for Mean Bias Error. Figure 6.9 below graphically illustrates the gradual improvement of the model over time. The earlier revisions (1 to 6) highlight the significant issues with using just MBE and $CVRMSE_{(monthly)}$ values as acceptance criteria.

Appendix D contains further results: Total, HVAC and LPE carpet plots for average absolute and biased percentage error at each model revision.

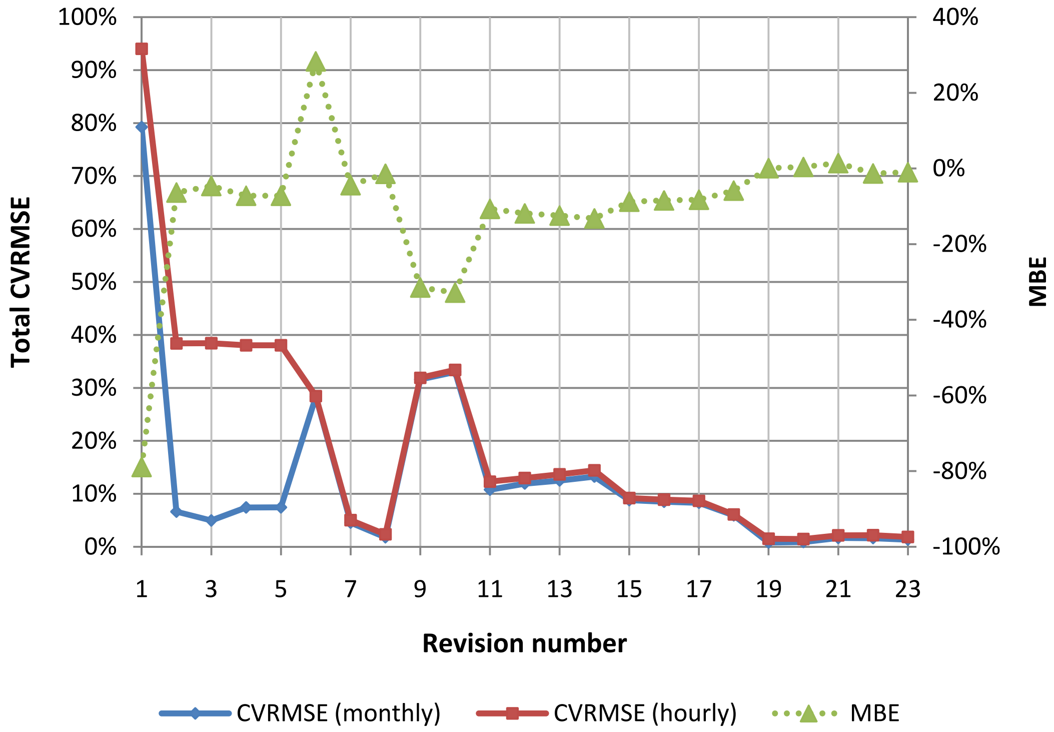


Figure 6.9: MBE and CVRMSE for total electrical consumption against revision model over the entire calibration process.

Table 6.1: Analysis of error in Total electricity consumption by revision.

Revision number	Stage of calibration process	Annual energy consumption (GWh)	Mean Bias Error (MBE)	CVRMSE (monthly)	CVRMSE (hourly)	Maximum error (hourly)	Minimum error (hourly)	Standard deviation of average biased error by bin: Hour	Day	Month	Drybulb	Meets hourly criteria?	Meets monthly criteria?
Measured		**4.581**											
Hourly	**Calibrated Model**	**+/- 10%**	**+/-10%**		**<30%**								
Monthly	**Calibrated Model**	**+-5%**	**+/-5%**	**<15%**									
1	Preparation	8.195	-78.89%	79.26%	94.02%	-21.52%	-263.30%	35.54%	21.08%	7.57%	36.41%	N	N
2	Zone-typing	4.872	-6.34%	6.63%	38.40%	35.42%	-99.49%	28.52%	18.03%	1.93%	17.19%	N	N
3	Constructions	4.792	-4.61%	4.97%	38.44%	37.15%	-98.15%	28.77%	18.26%	1.86%	17.22%	N	Y
4	Internal loads	4.911	-7.21%	7.43%	38.05%	34.33%	-98.38%	28.09%	17.81%	1.79%	16.84%	N	N
5	Internal loads	4.911	-7.21%	7.44%	38.04%	34.35%	-98.32%	28.08%	17.80%	1.85%	16.91%	N	N
6	Internal Loads	3.284	28.31%	28.33%	28.45%	62.19%	15.18%	2.93%	1.30%	0.80%	2.59%	N	N
7	Internal Loads	4.783	-4.40%	4.57%	5.03%	1.68%	-14.24%	1.11%	0.11%	1.25%	2.12%	Y	Y
8	HVAC and plant	4.645	-1.40%	1.79%	2.36%	4.38%	-9.07%	0.83%	0.08%	1.14%	1.46%	Y	Y
9	HVAC and plant	6.022	-31.44%	31.59%	31.90%	-21.34%	-53.36%	2.41%	0.26%	3.08%	5.39%	N	N
10	HVAC and plant	6.084	-32.81%	33.03%	33.40%	-21.23%	-56.14%	2.80%	0.30%	3.84%	6.49%	N	N
11	HVAC and plant	5.071	-10.68%	10.78%	12.31%	-0.32%	-47.79%	3.94%	1.40%	1.42%	3.76%	N	N
12	Error Check	5.125	-11.87%	11.94%	12.99%	-3.27%	-45.86%	3.10%	1.29%	1.16%	2.10%	N	N
13	Error Check	5.151	-12.45%	12.51%	13.67%	-3.54%	-47.72%	3.35%	1.41%	1.21%	2.13%	N	N
14	Error Check	5.186	-13.20%	13.26%	14.44%	-4.20%	-51.56%	3.40%	1.51%	1.20%	2.53%	N	N
15	Iteration 1	4.982	-8.75%	8.80%	9.21%	-1.40%	-24.50%	1.51%	0.54%	0.89%	1.81%	Y	N
16	Iteration 2	4.968	-8.45%	8.51%	8.91%	-0.87%	-23.38%	1.52%	0.47%	0.92%	1.92%	Y	N
17	Iteration 3	4.959	-8.25%	8.31%	8.68%	-0.76%	-22.26%	1.43%	0.42%	0.92%	1.87%	Y	N
18	Iteration 4	4.850	-5.86%	5.93%	6.11%	1.57%	-12.30%	0.57%	0.12%	0.92%	1.32%	Y	N
19	Iteration 5	4.578	0.08%	0.81%	1.53%	5.62%	-6.76%	0.63%	0.19%	0.83%	0.50%	Y	Y
20	Iteration 6	4.563	0.39%	0.89%	1.47%	5.82%	-5.43%	0.50%	0.13%	0.82%	0.50%	Y	Y
21	Iteration 7	4.517	1.41%	1.68%	2.16%	7.20%	-4.39%	0.78%	0.19%	0.93%	0.61%	Y	Y
22	Iteration 8	4.642	-1.32%	1.63%	2.19%	4.44%	-7.52%	0.83%	0.13%	0.96%	0.69%	Y	Y
23	Iteration 9	4.627	-1.00%	1.35%	1.87%	4.58%	-6.54%	0.64%	0.06%	0.93%	0.57%	Y	Y

Table 6.2: Analysis of error in HVAC electricity consumption by revision.

Revision number	Stage of calibration process	Annual energy consumption (GWh)	Mean Bias Error (MBE)	CVRMSE (monthly)	CVRMSE (hourly)	Maximum error (hourly)	Minimum error (hourly)	Standard deviation of average biased error by bin			
								Hour	Day	Month	Drybulb
Measured		**1.097**									
1	Preparation	4.851	-342.49%	343.65%	349.10%	-237.01%	-749.87%	38.84%	20.39%	28.77%	81.83%
2	Zone-typing	1.732	-57.93%	58.17%	59.68%	-23.67%	-139.42%	8.65%	3.05%	6.38%	10.04%
3	Constructions	1.652	-50.70%	50.97%	53.01%	-17.06%	-135.86%	9.53%	3.79%	6.19%	10.29%
4	Internal loads	1.771	-61.56%	61.76%	62.85%	-27.59%	-140.14%	6.86%	2.23%	6.26%	8.90%
5	Internal loads	1.771	-61.56%	61.77%	62.81%	-27.52%	-138.16%	6.81%	2.19%	6.29%	9.07%
6	Internal Loads	1.086	0.97%	5.07%	9.70%	21.90%	-45.64%	4.56%	0.81%	4.98%	8.12%
7	Internal Loads	1.296	-18.17%	18.89%	20.82%	5.93%	-83.95%	5.32%	1.17%	5.49%	8.03%
8	HVAC and plant	1.158	-5.61%	7.31%	9.72%	15.38%	-46.73%	3.70%	0.61%	4.83%	5.77%
9	HVAC and plant	2.534	-131.16%	131.78%	133.06%	-80.03%	-249.30%	12.70%	3.70%	13.63%	18.00%
10	HVAC and plant	2.597	-136.87%	137.77%	139.32%	-80.97%	-260.97%	14.58%	3.97%	16.37%	22.32%
11	HVAC and plant	1.583	-44.41%	44.83%	51.22%	-0.98%	-193.39%	18.36%	7.58%	6.80%	14.42%
12	Error Check	1.638	-49.39%	49.66%	54.06%	-11.39%	-194.78%	14.97%	7.24%	6.42%	7.36%
13	Error Check	1.664	-51.77%	52.06%	56.92%	-12.34%	-208.05%	16.10%	7.82%	6.68%	7.36%
14	Error Check	1.699	-54.92%	55.19%	60.13%	-14.65%	-209.48%	16.03%	8.31%	6.75%	8.80%
15	Iteration 1	1.497	-36.58%	36.79%	38.47%	-5.23%	-108.25%	7.37%	3.54%	4.88%	6.85%
16	Iteration 2	1.484	-35.32%	35.56%	37.23%	-3.62%	-104.23%	7.39%	3.22%	4.91%	7.31%
17	Iteration 3	1.474	-34.48%	34.71%	36.26%	-3.16%	-100.19%	6.95%	3.00%	4.87%	7.12%
18	Iteration 4	1.365	-24.48%	24.79%	25.52%	5.76%	-63.78%	2.97%	1.15%	4.46%	5.16%
19	Iteration 5	1.093	0.33%	3.40%	6.38%	19.80%	-33.69%	2.70%	0.84%	3.51%	1.95%
20	Iteration 6	1.078	1.63%	3.74%	6.14%	20.51%	-28.62%	2.13%	0.53%	3.45%	1.94%
21	Iteration 7	1.032	5.88%	7.01%	9.02%	24.75%	-23.76%	3.19%	0.66%	3.73%	2.48%
22	Iteration 8	1.157	-5.51%	6.80%	9.15%	15.63%	-39.05%	3.69%	0.78%	4.16%	2.75%
23	Iteration 9	1.142	-4.16%	5.67%	7.80%	16.15%	-34.21%	2.83%	0.43%	4.02%	2.34%

Table 6.3: Analysis of error in LPE electricity consumption data by revision.

Revision number	Stage of calibration process	Annual energy consumption (GWh)	Mean Bias Error	CVRMSE (monthly)	CVRMSE (hourly)	Maximum error (hourly)	Minimum error (hourly)	Standard deviation of average biased error by bin			
								Hour	Day	Month	Drybulb
Measured		**3.485**									
1	Preparation	3.344	4.04%	4.41%	50.10%	57.27%	-111.30%	37.41%	25.03%	1.81%	20.86%
2	Zone-typing	3.140	9.89%	10.03%	47.53%	59.88%	-98.43%	35.13%	23.51%	1.70%	19.59%
3	Constructions	3.140	9.89%	10.03%	47.53%	59.88%	-98.43%	35.13%	23.51%	1.70%	19.59%
4	Internal loads	3.140	9.89%	10.03%	47.53%	59.88%	-98.43%	35.13%	23.51%	1.70%	19.59%
5	Internal loads	3.140	9.89%	10.03%	47.53%	59.88%	-98.43%	35.13%	23.51%	1.70%	19.59%
6	Internal Loads	2.198	36.91%	36.94%	36.98%	79.11%	22.63%	3.05%	1.88%	0.90%	1.35%
7	Internal Loads	3.487	-0.07%	0.07%	0.07%	-0.03%	-0.17%	0.00%	0.00%	0.01%	0.00%
8	HVAC and plant	3.487	-0.07%	0.07%	0.07%	-0.03%	-0.17%	0.00%	0.00%	0.01%	0.00%
9	HVAC and plant	3.487	-0.07%	0.07%	0.07%	-0.03%	-0.17%	0.00%	0.00%	0.01%	0.00%
10	HVAC and plant	3.487	-0.07%	0.07%	0.07%	-0.03%	-0.17%	0.00%	0.00%	0.01%	0.00%
11	HVAC and plant	3.487	-0.07%	0.07%	0.07%	-0.03%	-0.17%	0.00%	0.00%	0.01%	0.00%
12	Error Check	3.487	-0.07%	0.07%	0.07%	-0.03%	-0.17%	0.00%	0.00%	0.01%	0.00%
13	Error Check	3.487	-0.07%	0.07%	0.07%	-0.03%	-0.17%	0.00%	0.00%	0.01%	0.00%
14	Error Check	3.487	-0.07%	0.07%	0.07%	-0.03%	-0.17%	0.00%	0.00%	0.01%	0.00%
15	Iteration 1	3.485	0.00%	0.01%	0.02%	0.03%	-0.09%	0.00%	0.00%	0.01%	0.01%
16	Iteration 2	3.485	0.00%	0.01%	0.02%	0.03%	-0.09%	0.00%	0.00%	0.01%	0.01%
17	Iteration 3	3.485	0.00%	0.01%	0.02%	0.03%	-0.09%	0.00%	0.00%	0.01%	0.01%
18	Iteration 4	3.485	0.00%	0.01%	0.02%	0.03%	-0.09%	0.00%	0.00%	0.01%	0.01%
19	Iteration 5	3.485	0.00%	0.01%	0.02%	0.03%	-0.09%	0.00%	0.00%	0.01%	0.01%
20	Iteration 6	3.485	0.00%	0.01%	0.02%	0.03%	-0.09%	0.00%	0.00%	0.01%	0.01%
21	Iteration 7	3.485	0.00%	0.01%	0.02%	0.03%	-0.09%	0.00%	0.00%	0.01%	0.01%
22	Iteration 8	3.485	0.00%	0.01%	0.02%	0.03%	-0.09%	0.00%	0.00%	0.01%	0.01%
23	Iteration 9	3.485	0.00%	0.01%	0.02%	0.03%	-0.09%	0.00%	0.00%	0.01%	0.01%

6.4.3 Comparison to further measured data

Historical weather data were obtained for 2008 as a means to further verify that the model is an accurate representation of the building. EMS data (LPE) was also obtained and added to the model. No further changes were made to any other parameters. Table 6.4 shows that the results of this simulation run meet the acceptance criteria. Figure 6.10 illustrates model HVAC error using the same analysis criteria as the 2007 analysis. Appendix D contains the simulation run, the measured data, the weather-file, average absolute and biased error carpet plots for Total, HVAC and LPE.

Table 6.4: Results of model error analysis using 2008 data

Consumption type		Total	HVAC	LPE
Simulated annual energy consumption (GWh)		4.545	1.138	3.408
Mean Bias Error (MBE)		-1.11%	-4.61%	0.00%
CVRMSE (monthly)		1.34%	5.53%	0.02%
CVRMSE (hourly)		2.11%	8.72%	0.02%
Maximum error (hourly)		13.89%	40.99%	0.04%
Minimum error (hourly)		-7.54%	-37.39%	-0.08%
Standard deviation of average biased error by bin	Hourly	0.49%	2.31%	0.00%
	Day of week	0.11%	0.18%	0.00%
	Monthly	0.76%	3.21%	0.02%
	Dry-bulb temp	0.58%	2.46%	0.01%

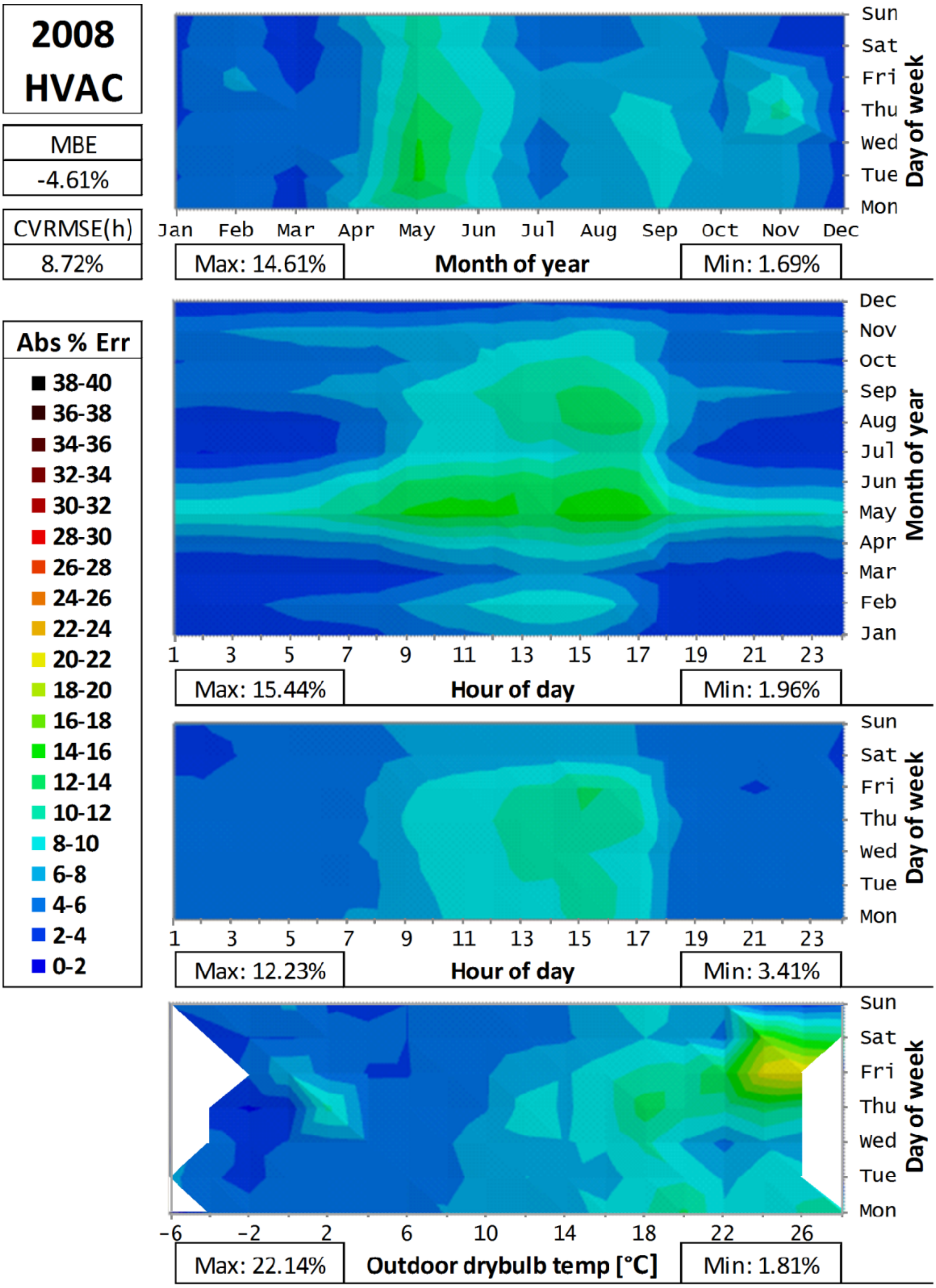


Figure 6.10: Calibrated model average absolute percentage error for HVAC electricity consumption for 2008.

6.5 Discussion

6.5.1 Issues with the acceptance criteria

Several revisions illustrate that monthly acceptance criteria do not adequately capture how well the model matches the measured data. For example, Table 6.1 shows that the revision 3 model has a MBE and $CVRMSE_{(monthly)}$ of -4.61% and 4.97% respectively, and thus it meets the monthly acceptance criteria. However, this model has a $CVRMSE_{(hourly)}$ of 38.44% and thus only serves to highlight the fact that it is possible for a model to meet even the most stringent *monthly acceptance criteria* without accurately representing the building. Figure 6.11 clearly demonstrates how inaccurate this revision is. This revision also illustrates the need for hourly measured data at sub-utilities level, as lighting and plug underestimation (by 245MWh) is partially offsetting HVAC overestimation (by 555MWh).

Table 6.1 also shows that the model met both the monthly and hourly *acceptance criteria* at revisions 7 and 8. This was before the HVAC equipment parameters had been updated from the initial model, which included major discrepancies such as automatically sized parameter values for large equipment and inlet vane fan part load curves instead of variable frequency drive fans. These major discrepancies between the model and the real building are clearly not captured by currently available *acceptance criteria*.

Furthermore, the model met the *acceptance criteria* at many stages of the iterative process, even though other significant errors remain. For example, the model comfortably meets the *acceptance criteria* at the beginning of the first iteration (revision 15). However, it still over estimates total electrical consumption by 24.5% and HVAC electrical consumption by 108.25% during the most extreme hour of the year (Table 6.1 and Table 6.2). Visualisation and analysis of the model error for HVAC consumption shows significant, systematic errors remain in the model (Figure 6.12). For example, the model over-estimates HVAC electrical consumption during peak occupancy period (10am-5pm, Monday to Friday) by an average of more than 48%.

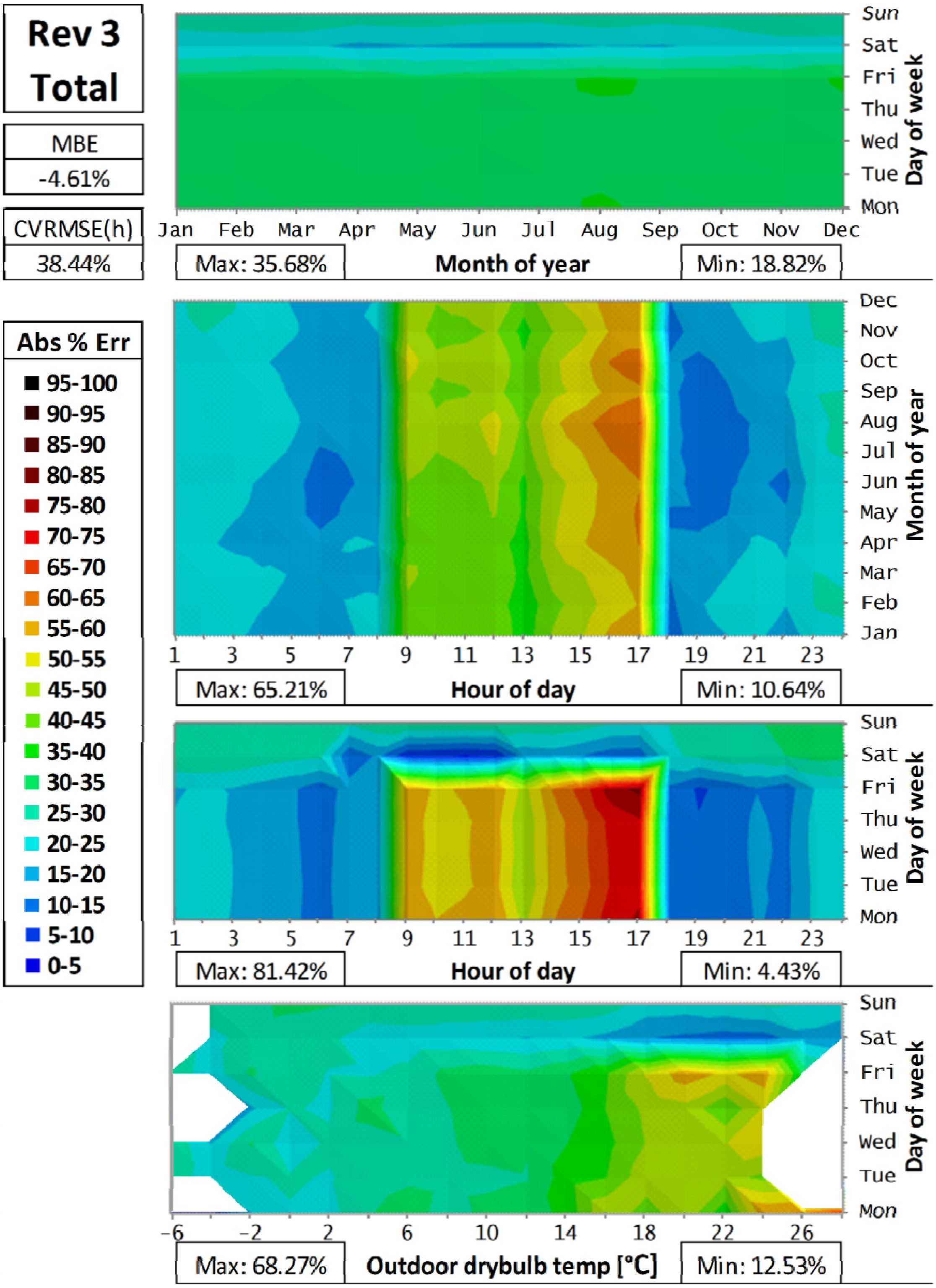


Figure 6.11 : Model (revision 3) average absolute percentage error for total building electrical consumption.

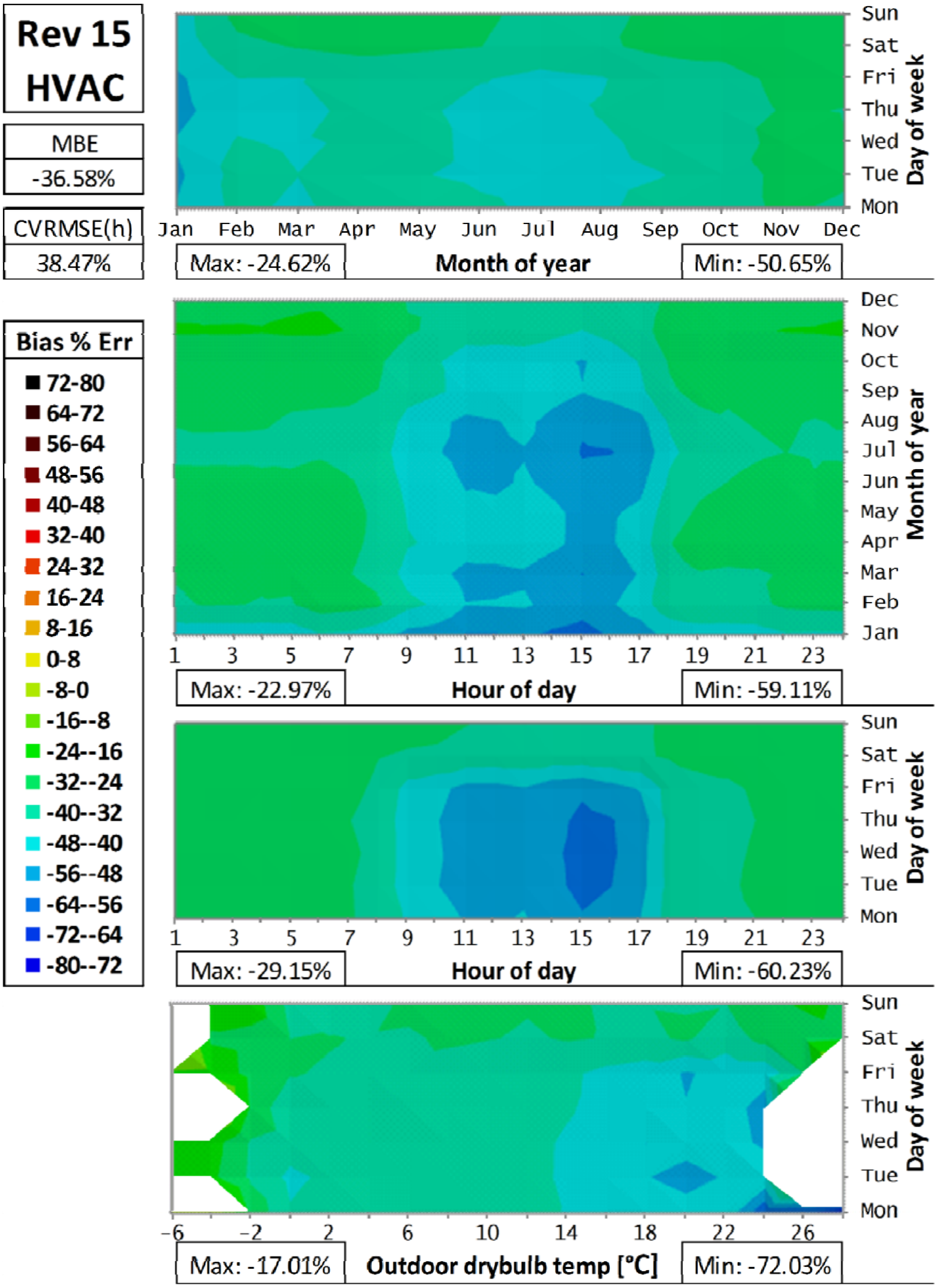


Figure 6.12: Model (revision 15) average biased percentage error for HVAC electrical consumption.

6.5.2 Energy Conservation Measures

Numerous Energy Conservation Measures were identified over the course of the demonstrator, as can be expected from any in depth audit of a building. Table 6.5 gives a brief description of each of these ECMs. Although a complete analysis of each of these ECMs is outside the scope of this thesis, the final calibrated model was used to analyse two specific ECMs as an example.

6.5.2.1 ECM 1: AHU static pressure reset

Based on changes made to the final model, implementing a static pressure reset (albeit a perfect one) on the office AHUs based on the damper positions of a representative sample of VAV boxes would have saved 181MWh of electricity and 28MWh of chilled water, offset by an increase of 71MWh of hot water, in 2007. These values correspond to 3.9%, 8.4% and -2.3% of simulated total building electrical, chilled water, and hot water consumption respectively. This estimate was obtained using the calibrated model and static pressure reset fan curve from the Advanced Variable Air Volume System Design Guide (Hydeman et al., 2003).

6.5.2.2 ECM 2: Conference room DCV

The conference rooms are sporadically occupied and have low lighting and equipment loads during these periods. However, these zones have fixed minimum ventilation airflow rates sized to supply ventilation air for the maximum design number of occupants. This unnecessary airflow overcools these zones during unoccupied periods. Thus, this situation wastes reheat energy and electricity (fan power). Some cooling energy is also wasted during hours when the additional heat added to the building and the minimum ventilation airflow at the AHU causes the AHU cooling coil to operate in order to maintain supply air temperatures. This is an example of a situation in which opposing heating and cooling loads (in the conference rooms and open office space directly outside these rooms respectively) would have opposed each other. Core-and-four-perimeter zoning strategies do not capture these effects, as Chapter 3 discussed. Also, this ECM analysis is an example of a situation in which a detailed model yielded an estimate with fewer assumptions than would be possible in a less detailed model.

Based on changes made to the final model, implementing rudimentary demand controlled ventilation (DCV) in these zones would have saved 19.5MWh, 5.09 and 40.9MWh of electricity, chilled and hot water respectively in 2007. These values correspond to 0.4%, 1.5% and 1.3% of simulated total building electrical, chilled water, and hot water consumption respectively. This estimate was obtained by reducing the VAV box minimum airflow fraction in these zones to the design leakage rate (taken from VAV box O&M documentation) during unoccupied periods. Implementing DCV using occupancy sensors (e.g. CO_2 or infrared) would yield further savings, however at additional initial cost.

Table 6.5: List of suggested ECMs identified during the calibration process.

Description	**Primary initial costs**	**Initial cost category**
AHU static pressure reset (ECM 1): Implement AHU pressure reset based on a representative selection of VAV boxes damper positions. (Taylor, 2007)	VAV damper position logging	3 (Med)
Conference room DCV (ECM 2): Implement DCV in conference rooms	CO_2 sensors	3 (Med)
Canteen DCV (ECM 3): Control canteen exhaust fan speed based on measured ventilation requirements	CO_2 sensors; exhaust fan VFD	4 (High)
Canteen ERV (ECM 4): Implement Energy Recovery Ventilation on Canteen AHU	ERV; ductwork; design cost	4 (High)
Pump differential pressure reset (ECM 5): Implement and test a pump (secondary) differential pressure reset based on AHU cooling coil valve positions.	Pressure logging and control	3 (Med)
AHU split signal damper control (ECM 6): Implement and test an AHU split signal damper control strategy.(Nassif and Moujaes, 2008)	Co_2 sensors; pressure sensors	2 (Low)
Night-time fresh air reduction (ECM 7): Reduce AHU outdoor air flow rate during low occupancy periods (currently fixed at the minimum fresh air rate based on maximum occupancy)	Co_2 sensors	2 (Low)
AHU preheat coils (ECM 8): Lower office AHU preheat coil set-points.	N/A	1 (Nil)
Reduce AHU supply air temperature (ECM 9): Reduce office AHU set-points for mixing box, cooling coil and heating coil to 15°C, 16°C and 14°C respectively.	N/A	1 (Nil)
VAV box re-evaluation (ECM 10): Examine design calculations, damper min/max positions, and control settings for VAV boxes. Monitor and investigate reheat coil usage on a floor by floor basis.	Personnel hours; flow & temp sensors	4 (High)
Computer standby (ECM 11): Use network wide program to automatically synchronic computer standby settings. (US DOE, 2009a)	N/A	1 (Nil)
Internal loads (ECM 12): Inform staff about shutting down unnecessary equipment and implement an A-rated equipment purchasing policy to address excessively high plug loads. Investigate high night-time plug loads. Perform a full lighting control schedule review and inform night staff how to operate the web-based control system.	N/A	1 (Nil)

6.5.3 Discrepancies remaining in the final model

The model still contains a significant number of discrepancies despite the level of calibration effort. Some of these discrepancies are due to poor estimates for parameter values due to lack of measurement or building information. However, some are due to the unpredicted operation of HVAC equipment. For example, in 2007, the model under-predicts HVAC consumption in November. Figure 6.8 shows the magnitude of this error, *biased* average error plots for HVAC at revision 23 in Figure 6.13 show that it is an under-prediction, rather than an over-prediction. BMS data showed that this was due (at least in part) to a large reduction in airflow at one of the AHUs. The second AHU that supplies the central duct in the west of the building compensated for this by increasing airflow to maintain the pressure set-point in the duct. However, power consumption is proportional to the cube of airflow at each fan and thus, this change caused increased power consumption. This issue was identified from the data in 2010 and the reasons for this remain unknown.

Also, many of the discrepancies in the model are due to the assumptions and simplifications inherently made by the simulation tool. For example, the model overestimates HVAC consumption during the summer months at peak occupancy (see Figure 6.8). This is due, at least in part, to the fact that the simulation tool models VAV terminal boxes with ideal control. Figure 6.14 compares the response of a VAV box (without reheat) in the simulation software and the idealized response in the actual IR6 building. When cooling is required, the software calculates the exact required airflow to maintain the cooling set-point (23°C) based on the total load in the zone (up to a fixed maximum airflow, after which zone air temperature begins to increase) (US DOE, 2009c). However, in the IR6 building, VAV box airflow is proportional to the error between current zone air temperature and the cooling set-point temperature over a fixed proportional band (2°C) (up to a fixed maximum airflow). Thus, simulated airflow is more responsive to loads than the actual building, causing fan power overestimation during cooling load periods. Aside from this issue, the simulation tool also does not account for pressure dependent airflow. This is a further approximation as the IR6 building does not use pressure independent VAV boxes.

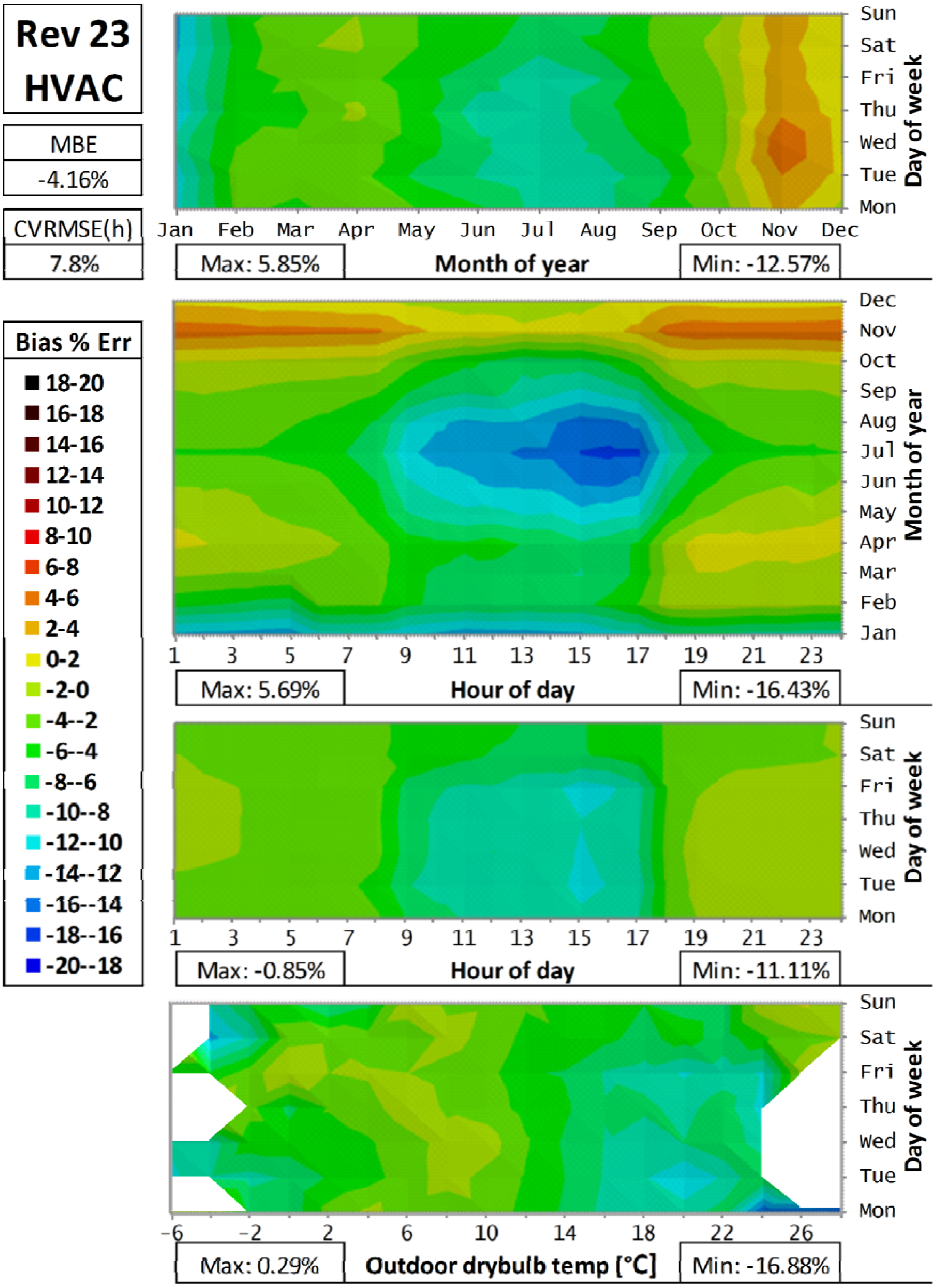


Figure 6.13: Model (revision 23) biased average percentage error for total building electrical consumption.

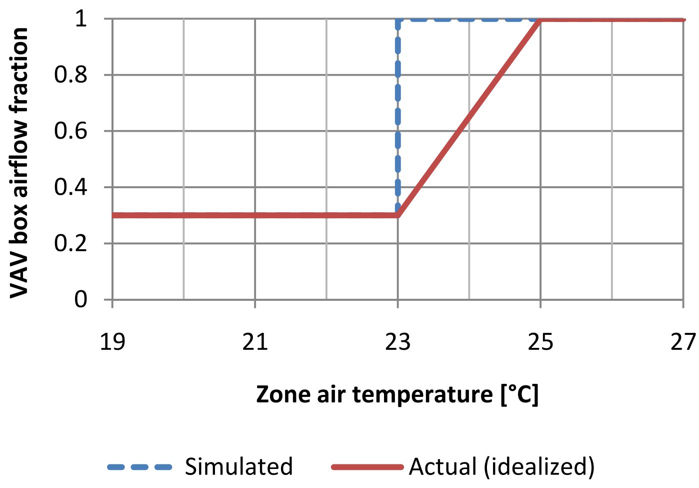


Figure 6.14: Simulated versus actual VAV box airflow control

6.6 Conclusion

This chapter describes the results of the demonstrator. The simulation results show excellent correlation with the measured hourly electrical consumption data both for the analysed year (2007) and for the subsequent year (2008) demonstrating the effectiveness of the methodology. The use of version control software yields a model based on clear sources of evidence and allows for reliable comparison of results at any stage of the calibration process.

This chapter contains several novel features in addition to the new methodology. Firstly, the final calibrated model is the first of its kind to be published in several ways: the level of detail (hourly calibration over a 12 month period, with further analysis for a second 12 month period); the resolution of measured data used (sub-utilities); and the use of measured internal load data on an hourly basis in the simulation. The evidence-based methodology combined with the detailed whole building energy model successfully identified numerous ECMs. The final model was then used to investigate two of these ECMs for feasibility.

Secondly, this chapter also presents a new method of visualising data that combines 3-dimensional plotting techniques with 'bin' techniques.

Chapter 7: Conclusions

7.1 Research conclusions

7.1.1 Methodology

This thesis proposes a new methodology for calibrating whole building energy models using a systematic, evidence-based approach. The methodology prescribes the use of version control techniques in the calibration process to organise and structure an analysts approach to the calibration process, ensuring that the final model is based on clearly referenced sources of evidence. A version control repository stores a complete record of the calibration process, including the evidence on which each change to the model was based.

This methodology also describes a novel zoning process that more closely represents the real building. The zone-typing strategy models many of the effects that are not captured by the traditional core and 4 perimeter zone strategy, while stopping short of representing each thermal zone in the building with an individual zone in the model. This is particularly applicable to deep floor plan buildings.

This methodology has the following advantages:

- Improved model credibility when compared to 'tuning' approaches: Only information about the building based on clear evidence is used to make changes to the model.
- Improved reproducibility in the calibration process: Any change, and the evidence on which is based can be reviewed by future users. Future users will be able to review the decisions made throughout the calibration process, both improving their understanding of assumptions made and reducing the likelihood of analysts tuning input parameters without supporting evidence.
- A systematic approach to the calibration process: Version control techniques helps to organise and structure an analysts approach to the calibration process. Version control software facilitates reviewing the changes between versions and enables an analyst to quickly revert to previous versions of the model if an error is discovered.
- An improved zoning strategy: The zone-typing strategy will yield a more accurate representation of a building when compared to a typical core-and-four-perimeter zoning strategy.

Overall, the end result of this research is that models calibrated using this methodology will contain only verified information about a building. This can allow researchers to draw conclusions related to the capabilities of current simulation tools (depending on the level of information available). The detailed calibrated models themselves can be used to investigate Energy Conservation Measures (ECMs) for feasibility. Furthermore, knowledge of mistaken design-stage assumptions gained in the process of detailed calibration can inform design stage modellers through the development of best practice procedures.

In the immediate future, this methodology applies to research rather than commercial applications due to the significant measurement and building information requirements; level of model detail; and documentation effort required to calibrate a model. However, aspects of this methodology, such as the use of version control techniques to track the calibration process, an evidence-based approach, and zone-typing, could be used in any calibration effort.

7.1.2 Results of the demonstrator case study

This thesis describes the results of the application of the methodology to a case study: the 4-storey, 30,000m^2, Intel IR6 office building. The results show excellent correlation with the measured hourly electrical consumption data both for the analysed year (2007) and for the subsequent year (2008). This demonstrates the effectiveness of the methodology described in Chapter 3.

The final calibrated model is the first of its kind to be published in several ways: the level of detail (hourly calibration over a 12 month period, with further analysis for a second 12 month period); the resolution of measured data used (sub-utilities); and the use of measured internal load data on an hourly basis in the simulation.

7.1.3 Carpet visualisation of binned variables

This research also presents a novel method for analysing annual building energy consumption data. This method combines 3-dimensional carpet plots with 'bin' techniques. The data is binned by variables on which consumption is dependent, in the demonstrator case, hour of day, day of week, month of year, and outdoor dry-bulb temperature. Carpet plots of average absolute and biased error are generated using independent variables on the horizontal and vertical axes. In this demonstrator case this yielded 4 individual plots: month/day, hour/month, hour/day, and dry-bulb temperature/day. This method presents an efficient way of visualising patterns in large amounts of data, as described in section 6.3.

7.2 Future work

7.2.1 Adding an optimisation approach to the calibration process

The problem remains that the final calibrated model is one solution in an enormous parameter space that contains multiple, non-unique solutions. However, this methodology has the advantage of yielding a solution in which all of the parameters in the model are based on evidence that is clearly defined, referenced, and visible to future users. An interesting further development would be to apply a parametric analysis approach to the final model that is output by this methodology. Such an approach could apply estimated uncertainty ranges to parameter values based on the expected reliability of the source of the evidence used to specify those values. It should be the case that the lower the level in the *source hierarchy,* the larger the uncertainty associated with the parameter value. A parametric analysis could then be performed to identify multiple solutions within this parameter space, such as that described in (Reddy et al., 2007b), and use those solutions to infer a level of uncertainty in the final solution set.

However, the author suspects that the number of individual parameters in a detailed model (thousands) combined with the significant simulation run-time (>3 hours) would make such an analysis infeasible. Numerous significant further assumptions and simplifications would be required to reduce the parameter space and required number of simulations to a reasonable level. A case study of a smaller building with fewer zones and systems could also bring such an analysis closer to the realm of feasibility by reducing the number of parameters in the model. However, it appears that calibrated whole building energy simulation will remain a fundamentally underdetermined problem unless high levels of simplification are assumed or until significant further measurement and information are available for buildings.

7.2.2 Acceptance and significance criteria

It is clear from the demonstrator that current acceptance criteria did not identify significant errors that remained in the model. Detailed calibration case studies using hourly data require more stringent criteria. For example:

- A 30% limit on maximum average absolute error for any combination of binned variables on which consumption is dependent. E.g., for the IR6 building, a 30% limit on the maximum absolute error in any of the 4 plots in Figure 6.7;
- Reduce the acceptable $CVRMSE_{(hourly)}$ from 30% to 20%;
- A requirement for sub-utilities measurement of HVAC consumption and the application of the above acceptance criteria to these measurements.

However, these recommendations are based only on a single case study - the demonstrator. A number of detailed calibration case studies are necessary in order to further develop and formalise new acceptance criteria. Specifically, these criteria may be unreasonably stringent for buildings with HVAC systems that are more difficult to model using currently available software, such as Natural Ventilation (NV), Mixed Mode (MM) or Thermally Activated Building Systems (TABS).

However, even the above recommended changes will not be sufficient to objectively quantify how well a model represents a real building. Final acceptance of the model would still rely on a detailed review of building performance and the judgement of the analysts. A further step to improve acceptance criteria would be to require more measurement in buildings. For example, measurements of energy consumption separated by end-use (e.g., fan consumption, pump electrical consumption, etc.). Outputs from the simulation could then be grouped to form a counterpart with each physically measured data-stream. For example, if there is a meter monitoring the load of a MCC supplying a group of fans, these could appear in a similar grouping in the simulation output. This would allow for direct comparison of detailed measured and simulated data and would help to identify discrepancies between them. Acceptance criteria similar to those currently defined at a whole building level (MBE and $CVRMSE_{(hourly)}$) could then be applied to these measured data streams.

In addition to improvements to the acceptance criteria, further work is required to develop robust significance criteria. For the demonstrator building, any modification to the model that yielded a change of greater than 1% MBE, 1% $CVRMSE_{(monthly)}$, or 2% $CVRMSE_{(hourly)}$ was considered significant. However, further case studies are required to determine what the values for these criteria should be. Furthermore, evaluating the effects of a change to a specific variable at the whole building level may not be appropriate in all cases. With the specification of new acceptance criteria (for example, on an end-use basis), new significance criteria could also be defined so that the effect of a change to a specific variable can be assessed in more detail. For example, a specific variable that only relates to HVAC energy consumption should be assessed at the HVAC level, rather than the whole building level.

7.2.3 Further automation in the calibration process

Even if the measured end-use data described in the previous section were available, it would still be difficult to calibrate a model in a cost-effective and timely manner. Significant issues remain in handling of this quantity of data with currently available tools. A systematic approach to measurement in buildings is needed in order to improve the availability and usability of measured data for calibration, along with a host of other reasons related to assessing operational performance.

In addition to this, there are difficulties related to the availability and accessibility of stock information about building. Processes whereby this stock information is used to automatically generate whole building energy models must be developed before model calibration in a timely manner is truly feasible. This is well beyond current capabilities in the construction industry. In the future, the above processes could be provided by a complete Building Information Model (BIM) that includes:

- Comprehensive and up-to-date information related to building geometry, materials, constructions and HVAC equipment;
- Linkages between energy consuming components and a structured database of measured building data (e.g. a data warehouse (Gokce et al., 2009)).

In the meantime, however, calibration case studies such as the one presented in Chapter 6 are a valuable way to test simulation tool capabilities, to investigate modelling assumptions, and to develop best-practice modelling approaches.

7.2.4 Further case studies

This research presents a detailed case study of one building that is conditioned by a particular group of HVAC system types (overhead air distribution systems). Significant additional knowledge could be gained by applying the methodology to buildings that use other HVAC systems, such as Natural Ventilation (NV), Underfloor Air Distribution (UFAD), and Thermally Activated Building Systems (TABS). Additionally, further work could perform calibrated simulation case studies of buildings types other than offices.

These further case studies could be used to aid in the development of more robust acceptance and significance criteria. In addition, the use of a common template and data storage format for documenting the model revision process allows for significant data-mining opportunities. Patterns in the model update process may be found where a large set of calibration case studies is available, allowing researchers to draw conclusions in regard to the variables that are most important to focus on.

7.2.5 Other developments and applications of the visualisation technique

Instead of comparing simulated and measured energy consumption, the new visualisation technique discussed in this thesis could also be used to compare current performance to historical average performance. For example, using this technique, a building operator could easily compare current energy consumption of a piece, or pieces, of equipment against historical mean performance on a weekly or outdoor dry-bulb temperature basis. Future work could also investigate comparisons with other statistical values, such as 10^{th} and 90^{th} percentiles as a means of quickly identifying when a component is performing poorly. In addition, capabilities could be added to improve this technique. For example, the ability to display BWM plots for a particular dataset when highlighted in the software (e.g., when the mouse cursor passes over a particular line in the carpet plot).

7.2.6 Customised version control software

Further improvements could be obtained by customising version control software to calibrated simulation applications. For example, the software could be programmed to:

- Quickly highlight what parameters in the model are still based on evidence from a particular level in the *source hierarchy*. This would aid in the iterative process, as a user could quickly identify the parameters that are still based on the initial model.
- Automatically request and store an evidence file for each change made.

7.2.7 Further development of the EnergyPlus HVAC Generator tool

Although the development of an EnergyPlus interface program is not a key aim of this research, such a program is necessary due to inadequacies associated with EnergyPlus tools available at the time of writing. With that in mind, development of EnergyPlus HVAC Generator will continue until a robust HVAC tool, suitable for research use, is available. There are several planned developments of the tool, for example:

- Update to function with the latest version of EnergyPlus (version 6.0 at the time of writing);
- Expand capabilities to model naturally ventilated buildings and several other features required for upcoming calibration studies;
- Tidying up the programming code, naming conventions, and general improvements to the user interface;
- Addition of further automated error checking capabilities.

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Appendix A
Zone-typing document

A.1 Overview

This document describes a new method for defining thermal zones in whole building energy simulation models known as zone-typing and describes the zone-typing process as it was applied to a demonstration project. The reasoning behind the specification of the individual zone-types is defined and the following pages contain tables describing the criteria used to define the zone-types for this demonstrator. A detailed description of the process for representing multiple thermal zones in the building as a single thermal zone in the model is also described. Screenshots of the model floor plan contrast the results of the zone-typing strategy with other strategies. The appendix concludes with other important notes on the additional aspects related to zone-typing involved in a detailed simulation model.

A.2 Zone-typing

The traditional method for defining the thermal zones in a simulation model follows a simple 5 zone per occupied floor approach – one core zone and 4 perimeter zones. This approach can be seen in benchmark and best practice models (US DOE, 2010e) as well as all published calibrated simulation case studies in which the zoning strategy used is described. Examples include (Pan et al., 2007; Tian and Love, 2009). Although it may be appropriate for buildings with small floor plans, it simplifies the model and moves away from accurately representing the actual thermal zones in the building. Agglomerating multiple actual thermal zones in the real building into one large thermal zone in the model results in a less accurate representation of the building for several reasons:

- It does not accurately represent situations where opposing cooling and heating loads in individual zones counter-balance each other. This is a common occurrence in large office buildings, where unoccupied conference rooms are in heating mode to maintain zone temperatures while supplying minimum ventilation and the remainder of the office space is in cooling mode to remove internal loads. The model does not capture these offsetting effects if the two thermal zones are represented by one zone.
- It does not allow for accurate representation of different occupancy profiles or internal loads (e.g., communications rooms), and different methods of conditioning (e.g., constant volume toilets, and VAV open office space).
- It yields a simplified floor plan, which is not acceptable for buildings with large floor plans. A more detailed floor plan allows ECMs to be investigated at higher resolutions and with fewer assumptions.

Based on the above bullet points, it is clear that a strategy that more closely represents the operation of the real building is required, particularly for buildings with a large floor plan. The strategy presented in this document is known as zone-typing. The objective of this strategy is to define zones in such a way as to minimise the inaccuracies incurred by representing multiple actual thermal zones in a building with a single large zone in the model.

Zone-typing is the process of defining the various types of thermal zones used in a model based on four major criteria: the function of the space, its position relative to the exterior, the measured data that is available, and the method used to condition the zone. These criteria capture the major differences between the thermal processes occurring in each zone and define how they appear in the model. Figure A.1 describes these criteria and the reasoning behind their inclusion.

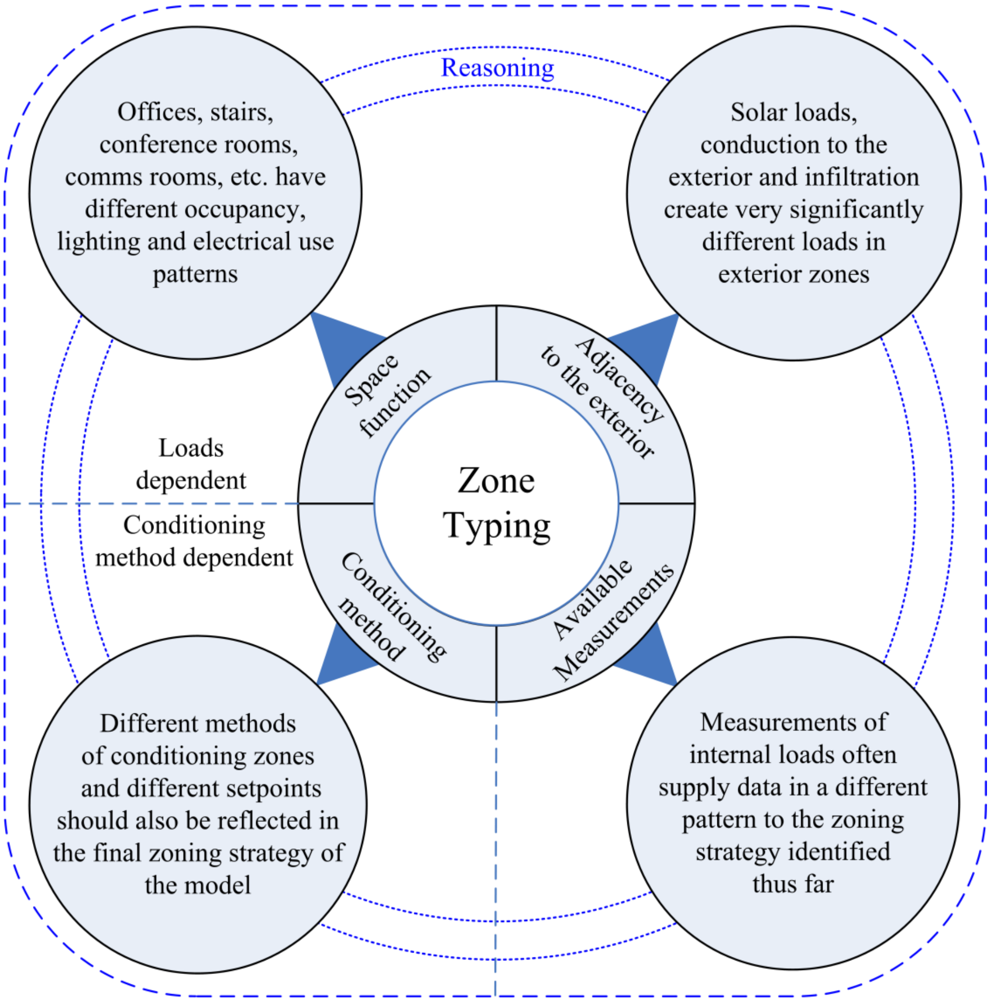

Figure A.1: Zone-typing process

Once the zone-types have been defined, they are applied to the model floor plan accordingly along with zone-type specific parameters, such as occupancy schedules, lighting loads, and conditioning methods. Although the results of this method may not represent each actual thermal zone in the building with a thermal zone in the model, zones are only agglomerated when the inaccuracies incurred are at a minimum. The criteria behind the agglomeration process are described later in this document.

The zone-typing strategy yields a more detailed floor plan than the traditional core-and-four-perimeter approach while stopping short of representing each zone in the building with one in the model. Though the fundamental mathematical techniques used differ between whole building energy simulation models (e.g. EnergyPlus – finite difference) and finite element modelling, zone-typing can be viewed as analogous to selectively and strategically increasing mesh density in a finite element model.

A.3 Demonstrator

A.3.1 Building and project description

Intel Ireland manufacture microprocessors at a production site in Leixlip, Co. Kildare, Ireland. The 4 storey Intel IR6 office building supports the manufacturing facilities. It has a floor area of circa 30,000m2 and was completed at the end of 2003. The ground floor contains a clean-room gowning area, a control room, a kitchen, a canteen, and a facilities area; the first and second floors consist of open office space and conference rooms; and the third floor is currently unoccupied. The goal of the project was to develop a whole building energy model for this building. Two zones were excluded from the model and analysis at Intel request: the clean-room gowning area and control room.

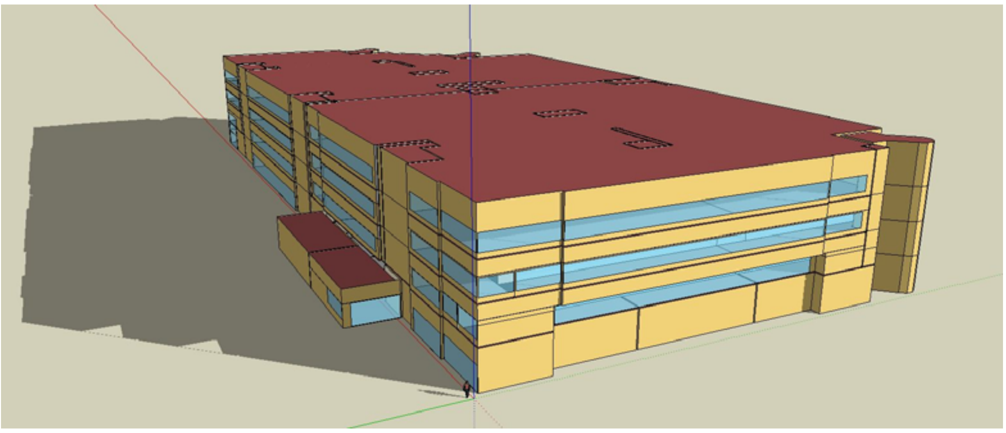

Figure A.2: Screenshot of EnergyPlus geometry in Google SketchUp

A.3.2 Relevance to zone-typing

Two zoning strategies are compared: the traditional core and four perimeter zone approach and the zone-typing strategy. In this example, the initial model for the calibration project used the traditional strategy, and this was changed at the first step of the calibration process (i.e. revision number 2). Floor plan screenshots of the initial model and the zone-typed model are included, along with a colour legend describing each zone-type. The initial model floor plan screenshots are intended to illustrate the different between the two zoning strategies. However, there is no requirement to create a traditionally zoned model if none exists, as the user can develop the zone-typed model directly.

A.3.3 Definition of the zone-types

The actual thermal zones in the building were identified based on as-built drawings and verified by a physical site survey. A series of parameters of interest were defined based on the reasoning in, detailed in Table A.1.

Table A.1: Zone-typing parameters used for the IR6 building

Figure A.2 criteria description	Associated parameter in the table
Space function	Occupancy
	Lighting
	Equipment
Adjacency to the exterior	External surfaces
Conditioning method	Local zone-level conditioning method
	Exhaust fan
	Return plenum
	Supply system
Additional measurements	Measured data specific to this zone type

Each zone was described by a parameter set (each column in the table represents a new parameter) and a new zone-type was created whenever a new parameter set occurred. Table A.2 describes the zone-types yielded by this process.

Zone-type	Description	External surfaces	Local zone-level conditioning method	Exhaust fan	Return plenum	Supply system	Occup.	Lights	Equip	Measured data specific to this zone type
Uncond	Unconditioned shell spaces within the building envelope	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	No
Toilet	Toilets and changing rooms	No	CAV HW reheat	Yes	Yes	Office AHU	Low	Med	Low	No
Stair	Stairwells	Yes	HW radiator	No	No	HW plant	Med	Low	Low	No
Plenum	Return air plenums	No	N/A	N/A	N/A	Airflow path	None	None	Very low	No
Office	Open office space	No	VAV	No	Yes	Office AHU	Med	Med	Med	No
N/A	Clean gown room and control room excluded from the demonstrator at Intel request.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
MiscGF	Miscellaneous ground floor spaces, hallways, small offices, equipment storage areas.	No	VAV	No	Yes	Office AHU	Med	Med	Low	No
Kitchen	Cooking area	No	VAV	Yes	Yes	Kitchen AHU	Med	Med	High	No
ExtOff	Exterior Office	No	VSF HW reheat	No	Yes	Office AHU	Med	Med	Med	No
ExtMiscGF	Exterior MiscGF	No	VSF HW reheat	No	Yes	Office AHU	Med	Med	Low	No
ExtKitchen	Exterior office space for kitchen staff	No	VSF HW reheat	No	Yes	Kitchen AHU	Med	Med	High	No
ExtCanteen	Exterior Canteen	No	VSF HW reheat	No	Yes	Canteen AHU	High	Med	Low	No
Elec_Battery	Uninterruptible power supply batteries	No	CAV HW reheat	Yes	No	Elec AHU	None	Low	Med	No
Elec	Electrical incomer, misc plant equipment	No	CAV HW reheat	No	No	Elec AHU	None	Low	Med	No
Duct	Main AHU supply risers, exhaust, supply and return ducts	No	N/A	N/A	N/A	Airflow path	None	None	None	No
Conf	Conference rooms	No	CAV HW reheat	No	Yes	Office AHU	High	Med	Med	No
Comms	Communications room (servers)	No	VAV	No	No	Office AHU	None	Low	High	Yes
Canteen	Open cafeteria and servery space	No	VAV	Yes	Yes	Canteen AHU	High	Med	Low	No

Table A.2: Description of IR6 zone-types

Zone-typing document

Thermal zones in the real building

Figure A.4 overleaf illustrates a close-up view of the actual thermal zones in the SW corner of the building, with the mechanical as-built drawings overlaid. Each zone corresponds to a floor area that is conditioned by an actuated component of the conditioning system.

For example, the floor area served by a VAV terminal box (an actuated component). This component has an associated thermostat which controls zone air temperature by modulating either air flow with an actuated damper (cooling mode) or hot water flow to a coil with an actuated valve (heating mode).

In locations where the conditioned volume has well-defined boundaries, such as walls, windows, floors, etc., these were used as the boundaries for the thermal zone. However, difficulties arise in open areas, such as open plan offices, and warehouses. In these cases, the boundaries for the thermal zones are not explicitly defined and must be assumed. The zone boundaries are defined based on equidistant lines drawn between air diffusers of adjacent zones. These surfaces are known as *virtual space boundaries*. The current standard industry practice (DOE 2008) is to specify an arbitrary construction for these surfaces (commonly a single 12.5mm layer of Gypsum). However, EnergyPlus has more advanced features than many other simulation tools and the Material:InfraRedTransparent object can be used as the surface construction material. This material allows for the transmission of long-wave radiation between zones, and is thus an improvement over current practice.

Figure A.3: Colour legend for each zone-type (applies throughout the document)

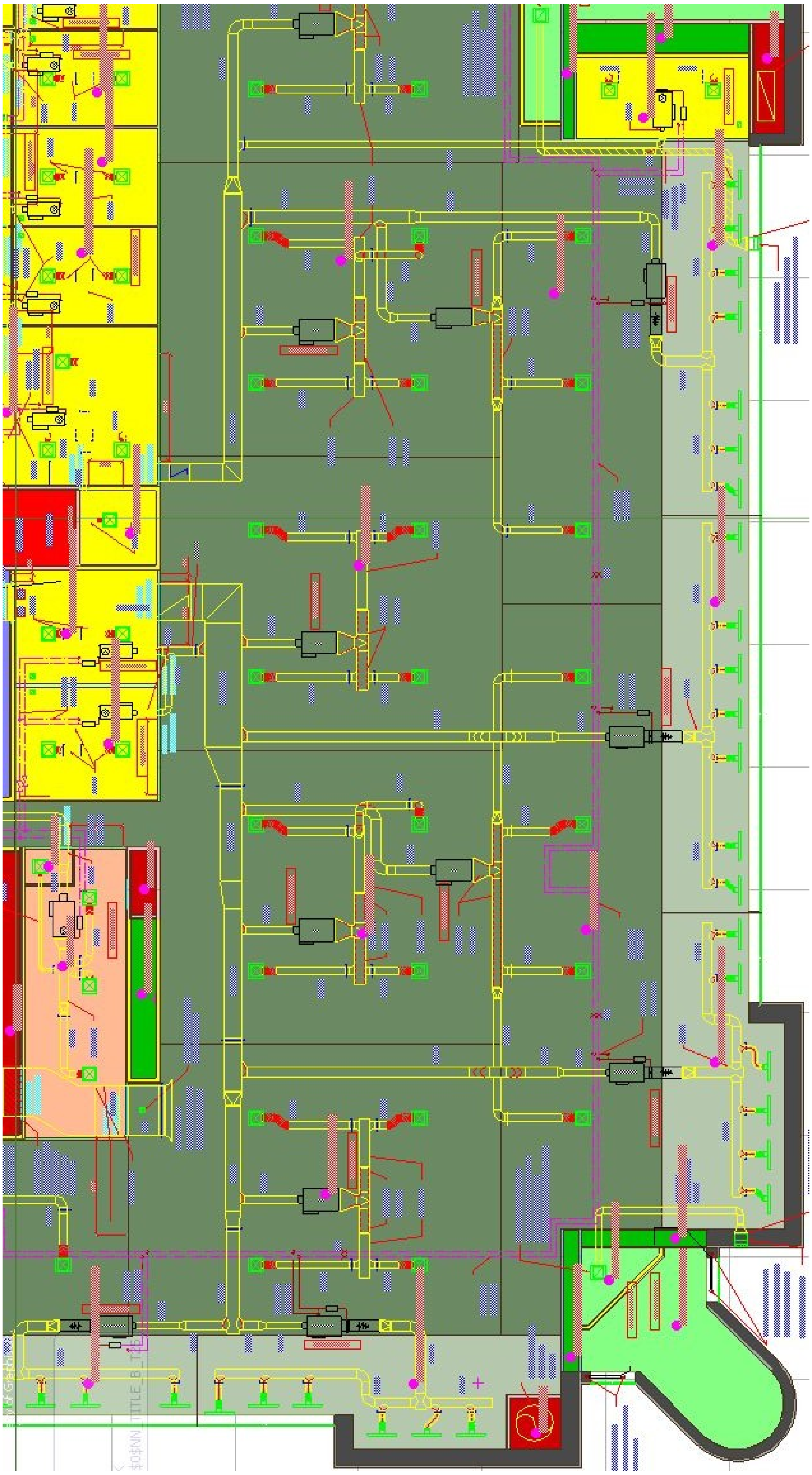

Figure A.4: ArchiCAD screenshot of the thermal zones in the SW section of the actual building, with the mechanical as-built drawings overlaid

A.3.4 Thermal zones in the model

This next step in the process is to define how these thermal zones in the building are represented in the model. This consists of agglomerating multiple thermal zones in the real building into a single thermal zone in the model. This reduces simulation time and unnecessary model complexity. Zones may be agglomerated if the following criteria are met:

- They are of the same zone-type;
- There is a significant inter-zone surface area with respect to total surface area of both zones. This criterion may also be specified as inter-zone surface length with respect to total zone perimeter if ceiling height is constant. For the demonstrator, the minimum ratio was 5% (of the perimeter);
- The resulting agglomerated zone would not be excessively large in any dimension. For the demonstrator, the maximum distance was 75m;
- The resulting agglomerated zone would not have an excessively large floor area. For the demonstrator, the maximum floor area was 1,500m^2.

When a zone is connected to multiple other zones of the same zone-type, the analyst begins by agglomerating zones with the largest inter-zone surface area.

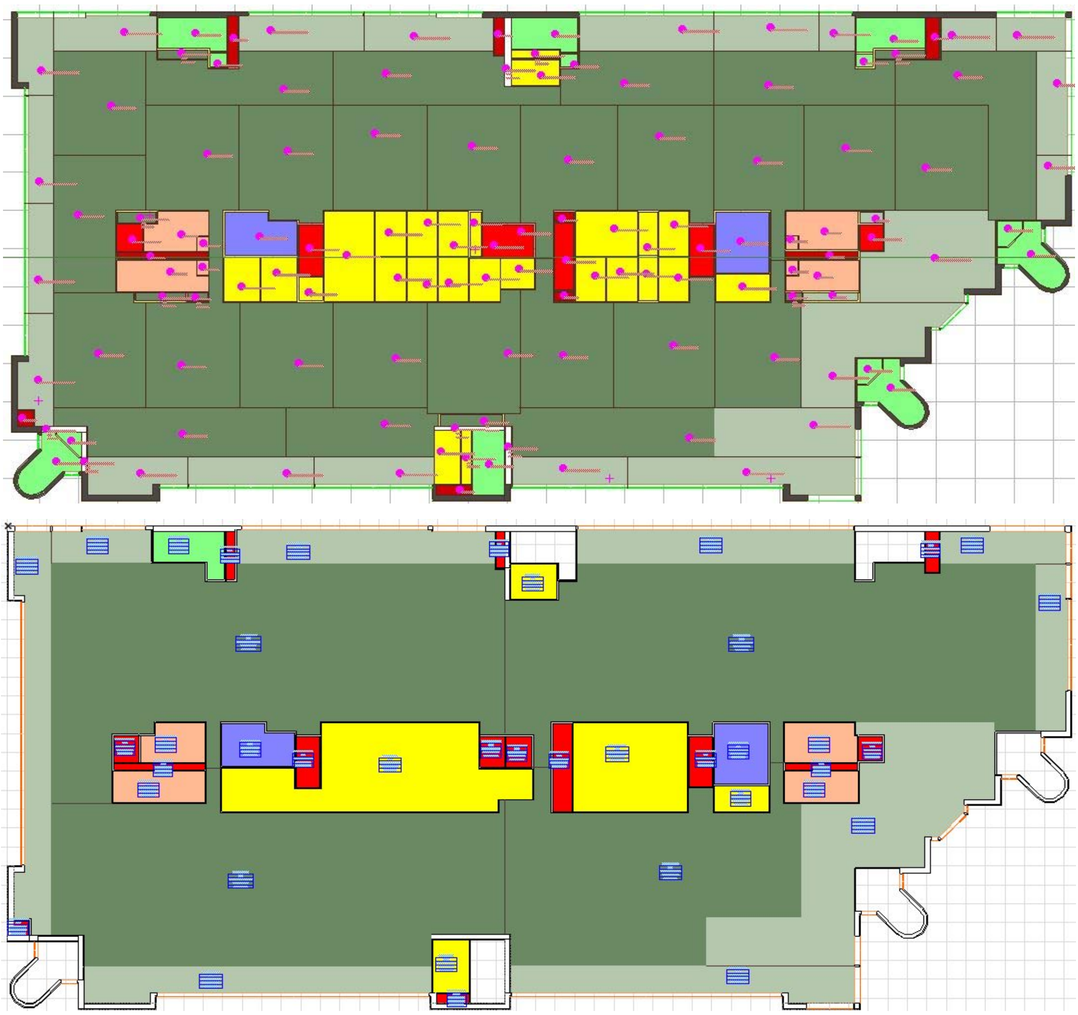

Figure A.5: Actual thermal zones and zone-types in the model on the first floor.

A.3.5 Traditional zoning approach versus zone-typing

This section illustrates the differences between the traditional zoning strategy, which typically uses one core and 4 perimeter zones per floor (except where areas are conditioned by different systems) and the zone-typing strategy. The next two pages contain screenshots of the ArchiCAD 13 floor plans taken from the initial model and from the zone-typed model:

As stated above, the zone-typing strategy yields a more detailed floor plan than the traditional approach. However, this increased complexity is not without cost, both in terms of time required to create the model itself and in subsequent model run-time. Although a detailed analysis of the increased in run-time between the two strategies is outside the scope of this research, for the demonstrator project, changing from the initial model strategy to the zone-typing strategy increased run-time from 2792 seconds to 13,122 seconds, an increase of 370%.

This increased run-time may have implications for real-time use of simulation models, as it will reduce the number of runs that can be made by fixed resources and in limited time. However, the run-time for a 24-hour run-period (the current minimum EnergyPlus run-period) including model warm-up is under 400 seconds. This would allow 8 or 9 parametric runs per hour (or more than 200 runs per day). Or, in other words, the model runs more than 200 times faster than real-time for this building, which should still allow for real-time uses of the model.

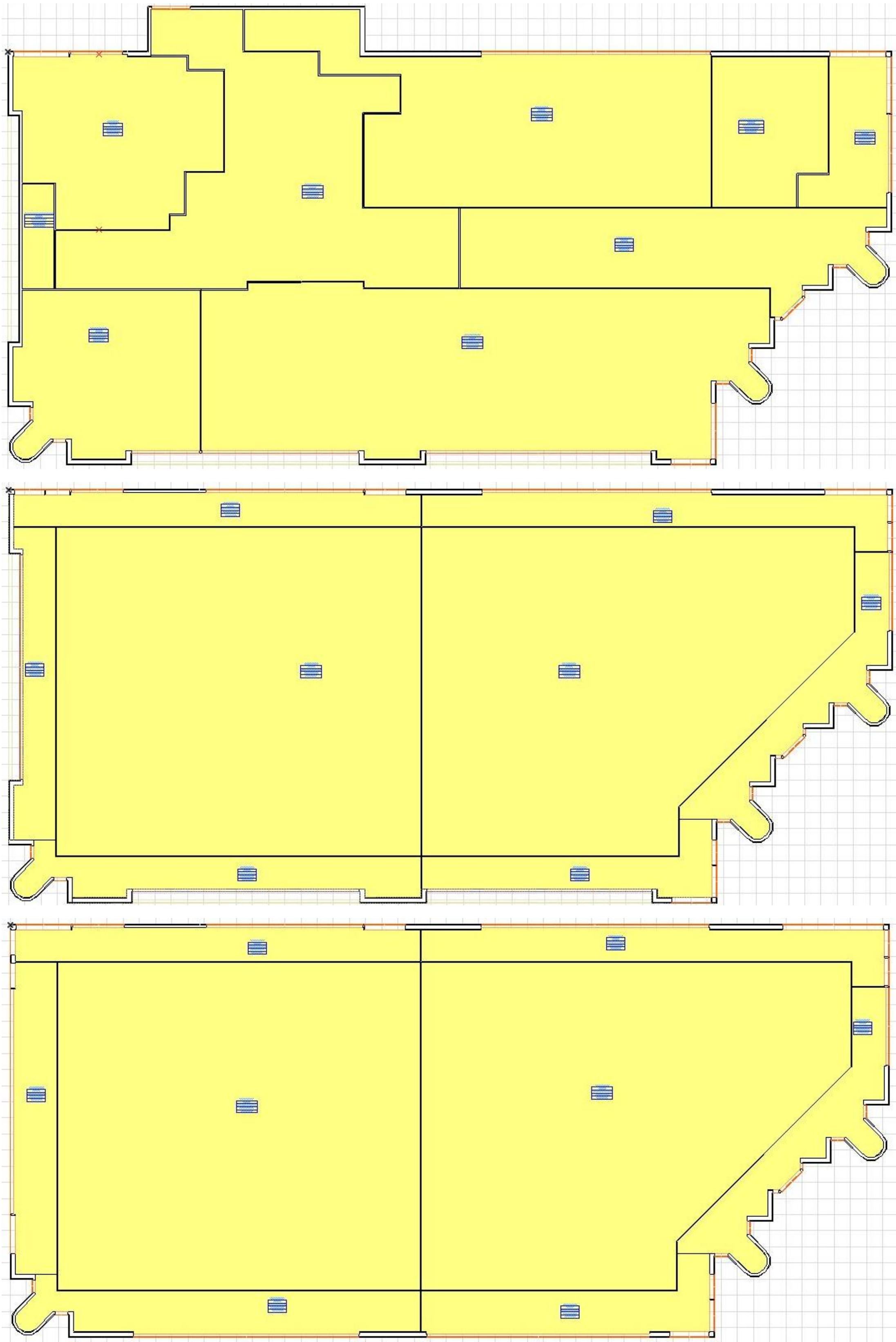

Figure A.6: ArchiCAD screenshots of the ground (top), first (middle) and second (bottom) floor plans illustrating the initial model (Revision 1) thermal zones.

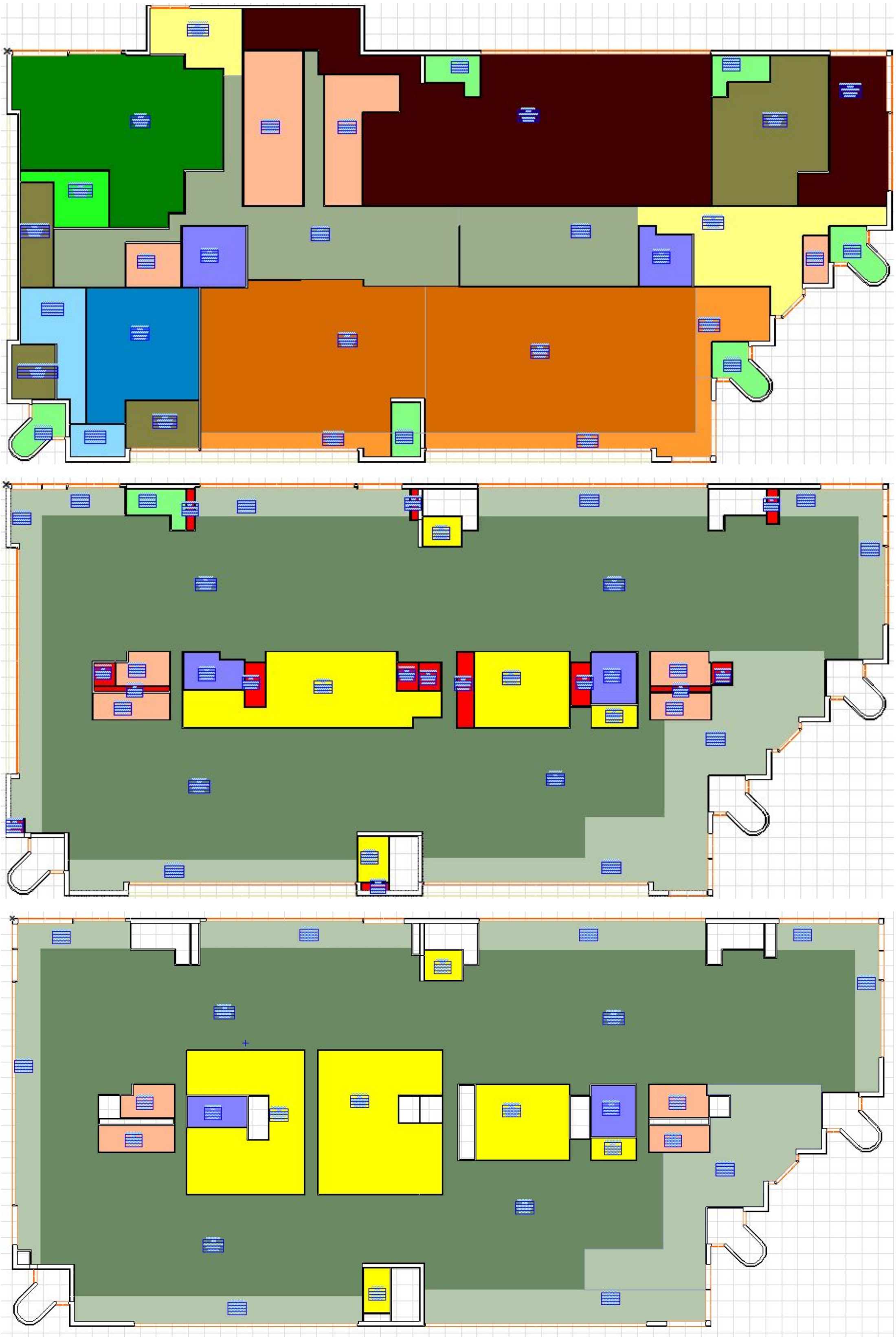

Figure A.7: ArchiCAD screenshots of the ground (top), first (middle) and second (bottom) floor plans illustrating the Zone-typed model (revision 2) thermal zones.

A.3.6 Further notes

A.3.6.1 Unoccupied third floor

The third floor of the building is unoccupied and unconditioned, and thus, is represented as simply as possible given other constraints such as external geometry. The zone-typed model also includes each of the riser, duct, and stairwell zones because these multi-floor zones are also present on this floor.

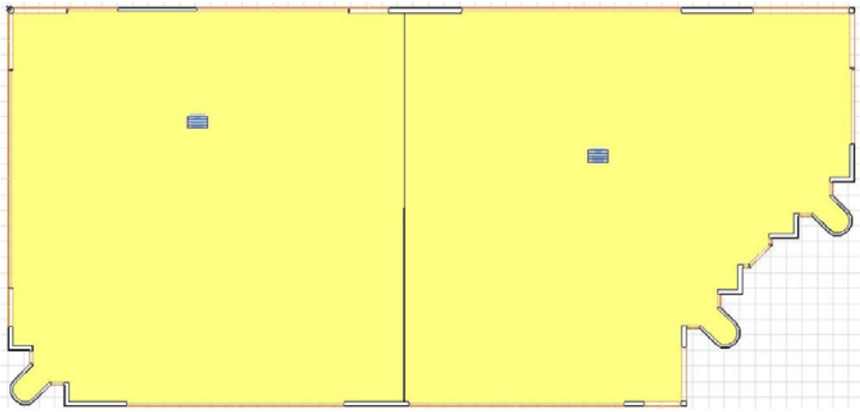

Figure A.8: Initial model (revision 1) ArchiCAD screenshot of the third floor.

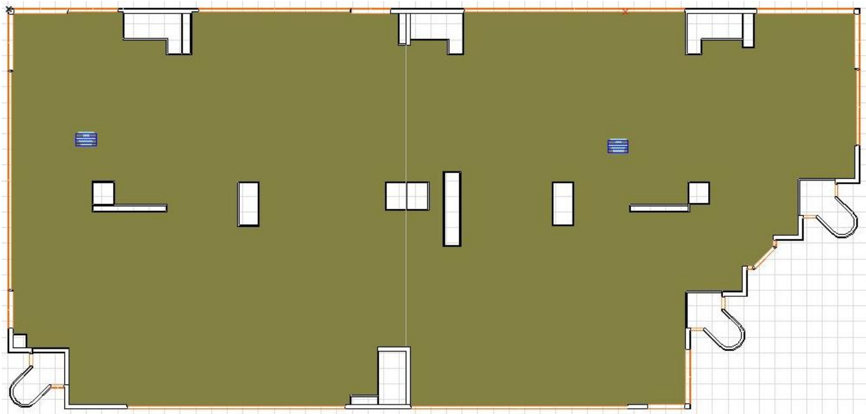

Figure A.9: Zone-typed model (revision 2) ArchiCAD screenshot of the third floor.

A.3.6.2 Return Plenums

The traditional zoning strategy attempts to account for return plenum thermal zones in the actual building by including an air gap thermal resistance and ceiling tile material in the floor slab and roof constructions. The more detailed approach described by the zone-typing method requires the analyst to describe return plenums as thermal zones in the model, as this zone has different internal loads and conditioning methods when compared to other zones. This also yields a model that is a far more accurate representation of the real building. For example, in the demonstrator the air temperature difference between the occupied zone and the return plenum can be as large as 4°C (based on in-situ measurements). This is a significant temperature differential within a building which impacts heat transfer between both the zones above and below the plenum, as well as surface temperature, radiant exchange and occupant thermal comfort. Accounting for the return plenum by reducing the thermal conductivity of the floor slab construction (as done when using traditional zoning strategies) does not capture these effects.

Ideally, the model would include multiple return plenums per floor with the return riser at the centre. This would capture the air temperature changes as return air flows through the plenum to the return bell-mouth at the riser. However, this is not possible due to EnergyPlus v3.1 software limitations on the number of Mixer objects per AirLoop object.

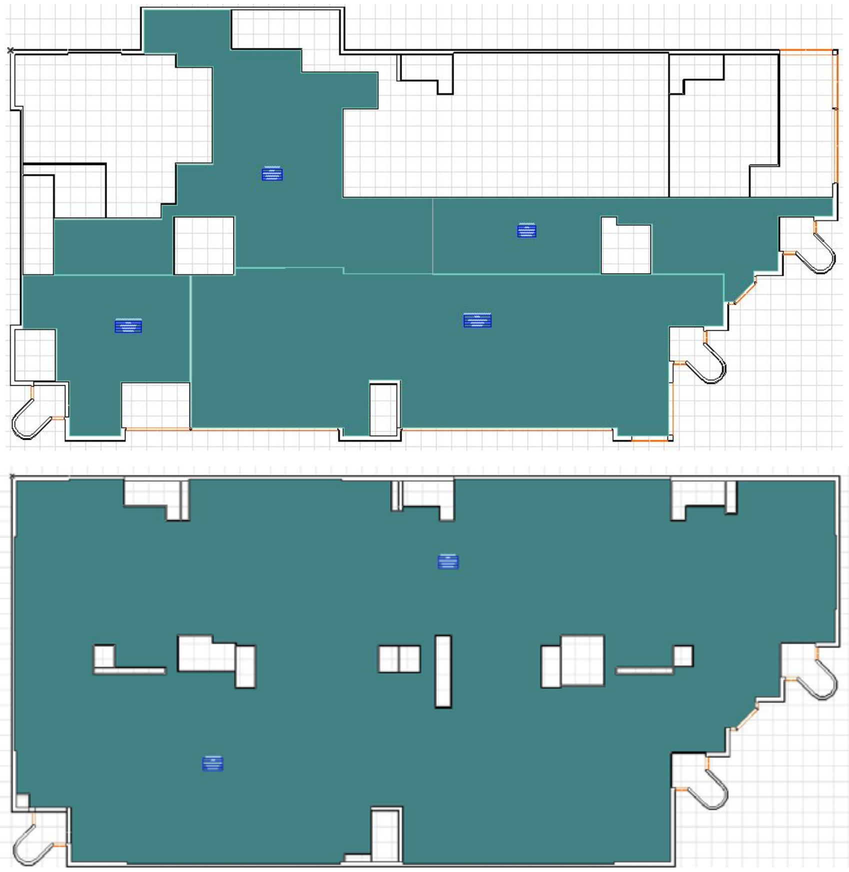

Figure A.10: Zone-typed model (revision 2) ArchiCAD screenshot of the ground (top) and second floor (bottom) plenums.

Appendix B
EnergyPlus HVAC Generator v1.11

The latest version of EnergyPlus HVAC Generator is stored in a .zip file on the DVD that accompanies this thesis.

B.1 Program overview

This tool was developed to generate all of the necessary EnergyPlus objects to run a simulation aside from those directly related to the building geometry and constructions. The majority of these objects relate to HVAC and plant systems, however, other objects such as those related to internal loads, are also included.

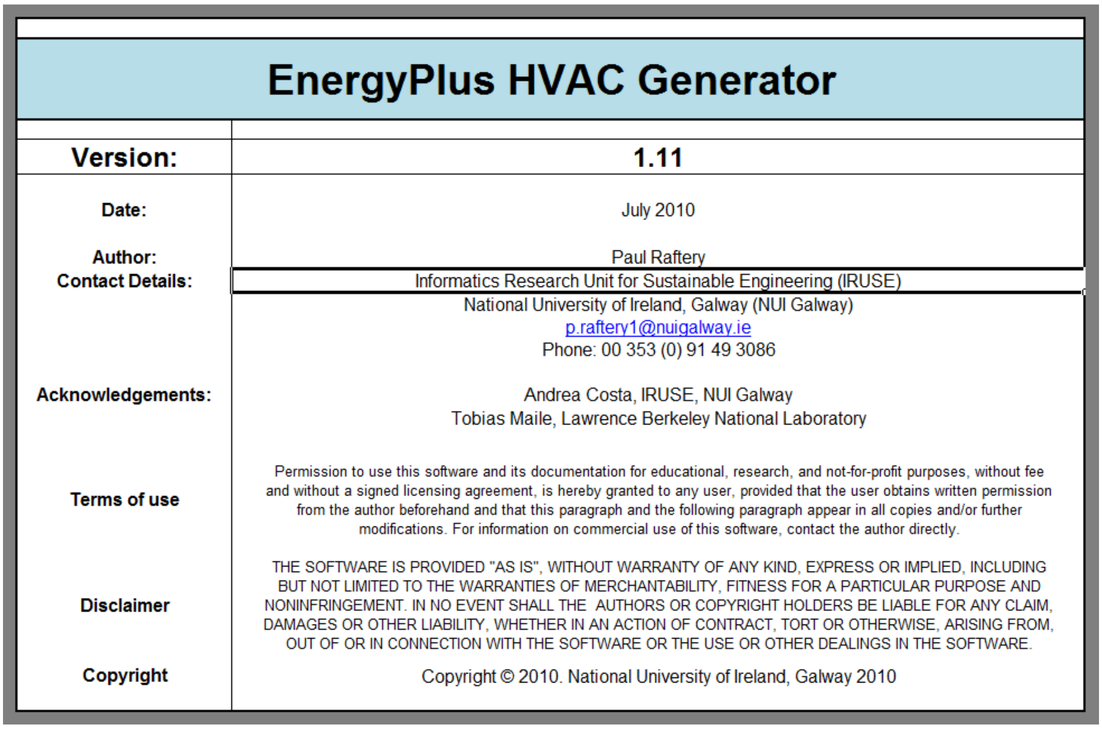

Figure B.1: Screenshot of program start page

The tool is based on the concept of splitting up the HVAC components of a model into three categories: Zone, System, and Plant. Zone objects include all those directly related to a zone, such as the conditioning system used for that zone, or the lighting load present in that zone. System objects include all those directly related to the air system supplying multiple zones, such as the type of fan, the coils in the AHU and fresh air rates. Plant objects include all those directly related to the water systems supplying the zones and the air systems, such as hot and chilled water supplies.

The software allows the user to specify parameters related to these categories either globally or locally. For example, the AHU fan type (a system variable) could be set to the same value for all AHUs (globally) or a different value for each AHU (locally). The user can specify global parameter values on the GlobalVariables sheet. Local variables are specified as a new column or row on the ZoneVariableValues and SystemVariableValues sheets respectively. When combined with the filter and listing features which exist in Microsoft Excel 2007®, this feature of the tool becomes very useful for models with large numbers of zones and systems with different parameter values. Screenshots of each of these sheets are on the following pages.

A set of Visual Basic macros output a file for each of the three categories: Zone, System and Plant. Each file sets the parameters in EnergyPlus Macro syntax and calls the relevant EneryPlus Macro block (similar to a subroutine). These blocks then create the corresponding EnergyPlus objects. A Visual Basic macro then creates the executable.imf file, which contains all of the global parameters. This file can then run using EnergyPlus (and an associated weather file). The executable.imf gathers all the .imf and idf files together to complete the model, including the geometry .idf file, which must be created with a different tool, such as OpenStudio or IDF Generator. It should be noted that the Visual Basic macros also generate all the objects that have links to other objects, or contain lists of objects, and adds them to the files. This is due to the extremely limited capabilities of the EnergyPlus Macro language, which does not include many features, such as counting, loops, arrays, etc.

Further information on the tool's capabilities, how it is used, how the tool operates, and how new features can be added, are available in the excel sheet that is used to generate the EnergyPlus model (Interface.xlsm). The tool was designed to be fully expandable. New HVAC capabilities and features can be easily added as needed. At the time of writing the tool is capable of modelling the following HVAC systems:

All Variable Air Volume (VAV) and constant volume systems with any configuration of:

- Preheat, reheat and cooling coils;
- Supply, return, relief and exhaust fans;
- Air economizers, e.g. differential dry bulb, enthalpy, etc.;
- Return plenums, supply and return risers, etc.;
- Hot water baseboard systems;
- Ideal air systems;
- All air systems at the zone levels, for example:
  - Variable and constant volume zone supplies;
  - Reheat coils;
  - Variable speed fans;
  - Exhaust fans.

Work is currently ongoing to further expand the capabilities of this tool and to update the tool in line with new releases of EnergyPlus.

People[]	Lights[]	Equipment[]	Internal_Mass[]	Infiltration[]	Sizing:Zone[]	ADU_Objects[]	Baseboard[]	PurchasedAir[]	Sizing:System[]	System_Objects[]	HW_Sizing:Plant[]	HW_Plant_Objects[]	CW_Sizing:Plant[]	CW_Plant_Objects[]	Variable (or Schedule) required	Schedule	Value
ZONE									SYSTEM		PLANT				FileName To Write Global Variables:	Executable.imf	
										1					AHU_Fan:VV_Relief_Motor_In_Air_Stream_Fraction[]		1
										1					AHU_Fan:VV_Relief_Pressure_Rise[]		750
										1					AHU_Fan:VV_Return_Fan_Coefficient_1[]		0.040759894
										1					AHU_Fan:VV_Return_Fan_Coefficient_2[]		0.08804497
										1					AHU_Fan:VV_Return_Fan_Coefficient_3[]		-0.07292612
										1					AHU_Fan:VV_Return_Fan_Coefficient_4[]		0.943739823
										1					AHU_Fan:VV_Return_Fan_Coefficient_5[]		0
										1					AHU_Fan:VV_Return_Fan_Efficiency[]		0.74
										1					AHU_Fan:VV_Return_Max_Flow[]		autosize
										1					AHU_Fan:VV_Return_Motor_Efficiency[]		0.9
										1					AHU_Fan:VV_Return_Motor_In_Air_Stream_Fraction[]		1
										1					AHU_Fan:VV_Return_Pressure_Rise[]		750
										1					AHU_Fan:VV_Supply_Fan_Coefficient_1[]		0.040759894
										1					AHU_Fan:VV_Supply_Fan_Coefficient_2[]		0.08804497
										1					AHU_Fan:VV_Supply_Fan_Coefficient_3[]		-0.07292612
							1								AHU_Fan:VV_Supply_Fan_Coefficient_4[]		0.943739823
							1								AHU_Fan:VV_Supply_Fan_Coefficient_5[]		0
														1	AHU_Fan:VV_Supply_Fan_Efficiency[]		0.74
														1	AHU_Fan:VV_Supply_Max_Flow[]		autosize
														1	AHU_Fan:VV_Supply_Motor_Efficiency[]		0.9
														1	AHU_Fan:VV_Supply_Motor_In_Air_Stream_Fraction[]		1
														1	AHU_Fan:VV_Supply_Pressure_Rise[]		750
														1	AHU_HW_Heating_Coil_Air_Inlet_Temperature[]		16.6
														1	AHU_HW_Heating_Coil_Air_Outlet_Temperature[]		32.2
														1	AHU_HW_Heating_Coil_Nominal_Capacity[]		autosize
														1	AHU_HW_Heating_Coil_Water_Inlet_Temperature[]		93.3

Figure B.2: Global variables sheet

Press Ctrl + Shift + M to run the macro

Possible values for the variable are listed in yellow above the variable name

Zone Name	Notes/Commen	/	F	N	Zone-type	Area	Sch_People	People_Calculation_Method	People_Variable	Sch_Activity
							Enter the relevant schedule name below. To maintain the current naming schema, this should begin with "Sch_"	People People/Area Area/Person	Numerical value	Enter the relevant schedule name below. To maintain the current naming schema, this should begin with "Sch_"
ZONE NAMES	ZONE DETAILS									
A0C_Comms		A	0	C	Comms		Sch_People	Area/Person	9.3	Sch_Activity
A0N_ExtMiscGF		A	0	N	ExtMiscGF		Sch_People	Area/Person	9.3	Sch_Activity
A0C_MiscGF		A	0	C	MiscGF		Sch_People	Area/Person	9.3	Sch_Activity
A0N_Toilet_1		A	0	N	Toilet		Sch_People	People/Area	0.021505376	Sch_Activity
A0N_Toilet_2		A	0	N	Toilet		Sch_People	People/Area	0.021505376	Sch_Activity
A0W_Toilet		A	0	W	Toilet		Sch_People	Area/Person	9.3	Sch_Activity
A0C_MiscRoom		A	0	C	MiscRoom		Sch_People	Area/Person	9.3	Sch_Activity
A1C_Comms		A	1	C	Comms		Sch_People	Area/Person	9.3	Sch_Activity
A1C_Conf		A	1	C	Conf		Sch_People	Area/Person	9.3	Sch_Activity
A1S_Conf		A	1	S	Conf		Sch_People	Area/Person	9.3	Sch_Activity
A1N_ExtOff_1		A	1	N	ExtOff		Sch_People	Area/Person	9.3	Sch_Activity
A1N_ExtOff_2		A	1	N	ExtOff		Sch_People	Area/Person	9.3	Sch_Activity
A1S_ExtOff		A	1	S	ExtOff		Sch_People	Area/Person	9.3	Sch_Activity
A1W_ExtOff		A	1	W	ExtOff		Sch_People	Area/Person	9.3	Sch_Activity
A1N_Office		A	1	N	Office		Sch_People	Area/Person	9.3	Sch_Activity

Figure B.3: Local zone variables sheet

Overall category	Variable description	Eplus Macro Variable name	Add AHUS below				
AHU Name	Name of AHU		AHU3	AHU4	AHU1	AHU2	AHU5
Coils	Preheat coil	HW_PreHeating	YES	YES	NONE	YES	NONE
	Reheat coil	AHURHCoil	YES	YES	YES	YES	YES
	Cooling coil	AHUChWCoil	YES	YES	NONE	YES	YES
AHU specifics	Supply riser	SupplyRiserPlenum	AXC_Riser_2	BXC_Riser_5	NONE	NONE	NONE
	Return riser	ReturnRiserPlenum	AXC_Riser_1	BXC_Riser_6	AXW_Duct_7	AXS_Duct_8	NONE
	Fan type	AHUFanType	VV	VV	CV	VV	CV
	Outdoor air settings	System_100%_Outdoor_Air_In_Cooling	no	no	yes	yes	yes
		System_100%_Outdoor_Air_In_Heating	no	no	yes	yes	yes
		System_Economizer_Control_Type	DifferentialDryBulb	DifferentialDryBulb	NoEconomizer	NoEconomizer	NoEconomizer
		System_Minimum_Air_Flow_Fraction	0.3	0.3	1	0.3	1
		Sch_System_Min_Fract_Outside_Air	NONE	NONE	Fixed_Fresh_Air_At_Max	Fixed_Fresh_Air_At_Max	Fixed_Fresh_Air_At_Max
		Sch_System_Max_Fract_Outside_Air	NONE	NONE	Fixed_Fresh_Air_At_Max	Fixed_Fresh_Air_At_Max	Fixed_Fresh_Air_At_Max
	Return fan?	AHU_ReturnFan	YES	YES	YES	YES	YES

Figure B.4: Local system variables sheet

Appendix C
Version control repository

The attached DVD contains the version control repository. The instructions for restoring and viewing the repository are stored in the "Instructions.txt" file on the DVD. The instructions are also printed below for ease of use.

C.1 Installation of required software (for Windows based systems)

Install TortoiseSVN using the installation file on the DVD (or download the latest version from http://tortoisesvn.tigris.org/).

Copy and paste the "svnadmin.exe" file available on the DVD (or download the latest version from http://nightlybuilds.tortoisesvn.net/latest) to the root directory (usually C:\).

C.2 Procedure for restoring a repository

Choose a location for the repository, say ***C:\RestoredRepository***.

Right click in the folder and go to "TortoiseSVN" → "Create repository here" to create a new empty repository in the above location.

Open a DOS command prompt and go to the root directory (i.e. ***C:***, where "svnadmin.exe" is located).

Run the following command, where ***C:\RestoredRepository*** is the location you wish to restore the repository to, and ***C:\DemonstratorRepository.backup*** is the repository backup file.

svnadmin load C:\RestoredRepository < C:\DemonstratorRepository.backup

The entire history of the calibration process has now been loaded to a repository located at C:\RestoredRepository

C.3 To review a particular file at any stage of the calibration process

Right click in any folder and go to "TortoiseSVN" → "Repo-browser" to view the repository.

Enter the location of the repository where you loaded the demonstrator, noting the forward slashes, rather than backslashes, e.g.:

file:///C:/ RestoredRepository.

The repository window opens on the latest (or "HEAD") revision. Drag and drop any required files out of this window on to the desktop.

To view files at other revisions, click the revision button at the top right of the repository window (this will read "HEAD" when you first open it). Enter the revision number that you are interested in and click "Ok". Drag and drop any required files out of this window on to the desktop.

Appendix D
Detailed demonstrator results

See attached DVD.