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Ph.D.

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Assessment of applications of optimisation to building design and energy modelling

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I, David Roderick Polson confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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Abstract

Buildings account for around 35% of the world's carbon emissions and strategies to reduce carbon emissions have made much use of building energy modelling. Optimisation techniques promise new ways of achieving the most cost effective and efficient solutions more quickly and with less input from engineers and building physicists. However, there is limited research into the practical applications of these techniques to building design practice.

This thesis presents the results of case-based research into the practical application of design stage optimisation and calibration methods to energy efficient building fabric and services design using building energy modelling.

The application during early stage design of a Non-dominating Sorting Genetic Algorithm 2 (NSGA2) to a building energy model EnergyPlusTM. The exercise was used to determine if the application of NSGA2 yielded a significant improvement in the selection of building services technology and building fabric elements. The use of NSGA2 enabled significant (£400,000) capital cost savings without degrading the comfort or energy performance. The potential capital cost savings significantly outweighed the cost of the engineering time required to carry out the additional analysis.

Three optimisation techniques were applied to three case study buildings to select appropriate model parameters to minimise the difference between modelled and measured parameters and hence calibrate the model. An heuristic approach was applied to the Institute for Life Sciences Building 1 (ILS1) at Swansea University. Latin Hypercube Monte Carlo (LHMC) was applied to the Arup building at 8 Fitzroy St London and compared directly with the results from an approach using Self Adaptive Differential Evolution (SADE). Poor Building Management System data quality was found to significantly limit the potential to calibrate models. Where robust data was available it was however found to be possible to calibrate EnergyPlus simulations of complex real world buildings using LHMC and SADE methods at levels close to that required by professional bodies.

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Impact Statement

The results of this research impact on those professions that utilize building environmental simulation i.e. designers of building services and other engineers brought in to deliver the environmental performance of a building including its energy consumption. The thesis suggests that the additional time and resource required for designers to apply optimization techniques is far outweighed by the potential capital savings without impacting on the comfort or energy performance of a building and hence the technology should be applied widely as part of the early stage design of buildings.

There are considerable benefits to the calibration of environmental building models to provide a sound basis for comparing energy savings measures and agreeing payment mechanisms in public private funding initiatives, however this requires reliable environmental monitored data from the buildings to be calibrated. This thesis shows that even for prestigious buildings with comprehensive monitoring via building management systems the data collected is just not available at the level of reliability required to undertake a calibration. Further research is required to determine how fit for calibration BMS systems are and professional practices may need to be significantly improved in their installation and operation. Buildings needs to be rigorously commissioned and maintained to provide useful information.

The case study on the application of optimization in early stage building design has been published in a peer reviewed conference paper, which is appended to this thesis. The case study on gathering data on the institute for Life Science Building 1 and the application of SADE to the calibration of building energy models will form the basis of two future papers.

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Glossary of Terms

ABCAT	Automated Building Commissioning Analysis Tool
AHU	Air Handling Unit (building services technology)
AR	Asset Rating
ASHRAE	American Society of Heating Refrigeration and Air-conditioning Engineers
BEM	Building Energy Model
BLAST	Building Loads Analysis and System thermodynamics (building simulation program)
BMS	Building Management System
BREEAM	Building Research Establishment Environmental Assessment Methodology
BRUKL	Building Regulations United Kingdom Part L
BS	British Standards
BSERT	Building Services Engineering Research & Technology
Cat 3	Category 3 laboratory
CAV	Constant Air Volume (building services technology)
CE	Common Era
CEC	California Energy Commission
CIBSE	Chartered Institute of Building Services Engineers
CHP	Combined Heat and Power (building services technology)
COP	Coefficient of Performance
CSV	Comma Separated Variables (computer file type)
CVRMSE	Coefficient of Variance of Root Mean Square Error
$CVRMSE_{hourly}$	Coefficient of Variance of Root Mean Square Error on an hourly basis
CWS	Chilled Water Service
DCLG	Department for Communities and Local Government
DEC	Display Energy Certificate
DHW	Domestic Hot Water
DOE	Department of Energy (United States)
DOS	Disk Operating System
DSA	Differential Sensitivity Analysis

DX	Direct Expansion (building services technology)
E+	*EnergyPlus™* (building simulation program)
EA	Energy and Atmosphere
EPC	Energy Performance Certificate
ECBCS	Energy Conservation in Buildings and Community Systems
ECM	Energy Conservation Measure
EDSL	Environmental Design Solutions Limited
EFA	Education Funding Agency
EN	European Standard
EPW	*EnergyPlus™* Weather (*EnergyPlus™* file type)
ESCO	Energy Service Company
ESP-r	Energy System Performance for Research (building simulation program)
EU	European Union
EuP	Energy using Products
EVO	Energy Efficiency Organisation
FCU	Fan Coil Unit (building services technology)
FOS	Facilities Output Specification
FTP	File Transfer Protocol
GB	Giga Byte
GEV	Generalised Extreme Value
GUI	Graphical User Interface
HVAC	Heating Ventilation Air Conditioning
HVAC&R	Heating Ventilation Air Conditioning and Refrigeration
HMI	Human Machine Interface
IBPSA	International Building Performance Simulation Association
ICT	Information and Communication Technology
IDE	Integrated Development Environment (computing)
IDF	Input Design File (*EnergyPlus™* file type)
IDLE	Integrated Development and Learning Environment (*Python*)

IEA	International Energy Agency
IES	Integrated Environmental Solutions
ILS1	Swansea Institute of Life Sciences Building 1
IPCC	International Panel on Climate Change
IPDSB	Invitation to Participate in Dialogue and Submit Bids
IPMVP	International Performance Measurement and Verification Protocol
Kf	Key factors
kW	Kilowatt
LAN	Local Area Network
LDF	Log Data File (*Microsoft SQL Server*)
LED	Light Emitting Diode
LEED	Leadership in Energy and Environmental Design
LHC	Latin Hyper-Cube
LLC	Limited Liability Company
LTHW	Low Temperature Hot Water
MCA	Monte Carlo Analysis
MCC	Motor Control Centre
MDF	Primary Database File (*Microsoft SQL Server*)
MDAC	*Microsoft Data Access Components*
Min FA	Minimum Fresh Air System
MSXML	*Microsoft Mark-up language*
NABERS	National Australian Built Environment Rating System
NC	New Construction
NCM	National Calculation Method
NMBE	Normalised Mean Bias Error
$NMBE_{hourly}$	Normalised Mean Bias Error on an hourly basis
NREL	National Renewable Energy Laboratory
NSGA2	Non-dominated Sorting Generic Algorithm 2 (optimisation algorithm)
OR	Operational Rating

PC	Personal Computer
PhD	Doctor of Philosophy
PFI	Private Finance Initiative
ppm	parts per million
PROBE	Post-occupancy Review Of Buildings and their Engineering
PSTAR	Primary and Secondary Term Analysis and Reconciliation
SADE	Self-Adaptive Differential Evolution (optimisation algorithm)
SAP	Standard Assessment Procedure
SHC	Solar Heating and Cooling
SQL	Structured Query Language
SSA	Stochastic Sensitivity Analysis
SSD	Solid State Drive
SSH	Secure Shell
STEM	Short Term Energy Monitoring
TAC	Tour and Anderson Controls
TER	Target Emission Rate
TM	CIBSE Technical Manual (e.g.: TM52 means Technical Manual 52)
TRNSYS	Transient System Simulation Tool
T-SQL	Transact Structured Query Language (programming language)
UFH	Under-floor Heating
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
USGBC	United States Green Building Council
VAV	Variable Air Volume (building services technology)
VBA	Visual Basic for Applications (programming language)
VE	Virtual Environment
VRF	Variable Refrigerant Flow (building services technology)

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Chapter 1 Introduction

Anthropogenic production of carbon dioxide is trending toward levels, which will have a significant negative impact on the inhabitants of our planet. Buildings are responsible for a significant contribution to these carbon dioxide emissions.

This contribution has been recognised by the building services profession who work to reduce the energy, and therefore carbon dioxide, which is associated with the operation of buildings. Building energy models are one of the main tools that building services engineers use to make decisions about which technologies should be employed to maintain comfortable environments in buildings and minimise energy use.

Optimisation routines have been applied in a variety of fields but are still not commonly used in building services design. Multi-objective optimisation could play an important part in decisions involving the placement of resources to produce energy efficient buildings while still maintaining comfortable working conditions.

Results from the measurements of the amount of energy used by buildings deviates substantially from the predictions of whole building energy simulations. There is a substantial need to improve the accuracy of building energy models.

There are a number of potential sources of the deviation between predictions and measurements of energy consumption from buildings in use, including the selection of the input parameters which are used to describe the building.

The input parameters which were assumed in the construction of building energy models can be modified using data obtained from buildings in use. This process, known as “calibration”, can reduce these deviations to within agreed limits.

There are many documented calibration processes, but in the commercial environment, not all of these processes are practical. Again, optimisation processes, where the deviation between modelled and measured energy use is minimised, may be usefully applied.

This thesis addresses the practicality of optimising building design and calibrating building energy models in a commercial environment by following the process though a case study.

1.1 Research questions and work programme

My research question is:

> *“How can existing building energy model optimisation techniques be used to provide a better process for designing buildings and calibrating building energy models?”*

This main research question has been addressed via two sub-research questions. The first deals with the usefulness of optimisation in early stage building design, for which the research question is:

> "*Does multivariable optimisation using NSGA2* [Non-dominated Sorting Genetic Algorithm 2] *yield savings significant enough to justify the engineering time which needs to be devoted to* the *optimisation process?"*

This research question is answered in Chapter 3 of this thesis.

The second deals with how useful a calibration technique is to support optimisation of a Building Energy Model (BEM):

> *"Which of the calibration methodologies is best suited to application by engineers who are working in practice?"*

This research question is answered in Chapter 4 of this thesis.

In order to answer the first research question the following work programme was set.

- Carry out a literature review to establish the current state of the art and chose appropriate software, algorithms and calibration methods.
- Select an appropriate building to use as a case study.
- Produce a BEM of the case study building.
- Obtain construction cost information sufficient to quantify the capital costs associated with building design decisions
- Perform building energy model optimisation
- Compare the theoretical operational energy efficiency and capital costs with the predicted performance during the original design.
- Assess results and document the process and findings.

For the second research question:

- Carry out a literature review to establish the current state of the art and chose appropriate software, algorithms and methods.
- Select an appropriate building to use as a case study.
- Produce an "as built" building energy model of the Institute for Life Sciences Building 1 (ILS1).
- Monitor over a period of a year the as built performance of ILS1 via its Building Management System (BMS).
- Calibrate the BEM with the monitored data.
- Assess results and document the process and findings.

During the monitoring of ILS1 the BMS failed and so the work programme adjusted as follows and a new case study building selected:

- Carry out a literature review to establish the current state of the art and chose appropriate software, algorithms and methods.
- Select an appropriate building to use as a case study.
- Produce an “as-built” BEM.
- Obtain and process meter energy readings to obtain a data set, against which, the BEM could be calibrated.
- Carry out a sensitivity analysis to determine the parameters with the greatest influence on the outcome of BEM calibration.
- Use *jEPlus™* to apply a Latin Hypercube Monte Carlo (LHMC) search to the BEM parameter space to identify the most influential parameters and find the most appropriate values for those parameters.
- Adapt a known Self Adaptive Differential Evolution (SADE) script for use with *EnergyPlus™*.
- Test the adapted SADE script to ensure correct operation.
- Apply the SADE script to the 8 Fitzroy St BEM to obtain values for the calibration of the BEM.
- Assess results and document the process and findings.

This thesis is divided into five chapters. The introduction deals with the primary research questions and the structure of the thesis. Chapter 2, the literature review, provides the background to the thesis, describes the current state of the art, and provides any information that the reader needs in order to understand the software, algorithms and calibration processes applied in the research. Chapter 3 describes the case study where optimisation was used in an early design stage to optimise the selection of building services and construction parameters in a new building. Chapter 4 uses a series of case studies to compare the efficacy of heuristic and deterministic optimisation methods in building energy model calibration. The final chapter discusses the results, draws conclusions and recommends future work. The structure of this thesis is outlined in Figure 1

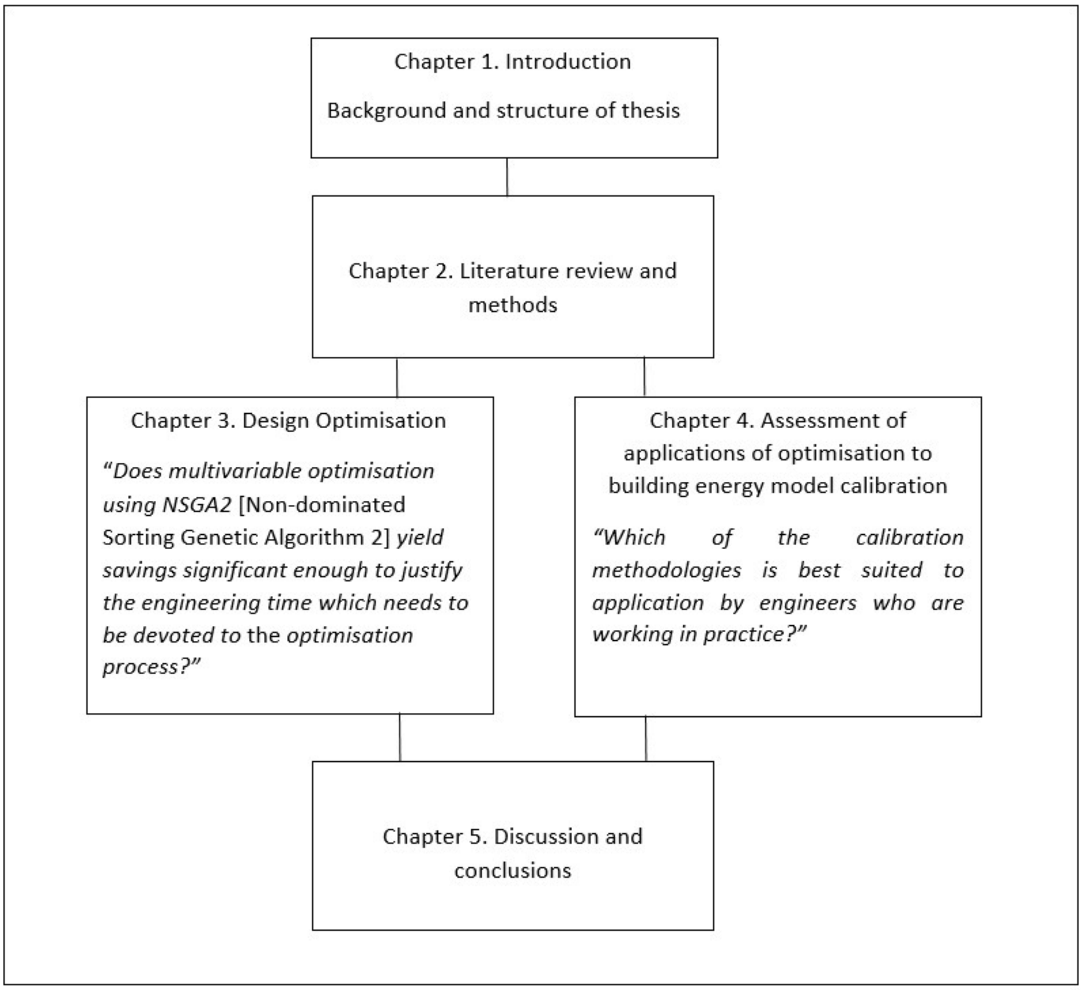

Figure 1. Structure of this thesis.

Chapter 2 Literature review and methods

In this chapter, the need to produce and test new processes for optimisation in building energy modelling is summarised with reference to the current literature. The literature review summarises the existing calibration methods and provides an overview of the software used, and options for research methods, including the ones used in this thesis.

2.1 Climate change

The motivation for developing energy efficient buildings is due to significant increases in anthropogenic carbon emissions. The levels of carbon dioxide in the atmosphere have been directly measured at Mauna Loa in Hawaii, since March 1958 (Pales and Keeling, 1965; Keeling et al., 1976). The Mauna Loa observatory is well placed, away from sources and sinks of carbon dioxide, to ensure accurate representative readings of atmospheric carbon dioxide (Pales and Keeling, 1965).

There is no doubt now that carbon dioxide production is anthropogenic and having a direct impact on the climate of the planet.

Building energy models play a key role in assessing the energy efficiency and therefore carbon impact of the building prior to construction. It should be noted that architectural design also has a key role in reducing energy demand, but that this thesis is focused on processes that do not require substantial change to a buildings essential architecture.

A more detailed overview of climate science and its relevance to building energy modelling is contained in Appendix B.

2.2 Accuracy of building energy models

Leaman and Bordass (1993) highlighted poor energy efficiency in buildings in a landmark series of studies conducted between 1995 and 2002. The studies were carried out on 19 buildings from around the United Kingdom (Bordass and Leaman, 2004) and on one from the Netherlands. The studies were called Post-occupancy Review of Buildings and their Engineering (PROBE) and concentrated on technically notable buildings which had been recently completed. The studies found a significant deviation between the predicted energy performance and the actual energy consumed by the buildings in use.

Ahmad and Culp (2006) produced DOE-2.1E building energy models of four buildings and compared the predictions for annual energy use from the building energy models with measured data. They found that total annual energy use varied over +/- 30% with one outlier compared to the simulated consumption. When they compared the simulated and actual energy use for individual components, they found that the predictions varied by +/- 90% of the predicted values.

In Raslan and Davies' study (Raslan and Davies, 2010), three notional buildings were simulated using thirteen software applications. The results were not compared to actual buildings but the highest predictions exceeded the lowest by up to 250%.

2.2.1 Improving building energy modelling

There are a number of areas where the deviations between the predictions of annual energy consumption by building energy models, and the measurements from buildings in use, could be reduced.

The three areas of uncertainty can be summarised (Yeo, Choudhary and Augenbroe, 2012) as:

- the deviation between the input parameters assumed before building completion and parameters which could be derived from a building in operation;
- uncertainty resulting from the application of the building modelling software to the building including the actions of the user and the capability of the software to accurately represent the physics of the building;
- uncertainty in the measurement of the energy used by the building.

Optimisation can be used in conjunction with building energy modelling in the early stages of design to ensure resources are best used to meet a client's requirements, and can be applied during model calibration to improve model inputs which in turn could produce more accurate future models.

2.2.2 Verification and validation

Processes which contribute to an assurance that building modelling software will be useful can validate or verify the model.

Verification is the process that ensures that the computational model represents the physics of the process being modelled.

Validation is the process of determining to what extent the model replicates the behaviour of interest.

2.2.3 Practice literature

The performance of building energy models is predicated on the selection of the input parameters. The validity of models can be improved if better sources for the values of the input parameters were available. Some technical references already exist.

The Chartered Institute of Building Services Engineers (CIBSE) provides comprehensive guidance for services engineers. Implicit in these guides is a need to produce physical and mathematical models of the operation of the building in order to estimate the volumes flow rates and energy transfers that will be required to maintain the buildings in operation.

CIBSE also provides a range of Technical Manuals (TM) to assist engineers in special circumstances. TM22: Energy assessment and reporting method, (CIBSE, 2006) and TM33: Tests for software accreditation and verification, (CIBSE, 2009), provide extensive guidance relating to the construction, use and testing of energy models in buildings. AM11: Building performance modelling provides guidance on the appropriate application of building energy model software. This includes *"quality assurance procedures compliance with UK and some international building energy efficiency codes, thermal environment and energy, ventilation, lighting and plant modelling"* (CIBSE, 2015).

2.2.4 Feedback from buildings in use

The values of input parameters would be more appropriate if more attention was paid to the operation of existing buildings.

Review of buildings after completion is not a new concept. *Plan of Work for Design Team Operation* (1963) included a Stage M: Feedback (cited in Bordass and Leaman, 2005), which was withdrawn in 1972 because, in practice, architects had found that clients would rarely pay for such a service (Bordass and Leaman, 2005).

Following the PROBE studies, a series of articles called *Making feedback and post-occupancy evaluation routine*, (Bordass and Leaman, 2005a; Way and Bordass, 2005; Bordass and Leaman, 2005b), provide recommendations for the improvement of the building design process, in which they call for the facilities manager to take the lead:

> "*Dependable comparison of actual and forecast performance will be impossible without regular recording of changes by the Facilities Manager"*

But this is not necessarily appropriate. Facilities managers do not have the time or the technical skills to rerun engineering models. Building Management Service (BMS) vendors might claim that recording building performance data and analysis against predicted models can be automated using the BMS and Internet Protocol services. However, this thesis demonstrates how far existing systems are from being able to do this. The reliability of recording and reporting this data is assessed in this thesis as part of an attempt at a heuristic calibration.

2.2.5 Verification of energy modelling software

The predictions of building energy models are reliant on the capability of the building energy model software to model the complex physics of a building. The applicable processes are called *verification* and *validation*, which are applied to software to ensure that it can achieve this. This section describes the current methods for verifying and validating building energy modelling software.

A clear distinction needs to be drawn between the verification of building energy modelling software, the validation of the software and the *calibration* of the models produced by that software. Verifying ensures that the software is capable of producing models which, if properly configured, will produce acceptable predictions about the performance of buildings. Unless the building modelling software is verified there could be little hope of producing a useful model.

Once a model of a particular building has been produced and the building has been constructed, the energy performance predictions of the model can be compared to recorded energy consumption of the building as measured using energy meters. At this stage, there is an opportunity to adjust the input parameters in the model so that the predictions of the model better reflect actual energy consumption.

The following sections are focused on the verification of building energy modelling software. Processes for the calibration of models are summarised in the literature review, following in the next chapter.

2.2.6 CIBSE Technical Manual 33

The 2006 edition of Technical Manual 33 (TM33) (CIBSE, 2006) has been developed to provide a formal process under the National Calculation Methodology to approve Dynamic Simulation Modelling (DSM) software for demonstrating compliance with Part L of the Building Regulations (CIBSE, 2006).

TM33 is comprised of sets of tests in which the results are expected to agree with documented results contained in the technical manual. The manual documents tolerances below which the software can be deemed to be in agreement with the standard calculation methodologies although some of the tolerances are as high as 10% (for G9: Infiltration and ventilation).

The tests are divided into:

- general purpose tests G1 – G10 which test the software's accuracy when handling operations including basic thermal calculations, glazing properties, steady state heat loss, annual cooling demand, overheating risk and infiltration;
- results of simulations compared against a test cell;
- CIBSE specific tests which examine the accuracy of the model to predict such parameters as solar position, material properties and psychrometrics.

2.2.7 International Energy Agency

The International Energy Agency (IEA) operates a number of working groups which work on a series of tasks, annexes and projects. The Energy Conservation in Buildings and Community Systems (ECBCS) and the Solar Heating and Cooling implementing programme (SHC) have both carried out projects related to the validation of building simulation software.

As a note to the reader who may wish to follow these references, these working groups have carried out a series of projects which sometimes overlap with different task numbers and subsequent references for the same study; this can lead to some confusion.

One of the goals for the IEA has been to develop analytical, comparative, and empirical test protocols which can be applied to building energy performance software. These test methods comprise the IEA Building Energy Simulation Tests (BESTest).

The BESTests were primarily developed under IEA SHC programme: Tasks 8, 12 and 22, with input into Task 12 from IEA ECBCS; these have subsequently been augmented by a series of projects under ECBCS Annex 43: Testing and Validation of Building Energy Simulation Tools which were jointly operated with the SHC Task 34.

The BESTests specify a series of cases which describe models to be produced by the software under test. The models are intended to test specific aspects of the software to identify potential errors. Predictions about energy consumption from the software are compared with analytical solutions, empirical data from equipment tests and between software applications.

The BESTest system does not provide a pass/fail, but instead provides a framework for comparison of the extent of deviations from standard results. The Class of BESTest tests should always be quoted and the results should be compared against the standard results.

2.2.8 ASHRAE 140 BESTest

The American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE) Standard 140: BESTest (ASHRAE, 2002) provides a suite of tests to identify specific types of errors in building energy modelling software. The tests consist of a series of test building plans and equipment specifications which focus on different aspects of building energy simulation to identify potential errors in code or methodology.

The tests are divided into Class I and Class II test cases. Class I tests contain detailed diagnostic tests which use some of the test principles which were developed by the IEA for their solar heating and cooling tasks. Class II tests are intended for simplified methods favoured in residential load analysis software.

Class I tests compare results from leading software which examine the predicted energy consumption as a function of the building fabric and mechanical equipment simulation. They also compare the results from software with analytical solutions.

Class II tests were originally developed for the Home Energy Ratings Systems (HERS) which also (confusingly) bears the name BESTest. The tests are divided into Tier 1, which consists of the analysis of a standard building, and Tier 2, which adds additional parameters intended to reflect a more realistic building.

2.3 Optimisation of building energy models

Optimisation is the process of finding the best combination of inputs to achieve a target; this could be finding the best combination of building fabric and services to achieve a comfortable and compliant building (Polson, Zacharis, Lawrie and Vagiou, 2017), or finding the best combination of values for parameters to minimise the divergence between measured and simulated data (calibration).

Optimisation processes depend largely on algorithms which search for the best combination of values for parameters under scrutiny. Searches may be heuristic, deterministic or stochastic. The techniques can include sensitivity analysis, Monte Carlo, Markov chains and evolutionary algorithms.

2.4 Calibration of building energy models

A building energy model can be adjusted using data from a building in use so that the predicted energy consumption better matches the actual energy consumed. This is an optimisation process where the cost function is the divergence. The process of minimising the divergence is called *calibration*.

Calibration of models is useful for improving the accuracy of the model and because the right process could produce a more useful estimation of input parameters for subsequent studies.

There is an increasing emphasis on the calibration of building energy models.

2.4.1 EFA energy input parameters and modelling guide

The Education Funding Agency (EFA) has produced a *Facilities Output Specification* (FOS) (EFA, 2013a) to document their requirements for the construction of schools as part of the Priority Schools Building Programme.

The FOS is augmented with the energy input parameters and modelling guide (EFA, 2013b) which contains guidance for providing models to meet the requirements of the FOS.

Under the FOS, contractors bidding on projects which are part of the Priority Schools Building Programme, are required to produce a series of building energy models. These models are in addition to the models which are normally produced to demonstrate compliance with the building regulations and are intended to predict energy consumption in the schools which are to be constructed.

Under the FOS, three building energy models are to be produced:

- The *Initial Baseline Energy Model* is produced at the Invitation to Participate in Dialogue and Submit Bids (IPDSB) which is based on the contractor's preliminary design and default parameters contained in the energy input parameters and modelling guide (EFA, 2013b).
- The *Final Baseline Energy Model* is produced for *Financial Closure* which is a revision of the Initial baseline Energy Model which has been revised to reflect actual legacy equipment.
- The *In-Use Energy Model* is produced in the first years of operation and is a calibrated model based on the Final Baseline Energy model.

The Initial Baseline Energy Model is used to demonstrate that the contactor's design meets the *Core Energy Cap* and *Design Energy Target*. These targets are defined in the FOS and *Energy input parameters and modelling guide* and split energy use according to the hour of the day and type of energy use. The Facility Output Specification seeks to place risk for the costs associated with energy consumption with the party that is best placed to manage consumption (EFA, 2013a).

The Final Baseline Energy Model is used as the initial basis of payment until the In-Use Energy Model can be produced after the first months of operation.

Neither the Facilities Output Specification nor the energy input parameters and modelling guide make any recommendations for the calibration of the building energy model, although they do refer to the *International Performance Measurement and Verification Protocol* (IPMVP) (EVO, 2012) and to ASHRAE 14 (ASHRAE, 2002).

2.4.2 LEED Credit 5

The United States Green Building Council (USGBC) has produced a series of metrics called Leadership in Energy and Environmental Design (LEED), which address issues of sustainability in the construction industry.

Many projects designed in the UK, often for construction in other countries, include a requirement for a LEED rating in their design brief.

LEED for New Construction (LEED NC) version 2.2 (USGBC, 2008) includes a credit under the Energy and Atmosphere (EA) section. EA Credit 5: Measurement and Verification allows for applicants to obtain one credit for preparing a measurement and verification plan which is in accordance with the IPMVP (EVO, 2012). The plan must be produced according to Part D which requires the production of a calibrated energy model in accordance with ASHRAE 14.

2.5 Conclusions

Increasing levels of carbon dioxide are anthropogenic and will result in significant climate change. The construction and operation of buildings is a significant source of carbon dioxide. Computational modelling of buildings is used to aid the design process.

Despite the imperfect nature of building energy modelling, there is an opportunity to make better use of optimisation, both in early stage design of buildings and in the post-occupancy calibration.

Optimisation in early design stage modelling offers a chance to reduce the carbon footprint of a building by ensuring that resources are directed where they can be of most benefit.

Rigorous calibration of building energy models is used to quantify the savings made under energy performance contracts. A calibrated model is required for new schools built under the Priority Schools Building Programme and can be used to obtain credits under the sustainability metric: LEED. Optimisation, as applied to the calibration of building energy models could be a useful service which can be provided as part of an engineering consultancy.

The information gathered during the calibration process could also be used to provide much needed feedback for the construction of future building energy models which need to be improved to close the credibility gap. This is needed to provide an improved basis for the decisions which are needed to reduce carbon dioxide production and the impacts of climate change.

The next chapter provides a literature review of existing processes for applying optimisation to building energy models. In it, existing optimisation and calibration processes are summarised and calibrated models are shown to be able to provide information, which enables building operators to improve the energy consumption of buildings.

2.6 Literature review of methods for calibrating building energy models

A substantial literature review on methods for the calibration of building energy models was carried out by Reddy in 2006. The literature review in this thesis follows the general outline by Reddy but has been extended to include:

- studies overlooked in Reddy;
- developments in processes since 2006;
- new processes including deterministic and stochastic methods;
- Arup company reports and internal documents that contain useful information;
- doctoral theses.

The requirements for inclusion in this literature review were:

- the research contained the construction of a whole building energy model which was then calibrated using data obtained from a building in use;
- a building was initially analysed using a whole building energy simulation;
- a calibration process was used to modify the model to reflect the performance of a building in use.

This part of the literature review focused on the calibration of whole-building energy models or simulations, so studies of sub-systems (e.g. Zhou, Wu, Wang, & Shiochi, 2007) were not exhaustively followed.

It might be noted that many of the references in this literature review are quite old, however the methods are included for completeness and to set the deterministic methods used in their academic context.

2.6.1 Structure of the literature review

This review starts with general references that provide standards by which results from the calibration of building energy models can be measured. This sets the target for the calibration of building energy models as optimising (to a minimum) the divergence between the predictions for energy consumption and the metered energy delivered to the building.

Most studies are discussed under the heading of one of the three main techniques for calibrating building energy models: heuristic methods, deterministic methods and stochastic methods.

There are four sections relating to analytical techniques which could be useful for optimising building energy models, so these techniques are discussed under separate headings; these are:

- sensitivity analysis which could be used to identify the relative influence input parameters have in any of the processes;
- Monte Carlo analysis;
- Markov Chains;
- Evolutionary Algorithms.

Monte Carlo, Markov Chains and Evolutionary Algorithms could be used in both deterministic and stochastic searches for values of input parameters which optimise a design or minimise the error between predictions and measured values.

Meta-modelling is discussed as a process which could provide a method for decreasing the time which is required to run building energy models.

Tools which have been developed to assist in calibration of building energy models are discussed in Section 2.6.10. These tools can be used to automate some of the repetitive process required in sensitivity analysis, deterministic processes and stochastic processes.

2.6.2 Previous literature reviews

In the process of carrying out this literature review, two earlier literature reviews were discovered.

A study by Palomo, Marco and Madsen (1991) provides a set of methods which the authors considered applicable to the comparison of results from building models and buildings. Their review includes a number of interesting mathematical procedures and provides a demonstration of the application of some of the methods to a test cell.

In his extensive literature review, Reddy (2006) concluded that the issue of uncertainty needs to be addressed and that a process is required that provides a “coherent and systematic calibration methodology”.

Cho (2009) included a section on building energy model calibration for his PhD thesis: *Methodology to develop and test an easy to use procedure for the preliminary selection of high performance systems for office buildings in hot and humid climates*. Cho focused on three calibration methods: a heuristic “rule of thumb method”, graphical methods and the signature method; he concluded that he needed to use a combination of all three methods for his thesis.

In her PhD thesis: *Bayesian calibration of building energy models for energy retrofit decision making under uncertainty* (Heo, 2011), Heo concluded that a building energy model calibrated using a Bayesian method can provide an adequate basis for making decisions about retrofit options.

The literature review in Raftery’s thesis: *Calibrated whole building energy simulation: An evidence based methodology* (Raftery, 2011) concluded that even though there are a large number of methods for calibrating building energy models, “there is no widely accepted method for calibrating a simulation model”. Raftery proposes a hierarchy of data sources which are then used to calibrate the building energy model. He argues that by using data from more reliable sources the calibration will be more realistic.

Bertagnolio (2012) draws some pertinent conclusions in his PhD thesis: *Evidence based model calibration for efficient building energy services*. In his literature review, he concludes that calibrating building energy models using a combination of intuitive and mathematical methods is an attractive solution. Importantly, he also concludes that because calibration is an underdetermined problem (there are many possible solutions) a “blind” calibration could miss contributions from important parameters.

2.6.3 General references

2.6.3.1 Assessment of energy model calibration using ASHRAE 14

ASHRAE Guideline 14: *Measurement of Energy and Demand Savings* (ASHRAE 2002) is intended to provide a method for standardising the estimation of savings resulting from the retrofit of buildings. The standard assumes that savings are the difference between the predicted energy use of a baseline model and the actual energy consumption of the building. It uses the term *Energy Conservation Measure* (ECM), which is also widely used in the literature, to describe the class of modifications to a building which are intended to reduce its energy consumption.

The standard describes a range of tools for establishing the baseline model, with a calibrated building energy model being the most sophisticated. Most importantly, it describes a set of stochastic parameters which can be used to measure the correlation between a model and the performance of a building and a set of values which can be used to demonstrate the adequacy of the calibrated model.

Coefficient of Variance of Root Mean Square Error (CVRMSE) and Normalised Mean Biased Error (NMBE) were chosen as the calibration quality metrics because they are most widely quoted in the literature and provide a comprehensive evaluation of a calibration method.

The definitions of the stochastic parameters are given in (1) and (2) below.

$$CVRMSE = 100 \times \frac{\sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{(n-p)}}}{\bar{y}}$$

(1)

which is equation (5.4) in ASHRAE 14:2002 and;

$$NMBE = 100\ \times \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{(n-p) \times \bar{y}}$$

(2)

which is equation (5.5) in ASHRAE 14:2002,

where:

- n is the number of data points or periods in the baseline model;
- p is taken to be 1 (ASHRAE 14, 2002, 5.2.11.3, P15);
- y_i is the i^{th} dependant variable of some function of the independent variables;
- $\hat{y}_i$ is the i^{th} value of the regression models predicted value of y;
- $\bar{y}$ is the arithmetic mean of the sample of *n* observations.

While this standard has been available since 2002, there are a large number of studies which do not use this standard to enable their method to be compared to those of others.

The uncertainty tolerances for calibrated models are reproduced from ASHRAE 14 for convenience.

Section 5.3.2.4.f requires that:

> *"The computer model shall have an NMBE of 5% and a CVRMSE of 15% relative to monthly calibration data. If hourly calibration data are used, these requirements shall be 10% and 30% respectively."*

Section 5.3.2.4.h requires that:

> *“The level of uncertainty must be less than 50% of the annual reported savings at a confidence level of 68%”.*

Section 6.3.3.4.2.2 states that over a year:

> *“Typically, models are declared to be calibrated if they produce MBEs within ±10% and CVRMSEs within ±30% when using hourly data or 5% to 15% with monthly data.”*

Since the requirements for CVRMSE are significantly different depending on whether the calculation is carried out based on hourly or monthly data, the subscript “$_{hourly}$” ($CVRMSE_{hourly}$) has been added to the data studied in this thesis, and similarly for NMBE.

2.6.3.2 International Performance Measurement and Verification Protocol

The *International Performance Measurement and Verification Protocol* (IPMVP) contains guidelines for quantifying savings which result from changes to energy or water systems (EVO, 2012). The standard broadly outlines four methods, of which the fourth (Option D) is to develop a calibrated building energy model which can then be used to provide a baseline of energy consumption against which post-alteration energy usage can be compared and used to determine on-going savings. The standard provides an example where an energy model is used to predict energy use following the replacement of a boiler in a factory and where an increase in production coincides with the period of expected energy savings.

A calibration process is loosely outlined based on literature, none of which dates from after the year 2000. After the collection of data, a series of steps are provided to guide the calibration of the Building Energy Model (BEM); these are:

- assume and document input data;
- gather weather data;
- verify that the model predicts operating conditions;
- compare the results for predicted energy consumption with metered data;
- use graphical techniques to discover patterns in the deviation from predicted results;
- revise [input] data and repeat the process until the predicted energy results fall within the acceptance criteria.

The protocol omits significant references that would be likely to be useful to an engineer tasked with calibrating a model. Particularly, reference should have been made to acceptance criteria such as NMBE and CVRMSE. Also, as described elsewhere in this review, there are a number of techniques for calibrating building energy models that are available, and which could be described in more detail or at least referenced.

The IPMVP process has been applied to two large offices in Shanghai. DOE2.1E and DOE2.2 models of an 88 storey, 300,000 m^2 multi-use office (Pan, Huang and Wu, 2007) and a 41 storey 67,000 m^2 multi-use office (Pan, Huang, Wu and Chen, 2008) were calibrated using the procedure in the IPMVP. The results obtained for monthly and annual electricity and gas use are given in Table 1.

Study	**MBE_{month}**	**MBE_{year}**	**CVRMSE**
Electrical Study 1	7.1%	1.2%	4.7%
Gas Study	13%	3.1%	8.9%
Electrical Study 2	10.0%	2.4%	5.7%

Table 1. Results obtained for the calibration of offices in Shanghai using IPMVP. (Pan, Huang, Wu and Chen, 2008)

These results are very good when compared to other processes and well within the limits of ASHRAE 14.

2.6.4 Heuristic methods for calibrating energy models

Heuristic methods depend on the expertise of the practitioner as they rely on the understanding of the problem and may draw on the practitioner's previous experience with similar problems.

Heuristic methods are discussed in depth in Reddy's literature review (Reddy, 2006). There has been subsequent development of these methods since 2006, focusing on developing systematic repeatable methodologies. Again, the various methods are developed from Reddy's classifications.

2.6.4.1 Manual, iterative and pragmatic intervention for calibrating models

Manual, iterative and pragmatic methods are by far the widest group of methods for the calibration of building energy models. The author would suggest this is also the most intuitive to a practising engineer. Calibration is carried out by manually manipulating the input parameters based on the experience and expertise of the practitioner. Various publications describe subtle nuances in technique or seek to produce a rigorous repeatable method. However, all these processes are dependent on the time spent by a suitably-qualified (and therefore expensive) practitioner. This is not to say that the process described cannot be adapted for automatic or low user-input implementations, but that the advances in computing speed and the reduction in cost of manufacturer and installing meters may have made these methods less attractive in their current form.

Clarke Strachen and Pernot (1993) used results from a test cell to validate an ESP-r model, which was then used to assess the impact of adding a conservatory to a building.

Reddy, Hunn and Hood (1994) used a process that started with the identification of uncertain parameters for a DOE2 simulation, which have the greatest impact on total energy use. Some of the values for the parameters were then measured in the field and substituted into the model. The remaining parameters were adjusted manually to match the energy use data. The process was demonstrated on a 23,200 m^2 education building in Austin Texas and was used to assess potential energy savings from ECMs.

Chimack, Walker and Franconi (2001) calibrated a DOE2.1E model of a 107-year old 55,700 m^2 Museum at the University of Chicago in Illinois. The process was iterative and the authors described a series of steps in the calibration process. The report is notable for the use of stochastic terms including those quoted in the subsequent ASHRAE 14 to quantify the accuracy of their calibrated model.

A three-step process is described in Pedrini and Lamberts (2001) and Pedrini Westphal and Lamberts (2002). The authors claim that the process is especially well suited to buildings in warm climates such as Brazil and Australia. The three steps are to:

- simulate the building using information from design plans and documentation;
- carry out an audit to identify changes to the original designs and gather data using data loggers and hand-held meters;
- take end-use measurements for the values of parameters used in the building energy model.

The three-step method is demonstrated on six buildings in hot climates; however the studies do not use metrics (such as CVRMSE), which would have enabled the results to be compared to other studies.

A seven-step method is proposed by Yoon, Lee and Claridge (2003) and Yoon and Lee (2003).

The seven steps are:

- model the base case;
- analyse the base case;
- calibrate the model using mid-season data;
- carry out site interviews and confirm changes to the model;
- calibrate the model for the heating and cooling seasons;
- validate the calibrated model;
- investigate promising ECMs.

The method is demonstrated on a 26-storey, 83,200 m^2 office in Seoul, Korea. A DOE2.1E programme was calibrated and the study quotes final values of MBE 2.3%, CV 3.6% based on monthly values.

Iqbal and Al-Homoud (2007) used a building audit to calibrate a Visual DOE4.0 model of 6-storey newspaper headquarters in Dammam, Saudi Arabia. The calibrated model was used to assess parameterised ECMs.

Cho and Haberl combined manual, graphical and signature methods (described in later sections) in a study of the seven-storey 11,500 m^2, John B. Connally Building at Texas A&M University in Texas (Cho and Haberl, 2008). While the study combined methods, these methods remains essentially heuristic. The methods achieved an overall CVRMSE of 8.4% based on hourly data, which compared well with the ASHRAE limit of 30%. This study is notable for the emphasis on the combination of techniques.

Lavigne (2009) calibrated a DOE2.1E model of a 14,500 m^2 Service Centre and an 8,000 m^2 Office, both in Quebec, Canada. In this study, the author uses a combination of methods in a tool which employs an optimisation algorithm which searches for five parameters which define energy use against ambient temperature. The five parameters were:

- baseline changes representing revised values for plug and lighting loads;
- heating slope which represents the rate of heating with outdoor air temperature;
- cooling slope which represents the rate of cooling with outdoor air temperature;
- the outdoor temperature at which heating is no longer required;
- the outdoor temperature at which cooling becomes necessary.

The algorithm then uses a minimisation process to select parameters that have the greatest influence over the energy use of the building. These factors are then applied over a range to select the best input for the simulation. The study highlights the necessity for engineering input in the selection of realistic parameters and the lack of adjustment of schedules as weakness in the method. While the results are only quoted in terms of monthly and annual under/over estimation, the results appear good and illustrate the potential of combining heuristic with deterministic methods.

Costa, Keane, Raftery and O'Donnell (2009) documented a system which they have termed: "Key Factors".

> *"Key factors (K_f) are those parameters of the operation strategy that influence the environmental and energy performance of the building."*

The study was intended to provide information to building operators to enable them to operate the building in the most efficient manner. At the time of publication an *EnergyPlus™* model had been constructed, but not calibrated. The paper was published to illustrate the process for which the calibrated model would be employed after calibration. It is included in this study because it refers to assumed roles in which an *energy consultant* provides a calibrated building energy model, and an *energy manager* specifies the metrics that are important and used to measure the performance of the building. The initial parameters suggested related to building energy consumption and user thermal comfort.

EnergyPlus™ 4.0 was used to model 8,400 m^2 classroom and office building at the University of California campus at Merced in an effort to diagnose a drop-off in energy performance between 2008 and 2009 (Dudley, Black, Apte, Piette and Berkeley, 2010). The processes are essentially heuristic based on a relatively short period in 2008 from August 15th to the 25th. Actual class schedules were used. For the period of calibration, the NMBE and CVRMSE quoted at 1% and 1.4% are excellent, although this cannot be directly compared with other studies due the short duration of the calibration data. A full check on the calibration was planned for 2009.

Raftery, Keane and O'Donnell (2011) introduced the use of version control software and adapted other heuristic methods to provide a more reproducible process, which they termed *An Evidence-based Methodology*. In this study the authors argue that rather than tune a calibrated model, changes in input parameters should only be "made according to the available evidence under clearly defined priorities".

The overall process is described in a flow diagram, which includes a rather substantial iteration loop. At each stage the authors take great pains to emphasise the importance of version control. Version control is managed using a software tool called *TortoiseSVN*. A four-floor 30,000 m^2 industrial office in Dublin, Ireland, was used to demonstrate the method. The case study only quotes results for the HVAC system which have an $NMBE_{hourly}$ of -4.2% and $CVRMSE_{hourly}$ of 7.8%.

Coakley, Raftery and Molloy (2012) later applied a similar system to the Galway Nursing Library in Ireland.

Taylor, Zhang and Bannister (2011) calibrated two EDSL Tas 8.5 models and a DOE2.1E model of buildings in Australia to assess ECMs intended to improve their building's *National Australian Built Environment Rating System* (NABERS) rating. The process was essentially heuristic following an audit as prescribed by AS/NZS 5398:2000. The deviations between the measured and simulated data were not quoted.

Srinivasan, Lakshmanan Srivastav and Rinker (2011) revised occupancy schedules to calibrate a model of a convention centre with what they termed the *Monthly Calibration Method*. The details of the method are unclear and results similarly vague.

A *Modellica* model of a theatre was calibrated by isolating the steady-state data and calibrating the flow network of the model (Eisenhower, Gasljvic and Mezic, 2012). The dynamic parameters were then adjusted to obtain a model that could be used to investigate the frequency response of the control system, which was represented on graphs.

2.6.4.2 Calibration using suites of informative graphical comparative displays

Reddy (2006) discusses graphic techniques under *Methods for Building Energy Modelling Calibration* and *Data Visualisation Tools* and cites Reddy, Maor, Ponjapornpon and Sun (2006) for a more detailed description. Here, graphical methods are presented together.

At the time of his writing, Reddy advised that graphical plots could not be generated using spreadsheets because common spreadsheet applications were limited in their ability to generate graphs of large numbers of data. However, with the development of more powerful personal computers and the corresponding advances in software, there are now a range of commonly available applications which could be used including *Microsoft Excel™*, *Python* and *Matlab™*.

The application of graphical techniques has undoubtedly been useful in the heuristic calibration of building energy models; however, as with the other heuristic methods outlined above, the high level of expert attention makes these methods less attractive. As such, these methods are only given brief consideration and the reader is again referred to Reddy et al., (2006) and the original literature.

Basic Monthly Time Series Plots

Basic Monthly Time Series Plots (Haberl, Kissock, Belur and Sparks, 1993; Haberl Sparks and Culp, 1996; Haberl and Abbas, 1998a; Haberl and Abbas, 1998b) are used in studies to give a quick visualisation of the deviation between simulated and actual use.

Scatter Plots of Energy Use and Ambient Temperature

Scatter Plots of Energy Use and Ambient Temperature are used to illustrate the disaggregation of weather-dependent and independent energy use; however, the usefulness of this approach in calibration is unclear. These plots can certainly be used to indicate a relationship between energy use and outdoor air temperature, but their usefulness in calibration is questionable. An example of a scatter plot is given in Figure 2.

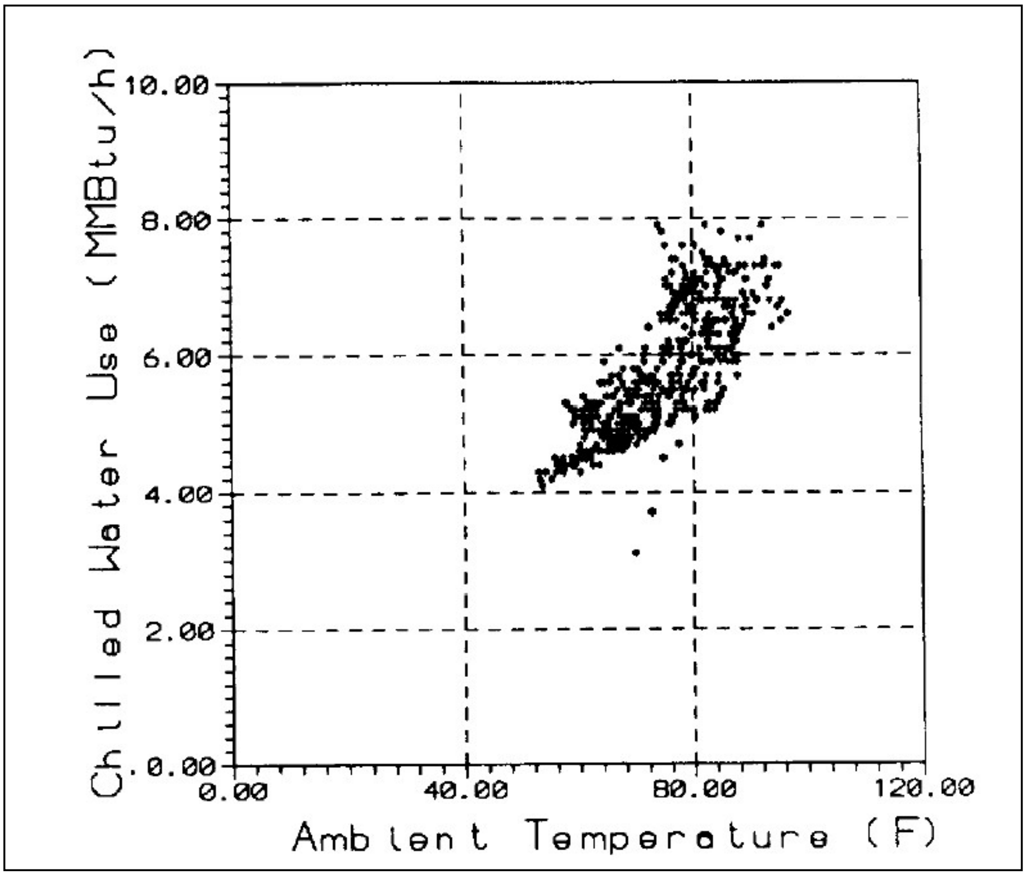

Figure 2. Example of x-y scatter plots from Haberl, Sparks and Culp (1996)

Diurnal Time Series Plots of Energy Use with Hour of Day

Diurnal Time Series Plots of Energy Use with Hour of Day can also be used to disaggregate energy use between occupied and unoccupied hours.

Advanced Visualisation Techniques

This term is reproduced from Reddy, although as already stated, with the advance in computer software and hardware, techniques which might be considered advanced in 2006 in some cases are routine at the time of writing.

Three-dimensional plots made from sequences of graphs can be used to illustrate an entire simulation, with each day represented by one graph and all graphs laid out to include a whole year of data (Christiansen, 1984). Glaser and Ubbelohde (2001) suggest the use of tessellations to describe four dimensional plots. Haberl, Kissock, Belur and Sparks (1993) advise that animated contour plots can provide excellent diagnostics.

This class also includes the augmentation of the processes above with stochastic information, such as standard deviation with Box-Whisker plots.

Raftery and Keane (2011) used carpet-contour plots to visualise a range of loads over *Month of the Year* (x-axis) and *Hour of the Day* (y-axis) as shown in Figure 3 and plots were used to illustrate electricity consumption over the *Day of the Week* (x-axis) and *Hour of the Day* (y-axis). The study uses colour to show a striking difference between energy use in different applications, compared with more historical Bow-Whisker Mean plots. Again, these types of plots provide a colourful indication of the relationship between parameters, but it is not clear that they are useful in the improvement of calibration techniques.

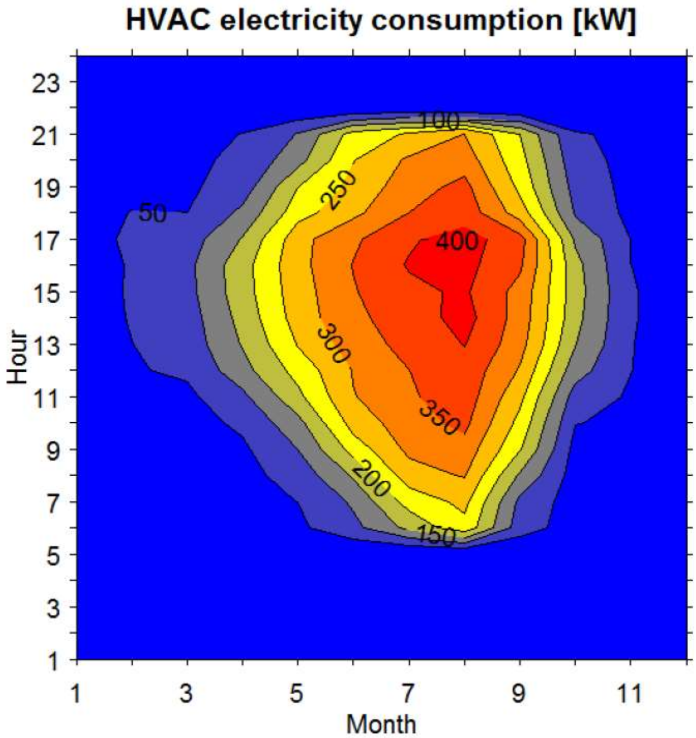

Figure 3. Example of a carpet-contour plot. Raftery and Keane (2011).

2.6.4.3 Calibration using intrusive blink tests

Data gathered from data loggers can be made more useful by the use of *Blink* tests (Soebarto and Degelman, 1996). Data loggers distributed through a building were used to gather data over a weekend. The tests consist of several periods when the electrical loads are turned on and then off again, after a relatively short period – in this case around 5 minutes, to allow the components of electrical loads to be separately identified – or *disaggregated*.

This method was applied to a four-storey *Engineering Centre at College Station* in Texas and used to identify lighting and receptacle loads by floor. The measured loads were compared to survey estimates and shown to improve accuracy by between 0.7% and 5.0%; the results were then used to calibrate an ENER-WIN energy model.

2.6.4.4 Calibration using short term energy monitoring: PSTAR and STEM

Primary and Secondary Term Analysis and Reconciliation (PSTAR) is a method for modelling a building using simplified processes (Subbarao, 1988) in software. Data from a building in use was used to construct a macrodynamic simulation of heat flows, which was designed to be calibrated using *Short Term Energy Monitoring* (STEM).

Koran, Kaplan and Steele (Koran, Kaplan and Steele, 1992) compared the calibration of a DOE-2 model using STEM with a process they called *Monthly Consumption Tuning* (MCT), which was essentially the reiteration of model inputs until the desired tolerance is achieved. In their STEM test, 14 parameters were monitored over a three-day period and applied to the DOE-2 model. The model was tuned heuristically and the results were then extrapolated over a year.

In a study of Symphony Towers, a 49,000 m^2 34-storey office tower in San Diego (Lunneberg, 1999) data loggers were used to collect lighting and small power loads for ten days. Notably, while the formulae for the calculation of NMBE and CVRMSE were not included, the results appear to be within the tolerances of ASHRAE 14 (which would only be published three years later).

The National Renewable Energy Laboratory (NREL) developed the STEM process into a three-day test sequence and applied the process to compare the performance of two test cells (Balcomb, Hancock, Barker, and Subbarao, 2000; Judkoff, Balcomb, Subbarao, Barker and Hancock, E. (2001).

The PSTAR method was used to define terms for an *EnergyPlus™* simulation of a house in Montecorto in Spain (Carrillo, Dominguez and Cejudo, 2009). The model was then calibrated using data from a variety of *Hobo* brand data loggers employed in STEM tests. The researchers found the STEM-PSTAR process highly dependent on the user and that the typical experimental data *"cannot sufficiently minimise the interactions between solar gains, mas and heat loss"*. Carrillo, Dominguez and Cejudo cite Balcomb, Burch and Subbarao, (1993) for a full description of the process. Reddy (2006) describes the process as a period over which the temperature is controlled to be constant and another during which the temperature is allowed to float.

Manke and Hittle (1996), cited in Reddy (2006), applied the STEM process to a BLAST simulation of two buildings (refer to Section 4.4 for information on BLAST) using STEM tests applied over five days.

An attempt has been made to provide several functions in one tool, including modelling and calibration using short term monitoring, by way of a *Workbench* programmed in *Matlab™* (Dybskiy and Richman, 2012). The Workbench provides a graphical user interface to allow a user to model the building and import short-term data from data loggers. The tool was demonstrated on a 250 m^2 1900s Toronto residence.

2.6.4.5 Calibration using macro parameter estimation

Reddy (2006) cites Reddy et al., (1999) as examples of *Macro Parameter Estimation Methods*. The system was developed to provide a non-intrusive model of a building to diagnose excessive energy consumption. The process is based on a simplified building energy model. Linear regression is used on monitored data to determine appropriate values for the parameters used in the model.

2.6.4.6 Calibration using signature analysis

In *Signature Analysis* (Wei, Liu and Claridge, 1998; Liu, Song, Wei and Claridge, 2004; Liu and Liu, 2011) the original assumptions in a model are substituted with the measured values, which is broken into two stages. The first stage uses scatter plots to compare measured and simulated energy consumption against outdoor air temperature to examine the weather dependence of the model. The second examines the dependence on time schedules by plotting measured and simulated energy consumption against time of day. In both cases, *residuals* – the difference between calculated and simulated results, are added to the plots. The characteristics of the residuals are called *signatures,* which reflect the impact of the input parameter under examination. Examples of characteristic signatures are given in Figure 4.The graphs show typical divergence between simulated and measured chilled water (CHW) and heating water (HW) use at various out door dry bulb temperatures.

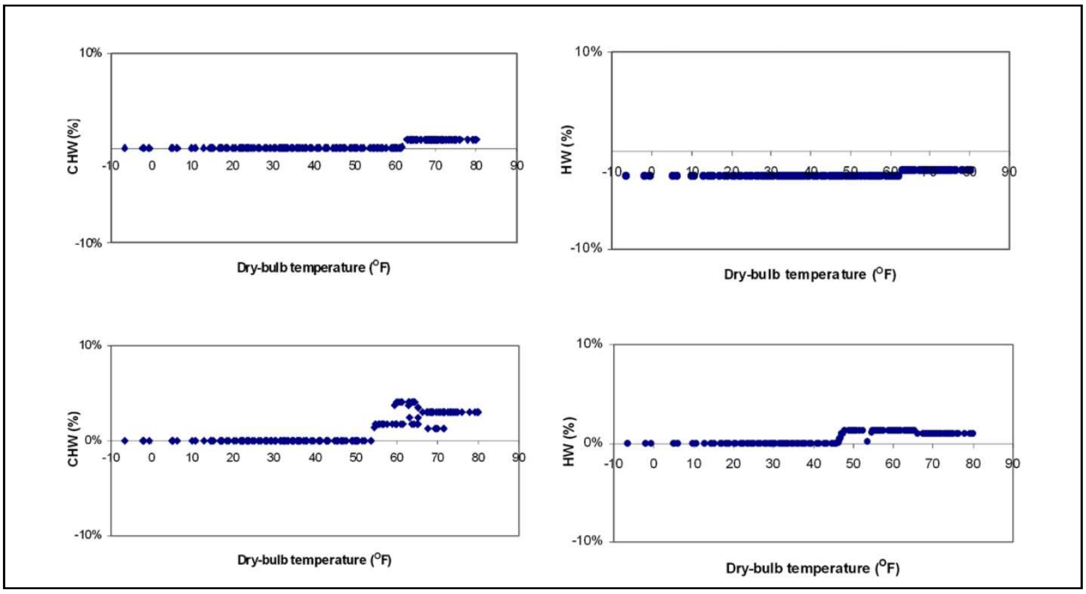

Figure 4. Example of signature plots from Liu and Liu (2011)

Liu, Song, Wei and Claridge (2004) demonstrated the *Energy Signature* method using a two zone simplified model of a 10,500 m^2 university teaching building in College Station in Texas. They argue that, while a more complex model using a greater number of inputs may be capable of producing more results that have closer agreement with measured data, the impact of fewer inputs may be more readily detected in a simplified model. They also contend these results may be sufficient for the purposes for which they are intended. The authors list only 14 *Major Simulation Inputs* from which their initial model is constructed.

The model in the case study consisted of only a perimeter zone and a central zone with one notional *Variable Air Volume* (VAV) air handler serving each zone. While the building modelled has a high degree of symmetry, this is a highly-simplified model which would not (for example) pass the requirements of ASHRAE 90.1 (2012), which requires that each floor be served by a separate air handler. Nonetheless, this study does demonstrate an ability to produce an accurate calibrated model.

An *Automated Building Commissioning Analysis Tool* (ABCAT) was developed to assist the commissioning and diagnosis of building faults (Bynum, Lin, and Claridge, 2009). The tool was tested on six retrospective and nine live buildings around the world. The report builds on the significant work carried out at Texas A&M, which has achieved substantial savings in energy consumption as a result. The process starts with the construction of a building energy model which is calibrated based on data from the building soon after the end of commissioning. Then, simulated and actual data are passed to an analysis routine. The building performance routine produces plots of performance and applies fault detection routines. The report does not detail the calibration routine, but the case studies emphasis the use of signature plots for the identification of faults.

A similar case study (Liu and Liu, 2011) demonstrated the use of the procedure on a 43-storey, 70,000 m^2 Office in Omaha, Nebraska. This study quotes $NMBE_{hourly}$ of 1% for cooling and 0.6% for heating and $CVRMSE_{hourly}$ figures of 31% for cooling and 28% for heating. The authors argue that while these results are not excellent, they are *fit for purpose* i.e., useful.

This process produces a calibrated model which is then applied to fault detection and diagnosis in the on-going operation of the building. The savings claimed would have greatly outweighed the cost of undertaking the study.

The process is highly dependent on the skill of the system modellers and calibrators to correlate the signature with the error in the model. Also, the calibration process effectively only calibrates a few factors against weather and time schedules. However, ABCAT does support a theme of fitness for purpose which can be combined with more sophisticated automatic processes to compensate for the reliance on heuristic expertise.

2.6.4.7 Calibration using day-typing and disaggregation

Day-typing can be used to describe a process whereby either 24 hours of energy use is categorised into a number of classifications that exhibit similar patterns, or *"characterize the behaviour of the system's response"* (Reddy, 2006). In this context it also includes the disaggregation (also see Blink Tests above) of energy into types of consumption.

Reddy (2006) refers to the "*widely used scheme"* of breaking loads down into *"weekday, weekend and holidays"*. Significantly, this system is used by the *National Calculation Methodology* (DCLG, 2013), which was used as the starting point for the estimation of building energy use for the *Priority Schools Building Programme*. However, Reddy goes on to say that finer groupings may be required to distinguish Mondays and Fridays from the remaining days of the week.

Dhar, Reddy and Claridge (1998) use Fourier series to approximate weather data and weather dependent data. This process is an interesting theoretical application, but it is unclear how the resulting transfer function could then be applied to any of the typical problems that building energy modelling calibration is used to solve.

Hadley (1993) uses statistical techniques to conclude that system operating schedules can be grouped as:

- heating only;
- no heating or cooling;

- cooling only.

Akbari and Konopacki (1998) proposed a process that they called the *"End-Use Disaggregation Algorithm"* to assign energy use to hourly load profiles for air conditioning, lighting fans and pumps and miscellaneous loads. The method is demonstrated on a United States of America Department of Defence site. The process consists of three steps:

- Regression analysis of hourly load for a whole building against external temperature. The load is divided into a temperature-dependant and a temperature independent load.
- A building simulation provides a ratio of the loads which make up the temperature-dependent load. The temperature-dependant load is divided according to this ratio.
- Estimated end uses are adjusted so that they reflect the figures obtained from the subdivided regression data.

2.6.5 Non-heuristic methods for calibrating building energy models

2.6.5.1 Sensitivity analysis in energy model calibration

Sensitivity analysis is given a separate heading here because it has implications for many parts of a calibration process.

The rate of error increases with the amount of data applied to a model, whereas the increasing capability of a model to predict the energy performance is subject to a law of diminishing returns (Chapman, 1991). Chapman argues that the accuracy of computer models is limited by the error rate during the input of data rather than the capability of the underlying model. His assertion implies that building practical building energy models needs to involve the selection of a suitable number of parameters, which could be done by starting a new modelling process with a few parameters and building until results indicate a point of diminished marginal utility. Alternatively, this could be done by starting with an accepted modelling process and deleting (or holding constant) parameters which have a lesser impact.

In commercial building services practice, simulation is commonly carried out on relatively few software applications. It was thought more practical to choose to reduce non-influential parameters in an existing application, than to build up a new building parametric. Sensitivity analysis was chosen as a means of determining which parameters were influential and an experiment was carried out to determine those parameters.

Palomo, Marco and Madsen (1991) divide sensitivity with regard to building energy models into:

- The sensitivity of the model to the various parameters from which the model is constructed allows inputs to be categorised according to their impact on the result.
- The collective uncertainty in the output due to all the uncertainties on the inputs allows the overall resolution to be defined.

The former (inputs categorised according to their impact) is used later in this thesis.

In an often-cited study, Lomas and Eppel (1992) divide sensitivity analysis into three techniques.

- Differential Sensitivity Analysis (DSA) measures the relative change in the output of a simulation due to a change in the input value of a parameter. Since the effect of each parameter is determined in sequence, this is sometimes called One At a Time (OAT) sensitivity analysis. There is a concern with DSA that the sensitivity to a variable might be strongly related to the combination of points chosen as the base case, i.e. that the results are only valid *locally* and miss *correlations*.
- Monte Carlo Analysis (MCA) is used to estimate the uncertainty in the results of a simulation using random combinations of values for parameters to evaluate the distribution of results from simulations.
- Stochastic Sensitivity Analysis (SSA) is described as similar to DSA in that the aim is to determine the effect of each individual parameter. The technique differs in that all parameters are varied simultaneously at each time step in the calculation.

Both DSA and MCA are applied in the chapter on sensitivity analysis.

Lomas and Eppel (1992) also list potential benefits of sensitivity analysis as:

(a) "To identify the inputs to which the outputs are particularly sensitive and those to which they are insensitive."

(b) "To identify inputs to which the programs are sensitive, but for which adequate data is not yet available so field experiments can be suggested to produce more accurate results."

(c) "To identify features of a building to which a particular output, e.g. energy consumption, is particularly sensitive."

(d) "To identify parameters which should be removed from the control of the program user because they cannot (except perhaps be very skilled users) be assigned sufficiently accurate values."

(e) *"The resolution of the programs (i.e. the maximum accuracy) which can be expected in absolute predictions."*

(f) *"The probability distribution of the results and hence a knowledge of, for example, the likelihood that the energy use will not exceed a particular value."*

(g) *"The significance of uncertainties due to computational inputs (such as time-step and node placement)."*

Macdonald and Strachan (2001) discuss DSA and MCA for the analysis of uncertainty in the outputs of models.

Palomo Del Barrio and Guyon (2003) classify the DSA as a deterministic process and MCA as a stochastic process. The authors were interested in applying sensitivity analysis to diagnose differences between the predictions of simulations of the behaviour of buildings. They also consider the heuristic bounding of input parameters, such that the ranges of input parameters are limited to realistic ranges.

Westphal and Lamberts (2005) employed DSA to determine the input variables which affected electrical consumption in an *EnergyPlus™* model. The method was demonstrated on a 26,000 m^2 public office in Florianopolis, Brazil. Once selected, the most influential parameters were heuristically optimised.

Sun and Reddy (2005) proposed a method to establish a firm mathematical basis for the calibration of models. Summarising their method:

- Sensitivity analysis is first used to identify the parameters which most strongly influence the results.
- Identifiability analysis is used to find out how many parameters should be used in the optimisation process and which are the most promising.
- Numerical optimisation is used to find the best values for those parameters
- Uncertainty analysis is used to evaluate the effect of variation of values for the input parameters.

The deterministic and stochastic aspects of the process will be discussed in subsequent sections in this thesis; however, it is noteworthy that Sun and Reddy (2005) define the sensitivity in terms of a *sensitivity coefficient vector*.

O'Neill, Eisenhower, Yuan and Bailey (2011) carried out an extensive sensitivity analysis of 1009 parameters used to define *EnergyPlus™* and *TRNSYS* models of a 6,400m^2 drill hall at the US Great Lakes Naval Station. The parameters were varied 20% from their nominal value.

In some cases, the ranges were limited because the values were fractional and the range would put the input values outside the maximum of 1or minimum of 0. Five thousand simulation runs were used to analyse their impact using a quasi-random approach on a 184-core Linux cluster. The study does not describe the tuning process used to refine the chosen parameters.

The process of varying the input parameters by 20% has inherent ambiguity. The input range would be different if the temperatures were defined in Celsius, Fahrenheit or Kelvin. However, the value of 20% is also arbitrary. Final confirmation of usefulness can only be determined by testing. If a sensitivity analysis based on 20% variation of a value recorded in Celsius is found to yield a calibration process that achieves a better CVRMSE than one that uses Kelvin, then it is appropriate to define sensitivity on that basis. However, in the short term, this is a refinement in a particular process. A consensus on the appropriate process is far from agreed.

In a related study (Eisenhower, O'Neill, Fonoberov and Mezic, 2011), the effects of the input parameters were examined in detail. The impact of the number of parameters analysed and the runs conducted was plotted against the resulting accuracy of the model. The model converged to within acceptable error after 5,000 samples.

Since models are particular to a building, the most influential input parameters in one model may not be the most influential set to another. Xu and Freihaut (2012) carried out sensitivity analyses to determine the ten most influential variables for an *EnergyPlus™* model in 16 cities representing a wide range of climate zones across the USA. The study found that some parameters were common to all zones, while others were highly dependent on location.

Nguyen and Reiter (2015) compared the application of nine sensitivity analysis techniques to building energy models. The methods are grouped below according to the author's method.

Regression-based sensitivity indices:

- PEAR (Pearson Product Moment Correlation Coefficient) is the usual linear correlation between variables;
- SRC (Standardised Regression Coefficient) gives a value for the strength of the relationship between variables;
- PCC (Partial Correlation Coefficient) attempts to isolate out effects between variables.

Regression-based sensitivity indices using rank transformation techniques:

- SPEA (Spearman Coefficient);
- SRRC (Standardised Rank Regression Coefficient) is used where the value of R^2 is low in SRC;
- PRCC (Partial Rank Correlation Coefficients).

Variance-based sensitivity methods:

- The Sobol index;
- FAST (Fourier Amplitude Sensitivity Test);

Both the Sobol and FAST methods calculate two levels of sensitivity; the first is the sensitivity to the main effect and the second includes interactions with other variables.

Screening-based methods:

- The Morris Method. The average of partial derivatives are calculated for evenly-spaced points and used to estimate the main effect of one parameter on another and to examine the interaction between parameters.

The authors found that PEAR, PCC and SRC can be used in the sensitivity analysis of building energy models; however the authors note that the analysis was only carried out on a limited number of parameters (six).

2.6.5.2 Monte Carlo methods for calibrating building energy models

The Monte Carlo method works by analysing results based on randomly generated combinations of parameters. It is a simple method to employ, but relies on large numbers of simulations which simply guess the answer and then test to see if the guess was correct.

Monte Carlo analysis allows the uncertainties in the inputs to be translated via the model to the results. The uncertainty in each input is defined in terms of a probability distribution over a range of potential values for the input. Where the input distribution is unknown, a Gaussian (normal) distribution may be assumed. Simulations are carried out with the random variations of the input parameters which overall follow the distribution of values for the inputs.

If the number of simulations is large, it is assumed that the output will have a Gaussian distribution, irrespective of the input distributions. In practice, *large* means between 60 and 80 simulations (Lomas and Eppel, 1992, cited in Macdonald and Strachen, 2001). The output distribution can then be expressed in stochastic terms, which define the uncertainty of the results.

Haarhoff and Mathews (2006) used the Monte Carlo technique to model the distribution of temperatures inside a building using approximate distributions for the inputs for dry bulb temperature and radiant gain.

Coakley, Raftery, Molly, and White (2011) applied *Latin Hypercube Monte Carlo* (LHMC) analysis to an *evidence-based* simulation. Raftery builds on the argument in his thesis (2011) that models should only be built using information taken in preference from a carefully controlled hierarchy of sources. In the case study, 100,000 *EnergyPlus*^{TM} simulations of the Galway Nursing Library were executed. *Latin hypercubes* are a method of constraining the search of the parameter space to ensure that the search is done efficiently.

The approach above has direct implications where extensive data is available from buildings in use. For example, if extensive data is available for the small power use in laboratory spaces in schools, then the input could be expressed not only as a nominal value, but as a probability distribution which reflects the uncertainty associated with that parameter. Then by applying a Monte Carlo technique this uncertainty can be propagated through the building energy model into the distribution of results from the simulations.

2.6.5.3 Monte Carlo Markov chains

Monte Carlo Markov Chains (MCMC) are a series of searches that depend only on the data obtained in the most recent search. Previous results are *forgotten* from the search.

An initial guess is followed by evaluation of the results; then a guess is made in the vicinity of the previous guess. At each stage of the search the output of some analysis is quantified and recorded.

MCMCs are useful for exploring the parameter space but may lead to local minima because the algorithms are not designed to rigorously search the whole parameter space.

The advantage of MCMC is that as they are carrying out simulations and obtaining results the results can be collected and used to make determinations about the statistics of the parameter space. This makes them attractive for use where optimisation and calibration are treated stochastically as in Heo, Augenbroe and Chaudhary (2011) which is discussed in more detail in Section 2.6.7: Stochastic methods.

2.6.5.4 Evolutionary Algorithms

Evolutionary Algorithms make use of historical data in the development of the solution.

Typically, a set of simulations, called a *generation* are carried out based on a random set of inputs. The results of the simulations are examined and values that are more successful are stored. Another random set is generated, but this time, vectors representing the more favourable of the previous results are bred back into the new generation. The algorithm for how these vectors are generated and employed defines the evolutionary algorithm.

It is worth noting that as the random search for the best set on input variables becomes more sophisticated, the selection of the “best” set on input variables becomes replaced with a search for values for *hyper-parameters,* which define how the algorithms operate rather than act as a solution to the problem under examination (Worden, Dervilis, Sator and Capener, 2018).

2.6.5.5 GenOpt

Whereas evolutionary algorithms are a method for finding optimal solutions, *GenOpt* (Wetter, 2000; 2001) is a genetic optimisation tool which works with a range of text input simulation programs like *EnergyPlus^{TM}*, *DOE-2* and *TRNSYS*.

GenOpt minimises the input parameters of a system by using external software to evaluate the *cost* of the system. In the case of building energy modelling, it allows the input parameters that define a building to be optimised to find the closest deterministic fit to the operating data.

GenOpt also provides tools for monitoring the convergence of the model and allows the addition of user-defined algorithms.

Wetter and Wright (2004) compared the results of *Hooke-Jeeves*, *Particle Swarm Optimisation* (PSO), *Armijo gradient*, *Nelder-Meade* simple and co-ordinate search algorithms, together with hybrid systems containing features of more than one algorithm. The authors found that some optimisation algorithms that require smoothness, fail far from the solution. The most effective algorithm was a hybrid *particle swarm* and *Hooke-Jeeves* algorithm, however simple *genetic algorithm* could be used where a small loss in performance can be tolerated in return for fewer simulations.

2.6.5.6 Differential Evolution

The differential evolution algorithm (Storn and Price, 1997) was shown to provide a fast method for minimising nonlinear and non-differentiable continuous space functions.

Differential evolution was extended to Self-Adaptive Differential Algorithm (SADE) for application to the identification of the automotive hydraulic engine mount model parameters. (Kyprianou, et al, 2000).

An overview of the differential evolution algorithm is given in Figure 5.

A *population* is randomly selected and the cost functions are evaluated for each set of values (or *vectors*). Two randomly-selected vectors are combined to form a *scaled difference vector*. The scaled difference vector is mutated by multiplying by a scaling factor and adding the result to a third randomly-selected vector. A series of experiments are carried out to obtain *Uniform Cross*over between the mutated scaled difference and *target vectors* which produce a *trial vector*. The trial vector is assessed against the target vector by a simulation. The target vector/trial vector process is repeated until a new population is produced to form the next generation and the algorithm repeats until a whole generation of suitable vectors is produced.

As noted in the introduction to Section 3.5.4, while the differential algorithm automates an efficient search for values for parameters, the search is somewhat replaced by a search for *hyper-parameters* which define the efficiency of the differential algorithm search. The hyper-parameters in differential evolution include:

- population size;
- number of generations to run;
- the scaling factor;
- cross-over probability.

Self-adaptive differential evolution was developed to establish optimum values for these hyper-parameters in the course of the algorithm.

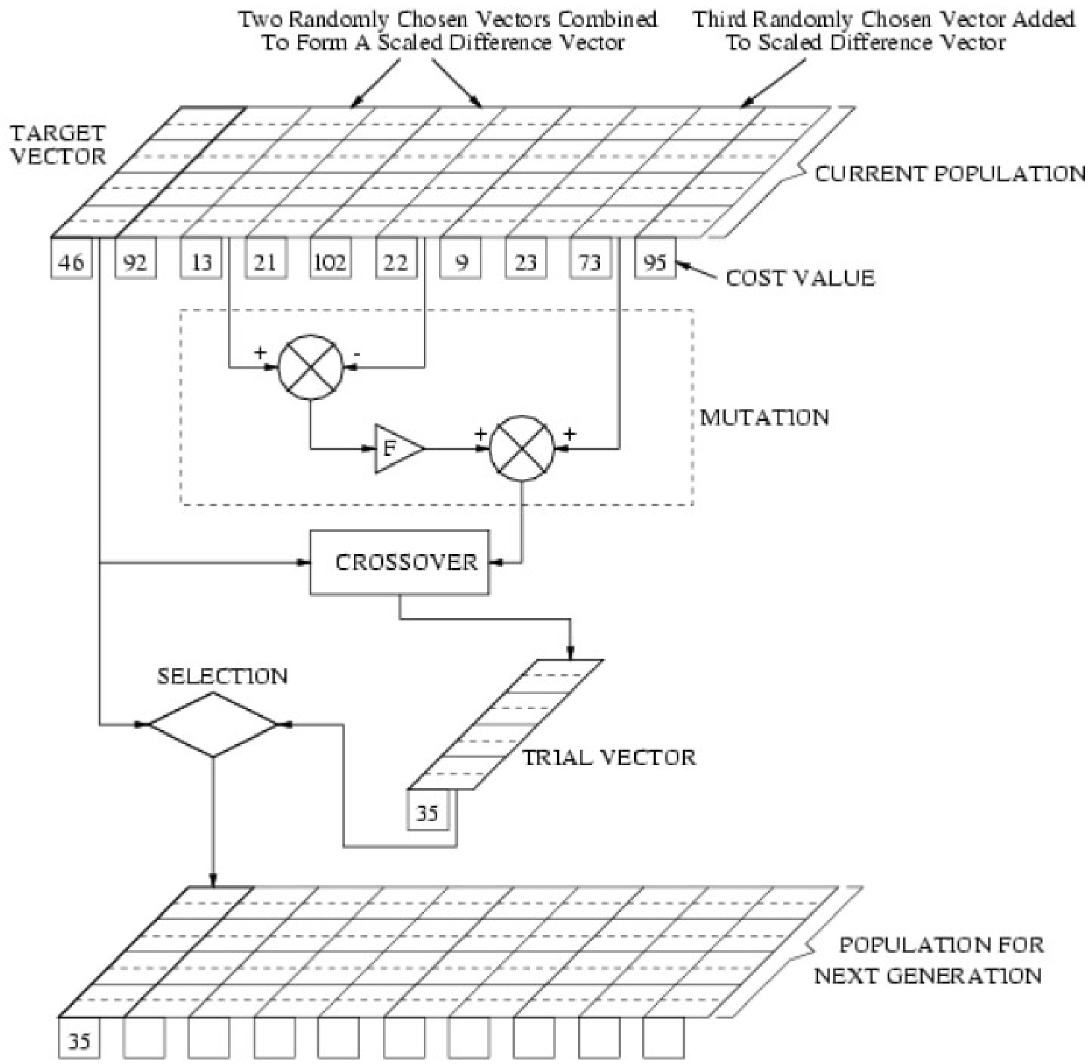

Figure 5. Schematic of the differential evolution algorithm. (Worden, Dervilis, Sartor and Capener, 2018)

To make it *self-adaptive*, the differential evolution algorithm was modified by introducing a learning period into the algorithm. During the learning period, a set of strategy probabilities are developed which define the likelihood that a mutation would be introduced into the trial vector. At the end of the generation, the number of successful and unsuccessful vectors are used to update the strategy probabilities.

At the end of the learning period, the strategy probabilities are updated every generation using the previous generations.

The substitution of one set of *hyper-parameters* (population size, scaling factor) with another (learning period, number of previous generations) might appear self-defeating but results bear out the efficiency of the process.

2.6.6 Deterministic methods for calibrating building energy models

Deterministic methods focus on an automated process for mathematically optimising a solution for a given data set. The problem of minimising the error between the predictions of the energy model and the energy consumption of a real building, is framed in mathematical terms. A *cost* or *objective* function is assigned to evaluate the error and the input parameters of the energy model are adjusted to minimise this cost function.

The origins of *automatic* calibration came from work in the hydrological science (Sorooshian et al., 1980, 1981, 1983, 1993 cited; in Lee and Claridge, 2002). Lee and Claridge (2002) optimised an *objective function* using a set of five parameters using a simplified model based on ASHRAE's simplified Energy Analysis Procedure (Knebel, 1983). The objective function used is given in Equation 3. The model was then calibrated against results to which white noise had been added. The optimisation was carried out using commercial optimisation programme called Solver.

$$Objective\ function = Minimize\ \frac{1}{2} \times \left(\frac{\sum_{i=1}^{n} \sqrt{(CHW_{sim} - CHW_{mea})^2}}{(n-1)} + \frac{\sum_{i=1}^{n} \sqrt{(HW_{sim} - HW_{mea})^2}}{(n-1)} \right) \quad \textbf{(3)}$$

where:

- n is the number of data points or periods in the baseline model;
- i is the *ith* dependant variable of some function of the independent variables;
- CHW_{sim} is the simulated temperature of the chilled water;
- CHW_{mea} is the measured temperature of the chilled water;

- HW_{sim} is the simulated temperature of the chilled water;
- HW_{mea} is the measured temperature of the chilled water;

The process is computationally expensive with the number of simulations typically running into several thousands. To overcome this, a sensitivity analysis may be carried out to cull the number of input parameters from around a few thousand down to a few tens (Sun and Reddy, 2006).

Nassif, Moujaes and Zaheeruddin (2008) used a genetic algorithm to optimise *Heating Ventilation and Air Conditioning* (HVAC) component models for system diagnostics. Data were obtained from an *Energy Management and Control System* (ECMS) and the calibrated models were intended to be reincorporated in the ECMS.

Munshi, Tuhus-Dubrow, An and Coffey (2012) used *GenOpt* (Wetter, 2009) to calibrate a DOE2 model of the Toledo Zoo Aquarium. The authors adopted a heuristic approach to the selection of the initial parameters for optimisation and performed an initial grid search. The grid search consisted of between 6 and 10 steps within a large initial range of the selected parameters. The simulation was then optimised used *GenOpt*; however, this did not result in an acceptable level of accuracy, so four more parameters were added and the process repeated.

The Vienna Institute of Technology building was used to explore the optimisation of an *EnergyPlus™* model (Tahmasebi and Mahdavi, 2012; Tahmasebi, Zach, Schuss and Mahdavi, 2012). The model was initially constructed using *DesignBuilder™* and optimised to minimise the "cost function" given in (4) below, which used was evaluated using the *EnergyPlus™* runtime function (DOE, 2011).

$$f_i = \frac{1}{2} \times CVRMSE_i + \frac{1}{2} \times (1 - R_i^2) \times \frac{CVRMSE_{ini}}{(1 - R_{ini}^2)}$$

(4)

where R^2 is the coefficient of determination defined in Tahmasebi and Mahdavi (2012) as:

$$R^2 = \left(\frac{n \sum_i^n m_i \, s_i - \sum_i^n m_i \sum_i^n s_i}{\sqrt{\left(n \sum_i^n m_i^2 - (\sum_i^n m_i)^2 \times (n \sum_i^n s_i^2 - (\sum_i^n s_i)^2 \times) \right)}} \right)^2$$

(5)

and:

- The subscript ini is used to denote the initial value;
- m_i is the i th measured value;
- n is the total number of time steps;
- s_i is the i th simulated value.

A potential failing of this process is that the parameters become mathematical abstractions, free to be manipulated without relevance to the real parameters they represent. While the results may compensate for errors between the capability of the model and the performance of the building, deviations could lead to a lack of credibility for the results. For example, small power usage often has a significant impact on overall energy consumption and can be readily metered. If a parameter for small power were to be optimised, then it is feasible that the theoretical value might fall outside the tolerances of actual meter readings. While the calibrated model might be accurate, the model would not be useful because it could not then be used as evidence to feed back the small power usage to building occupants. The previous authors attempt to minimise this effect either by heuristically setting bounds or by applying algorithms which limit the range of the inputs.

There are a number of processes for searching the parameter space which include sensitivity analysis, Monte Carlo, MCMC and evolutionary algorithms discussed previously.

2.6.7 Stochastic methods for calibrating building energy models

Stochastic models seek to include the statistical distributions of input parameters in the model and reflect the influence of the uncertainties in the process in the results.

A Monte Carlo process can be used in both deterministic and stochastic approaches. In the deterministic approach, a random selection of values is used to try to determine the most appropriate inputs into a model. The input selection might be assumed to have any sort of distribution including a Gaussian. In a stochastic approach, the modeller is not only seeking to find the most appropriate value for the parameter, they are also seeking to refine the stochastic values that define the input distribution.

For example, a modeller carrying out a deterministic approach might assume a Gaussian distribution for small power with a mean of 20 W/m^2 and a standard deviation of 5 W/m^2. After carrying out a Monte Carlo search over that distribution, they might discover that a value of 17 W/m^2 yields the lowest value for the $CVRMSE_{hourly}$ between the simulated and measured hourly energy consumption. This value might then be able to be applied in the later design of a similar building.

In a stochastic approach, the modeller would be seeking to refine the uncertainty associated with the input distribution. As the search proceeds, the modeller might also be seeking to refine the value for the standard deviation of the input parameter. In the case of the example above, the modeller might not only find that the value that yields the lowest $CVRMSE_{hourly}$ is 17 W/m^2 but they might also be able to reveal that the input distribution into a Monte Carlo search that yields the lowest value of $CVRMSE_{hourly}$ also has a standard deviation of 2 W/m^2. This has the added benefit that the optimisation is able to provide additional information about the operation of the building. In this hypothetical case, there would be a 67% confidence interval that the average small power load (as defined in the building energy model) is between 15 and 19 W/m^2.

In a subsequent hypothetical modelling exercise, the model might be able to propagate this uncertainty through the model and provide valuable confidence information about the predicted operation of the building. Alternatively, this information might be able to be used to help diagnose problems with the energy performance of the building.

Types of uncertainties are summarised (Heo, Augenbroe and Chaudhary, 2011) as due to:

- The deviations between the input parameters used in the design model and the input parameters needed to reflect actual operation.
- The deviations between the readings of instruments and the actual measures which are required to represent the actual building
- The deviations inherent in the modelling process; that is, the predictions of a model with perfect inputs and the real transfer function of the building.

Stochastic processes can include the application of Bayes' Rule (Kennedy and O'Hagan. 2001) and provide for the propagation of uncertainty, notably by using Monte Carlo techniques.

Kennedy and O'Hagan (2001) presented a Bayesian calibration technique to the Royal Statistical Society. The technique was used to calibrate a hydrological model and a model of the dispersion of radionuclides. The paper provides a firm statistical foundation which is cited in later works. The paper recommends Markov Chain sampling as the *"obvious approach"*.

Higdon et al. (2004) noted that there is a limitation on the number of simulations which can be carried out and that this also represents a source of uncertainty. A Bayesian process was applied to models of a charged particle accelerator and a spot welding process and again used Markov Chain Monte Carlo sampling.

Having optimised the calibration process deterministically, uncertainty has been determined for the calibrated model in a separate process using Latin Hypercube Monte Carlo sampling (Sun and Reddy, 2006).

Tarlow, Peterman, Benedict, Schwegler and Trigg (2009) criticise the IPMVP methods (EVO, 2012) (see Section 2.4.1) described as requiring:

> *"special equipment and manual effort, making the calibration of a large number of buildings expensive and time consuming."*

Instead, the authors constructed a Bayesian network consisting of a graphical structure of nodes with a probability distribution at each node. The relationships between the nodes are mathematical and then comprise the overall model. The authors also note that one of the strengths of the Bayesian approach is that is can be used without values for some parameters when those variables are not observed. This leaves the model open to criticism because the values of the parameters may not be realistic but this is neglected because the authors are willing to sacrifice some accuracy for speed of simulation and because the object of the exercise is prediction not parameter estimation. The authors argue that the main strength of this technique is that it is massively scalable and therefore applicable to the huge portfolio of buildings operated by The Walt Disney Company and similar organisations.

Heo, Augenbroe and Choudhary (2012) used a Bayesian approach to calibration which allowed the uncertainty to be quantified as part of the calibration process. The results were compared with a deterministic process and found to be slightly more accurate. The process is described in her PhD thesis (Heo, 2011) and published article (Heo, Chaudhary and Augenbroe, 2012). A case study was based on the five-storey University of Cambridge Faculty of English.

In the Bayesian approach, the calibration parameters are assigned probability distributions called *prior distributions* or *priors*. The results can be compared against the calibration data and used to formulate probability distributions for the input parameters, which are known as *posterior distributions*. The posterior distributions contain information about the implied uncertainty of the input data. In their study, triangular input (prior) distributions were assumed for:

- Intercept C for window opening; this is a constant in a regression formula modelling the relationship between outdoor temperature and the likelihood that a window will be opened;
- Indoor temperature during heating;
- Infiltration rate;
- Discharge coefficient through single sided open windows.

The distributions were transformed (into posterior distributions) and the results were overlaid onto the prior distributions. The resulting graphs in Figure 6 show compelling evidence of the power of this technique, not only to calibrate a model but also to also quantify the uncertainty in the inputs and in the calibrated model.

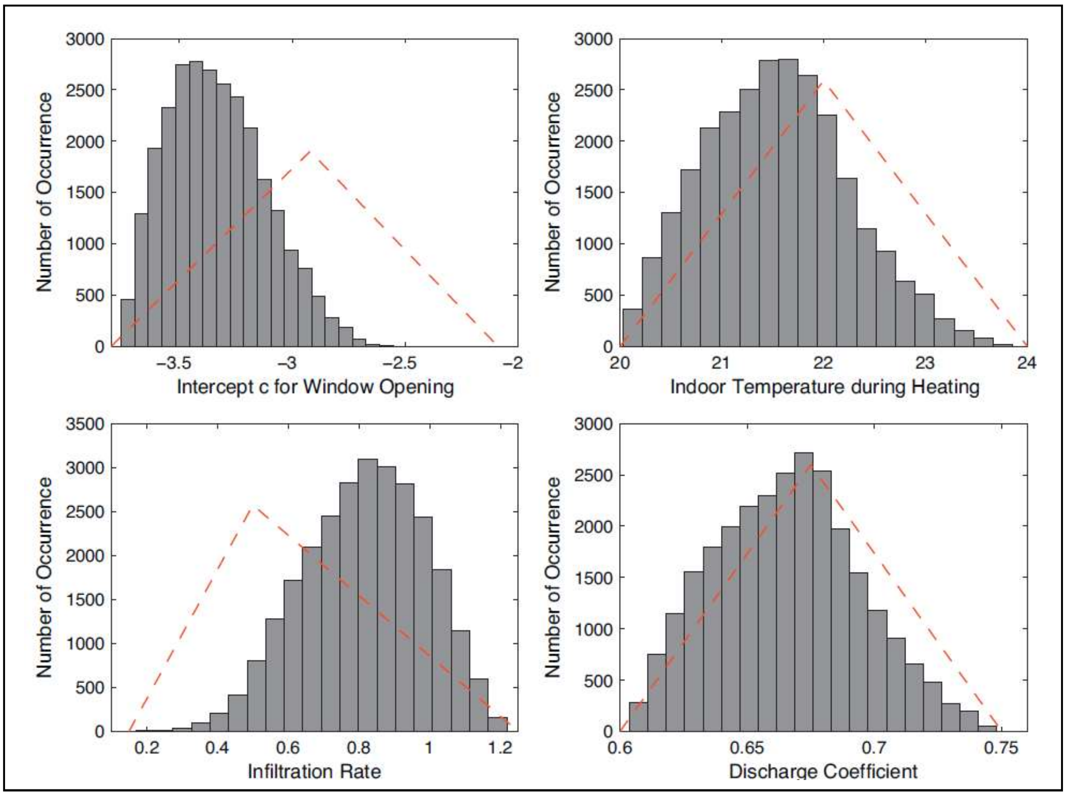

Figure 6. Example of superposition of Prior and posterior distributions for four input parameters. (Heo, Augenbroe and Choudhary, 2011)

Lee, Kim and Park (2012) applied the delayed rejection adaptive metropolis (DRAM) method of Markov chain Monte Carlo (MCMC) in a case study. The building was a five-storey 6,125m^2 office located in Seoul Korea. The study compares the prior and posterior distributions of 28 input parameters by tabulating their mean and standard deviation.

2.6.8 Meta-modelling for calibrating models

Meta-models are another approach to modelling, optimisation and calibration. By building another model, based on another (more sophisticated) model and a calibration process, a second layer of abstraction can be produced which provides the functionality of a complex model but without the computational overhead. By using a simpler meta-model, simulations can be run much more quickly, searching a larger number of parameters to potentially reveal a more accurate set of values for the input parameters and a better overall CVRMSE. The problem with this approach is that another calibration is required to ensure the meta-model aligns with the primary model.

Eisenhower et al. (2012) used an *EnergyPlus™* model to produce a meta-model which could run more quickly. While the authors describe the direct comparison of computational cost as "challenging", the number of computations for an *EnergyPlus™* model was reduced by a factor of 200.

Manfren and Moshksar (2013) used a supervised learning algorithm to produce a meta-model which also included uncertainty analysis.

2.6.9 Conclusions from literature review into building energy model calibration

The requirement to apply optimisation in design models and to the calibration of early stage design models was a driver for this Ph.D.

There is a range of techniques available which are able to calibrate models within the requirements set out in ASHRAE 14.

The main processes are heuristic, deterministic or stochastic.

- Traditional heuristic processes rely on site data which is time consuming and therefore would be expensive in a commercial environment.
- Deterministic and stochastic calibration processes are heavily dependent on computational capacity.
- Deterministic methods may produce well-calibrated models but because the optimisation is divorced from the details in the operation of the building, the process may overcorrect input parameters to compensate for errors in the modelling software. This could lead to unrealistic estimates for input parameters.

There have been a number of studies which have identified important parameters in building energy models but there is no universal hierarchy of input parameters. Furthermore, one study has demonstrated that the importance of input parameters changes according to the location of the building being modelled. This means that a sensitivity analysis is required for each model to assess the relative impact of each input parameter for that model in that location.

The key knowledge gaps are that:

- There is a clear lack of case studies that demonstrate the application of optimisation in early stage design.
- There are no methods for calibrating building energy models that don't require extensive input from expensive specialists.

Therefore, there is a significant opportunity to apply optimisation processes to design and calibration.

2.6.10 Review of computational methods in building energy modelling

This chapter contains an overview of the computational methods used during this thesis and the professional background to this Ph.D.

These investigations have been guided, and in many cases restricted by the current state of information technology. The processes of optimisation and gathering data for calibration are heavily reliant on modern computing technology. The process of carrying out the research detailed in this thesis has required the learning of transferrable skills in information technology and computing science.

These fields have their own jargon. This chapter on the technology and terminology of the modern computing environment has been included to:

- Demonstrate the breadth of work that has been undertaken;
- Show transferable skills and understanding that have been gained by the author;
- Assist readers who may have a less comprehensive understanding of the modern computing.

An overview of the common operating systems and softwares that were used in this research are contained in Appendix 1. Software more specific to the results of this research are described in the following sections.

2.6.10.1 Microsoft SQL Server

Microsoft Structured Query Language (SQL) Server™ is a *relational database* software that enables the storage, organisation and retrieving of large volumes of data. Microsoft makes a scaled down version called *Microsoft SQL Server Express™* which limits the size of the database files to less than 1GB. The databases can be searched and data can be retrieved by Microsoft's tool *Microsoft SQL Server Management Studio™*. Microsoft SQL Management Studio is provided with *Microsoft SQL Server Express 2012™* which was available free of charge.

The version of SQL Server used was made up of the following components:

• *Microsoft SQL Server Management Studio™*	11.0.2100.60
• *Microsoft Data Access Components™ (MDAC)*	6.1.7601.17514
• *Microsoft MSXML*	3.0 4.0 5.0 6.0
• *Microsoft Internet Explorer™*	9.0.8112.16421
• *Microsoft .NET Framework™*	4.0.30319.17929
• *Operating System*	6.1.7601

Reports can be generated using *MS SQL Server Express™*. Queries are written in Transact Structured Query Language (T-SQL) which is Microsoft's proprietary version of SQL. SQL allows database administrators to write scripts to retrieve and arrange the data in the format they specify. Initially, it was hoped that this would be useful when compiling input data to calibrate an *EnergyPlus™* model; however, it was still useful in the examination of the contents of ILS1's data files.

2.6.10.2 EnergyPlus™

EnergyPlus™ is the United States Department of Energy (US DOE) flagship building energy simulation tool (US DOE, 2018). It was built from two existing tools: the United States Army's tool *Building Loads Analysis and System Thermodynamics* (BLAST), and *DOE-2* from the US DOE. It enables modelling of a building's geometry, construction, Heating Ventilation and Air Conditioning (HAVC) systems, power and lighting systems, and the interaction of the building within the outdoor environment.

EnergyPlus™ provides simultaneous solutions which integrate the various aspects of building operation. The simulation of the building is carried out using sub-hourly time steps which include iteration where necessary to resolve tightly-coupled energy balances. Heat balances allow for the modelling of both radiative and conductive heat flows and transient effects. Mass balances account for both air and moisture flow, including moisture adsorption and desorption. *EnergyPlus™* allows for detailed modelling of loop-based HVAC systems including control strategies. It contains daylighting calculations including the modelling of daylight controls and luminaire control algorithms. An overview of the operation of *EnergyPlus™* is given in Figure 7.

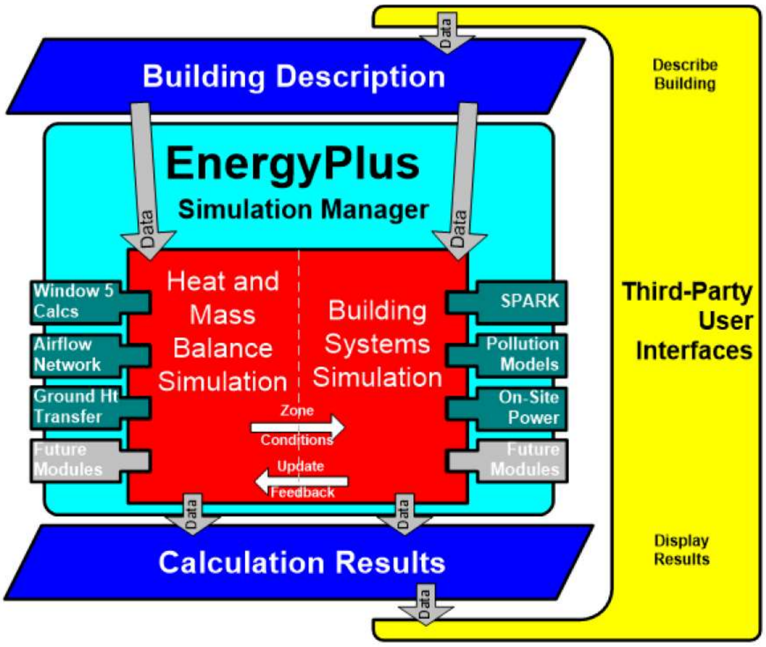

Figure 7. *EnergyPlus™*: The Big Picture.

EnergyPlus™ only requires an Input Definition File (IDF) and *EnergyPlus™* Weather (EPW) file to run. Both files are written in plain text. In the IDF, the code includes the facility to record comments on the definition, meaning and source of values that are used by *EnergyPlus™*.

EnergyPlus™ is well documented with a user manual that runs to over 2000 pages. It is also well tested in the literature. Other notable features include:

- In 2014, the *EnergyPlus™* source code was rewritten from *FORTRAN* into *C++*.
- *EnergyPlus™* is also open source. The source code is available for anyone to inspect or revise.
- *EnergyPlus™* is also available free of charge.

EnergyPlus™ was intended to be provided as an energy analysis engine. The provision of the graphical user interfaces that would enable users to create and run *EnergyPlus™* simulations was intentionally left to third-party developers. While *EP-Launch* is available for users who choose not to run *EnergyPlus™* from a command line interface, it lacks the tools to help users define the geometry of a building which would be the main challenge for anyone trying to write an IDF using a text editor.

2.6.10.3 EP-Launch

EP-Launch (US DOE, 2018) is a graphical user interface which is provided as a primary means of running *EnergyPlus™* and recovering useful data from the program. In its simplest form, it only needs the IDF and applicable weather file. The EP-Launch graphical user interface showing the "Browse…" buttons that enable a user to select IDF and EPW files is shown in Figure 8.

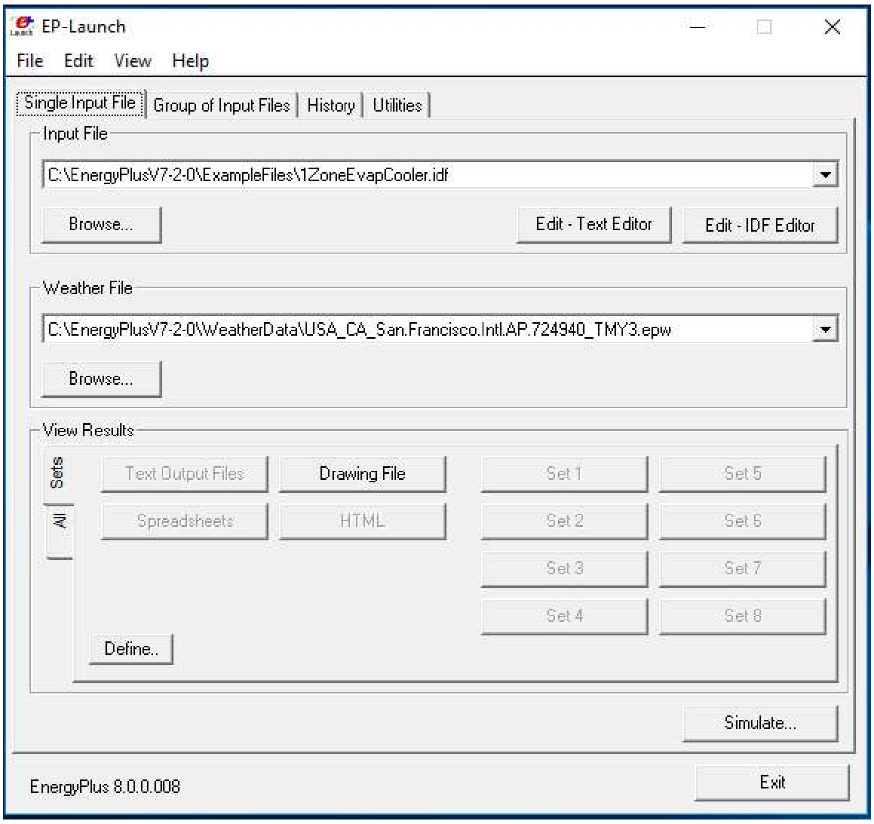

Figure 8. EP-Launch graphical user interface

2.6.10.4 DesignBuilder™

DesignBuilder™ is a proprietary application which provides a third-party graphical interface to assist users to produce, run and analyse *EnergyPlus™* simulations. It provides dropdown menus and tabs to enable users to specify the various parameters needed to produce a robust building energy model. It also has a series of tabs which provide facilities to render an image of the building, to run sizing tools based on *EnergyPlus™* simulations, to run and analyse *EnergyPlus™* simulations, and a basic computational fluid dynamics facility.

DesignBuilder™ also has a feature to enable users to parameterise and solve multi-objective optimisation problems using the evolutionary algorithm: Non-dominated Sorting Genetic Algorithm 2 (NSGA2).

Typically, engineering problems involve a trade-off between constraints. Defining and finding the optimum solution to a design problem may not give decision-makers the tools they need. This can be improved by defining a curve representing a series of optimised solutions known as a *Pareto Front*. For example, in building design there is a trade-off between the cost of construction of a building and the energy efficiency. By creating a Pareto Front of pre-optimised solutions, decision makers have the freedom to choose any level of expenditure that satisfies their sustainability criteria or vice versa.

Deb, Pratap, Agarwal, and Meyarivan, (2002) proposed the use of NSGA2 in response to criticisms of multi-objective evolutionary algorithms for their computational complexity, non-elitist approach and the need to specify a sharing parameter. In their paper they demonstrated that NSGA2 outperformed other multi objective evolutionary algorithms.

The algorithm is summarised from *DesignBuilder^{TM}*'s explanation (*DesignBuilder^{TM}* Software, 2018) as follows.

- A random selection of values are assigned to a series of simulations which make up an initial population.
- Design variants are sorted and analysed for Pareto efficiency. The design variants are termed *chromosomes* and ranked based on the distance between solutions.
- The values which give the best solutions are returned to a *mating pool*
- In the mating pool a series of algorithms compare and test the chromosomes.
- The mating pool of values is combined with the current population to produce a new population.

When *DesignBuilder^{TM}* runs an *EnergyPlus^{TM}* simulation it creates IDF and EPW files before executing *EnergyPlus^{TM}*. The IDF is well commented which enables users to modify the text file directly using a text editor such as *Notepad*++. All the *EnergyPlus^{TM}* files that were used in this thesis were created using various versions of *DesignBuilder^{TM}*.

2.6.10.5 jEPlus

Zhang and Korolija (2010) followed on from Zhang (2009) to release jEPlus. *jEPlus* allows users to configure large batches of parametric runs for tasks such as parameter analysis. The report includes a parametric assessment of a test case involving 34,560 simulations which were carried out on a 256-core Linux cluster over a weekend in 2010.

jEPlus (JE+.org, 2018) is a tool that was written in Java (hence the "j") to manage large numbers of *EnergyPlus^{TM}* simulations, although it is capable of running other simulations which are text based. To use *jEPlus*, the user replaces values in the input text file (in this case the *EnergyPlus^{TM}* IDF) with searchable strings. The format of the searchable strings given by the authors is @@*Parameter_Reference*@@*,* however any string could be used providing it is not already included in the text and does not have a specific meaning to the *EnergyPlus^{TM}* program. The location of the weather file and information on post processing, is also required.

jEPlus opens the IDF, searches for the string and replaces the string with the next numerical values from a control tree, runs *EnergyPlus^{TM}*, post processes the results and stores the results in a folder. It then runs the next simulation in the batch.

jEPlus allows users to take advantage of multiple core processors to run several simulations simultaneously by assigning a parallel simulation to each core.

Zhang (2009) also mentions a number of tools which were examined before going on to develop *jEPlus* described below. The other tools mentioned are *EP-Macro, Ez-Plus-Param, COMFEN 2.0, GenOpt* and *DesignBuilder^{TM}*.

jEPlusV1.4 was the main tool used in this thesis to carry out Differential Sensitivity Analysis (DSA) and Monte Carlo Analysis (MCA). This was because it enabled large numbers of simulations to be run in parallel to improve computational efficiency and reduce time taken to find solutions.

2.6.10.6 SADE

SADE_build.m and *SADE_build_cost.m* are *Matlab^{TM}* scripts written to enable the Self-Adaptive Differential Evolution (SADE) algorithm to be applied to *EnergyPlus^{TM}* building energy models.

SADE_build.m starts with initial ranges of four variables defined in a matrix. It generates each population and selects Target Vectors and generates the Trial Vectors. To generate the cost value, *SADE_build.m* calls *EnergyPlus^{TM}* and runs each simulation. The simulation generates output files which *SADE_build_cost.m* post-processes using *ReadVarsESO* to produce a CSV input file with the correct format. *SADE_build_cost.m* evaluates the $CVRMSE_{hourly}$ for the simulation output as compared to the metered data and *SADE_build.m* iterates until the specified number of generations is complete.

For testing and verification of the script, refer to Section 4.4.

2.6.11 Overview of research methods for use in building energy model research

This section explains the process used to select the research methods to investigate the following research question.

> *"How can existing building energy model optimisation techniques be used to provide a better process for designing buildings and calibrating building energy models?"*

This Ph.D. thesis demonstrates how the practical application of knowledge can be of benefit, rather than the development of understanding independent of its setting in the community.

Aristotle distinguished between three types of knowledge:

- *Episteme* – pure knowledge.
- *Techne* – technical expertise.
- *Phronesis* –wisdom or intelligence, skilful action.

Flyvbjerg (2006) argues that professional work lies in skilful action rather than technical expertise. While an academic might be concerned about truth which is independent of context, a practitioner also needs methods concerned with applying pure knowledge and the wisdom to make good decisions. There are a large number of research methodologies which could be applied. These are described in the following sections.

This research has been carried out as a professional doctorate while the author was employed as an engineer for Ove Arup and Partners Ltd. The fact that this research has been carried out in a commercial environment has directed the research towards discovering how the conduit for innovation from academic investigation to implementation by engineers might be improved. New methods are required to better use building energy models and allow building energy models to be better calibrated. However, the development of new methods does not necessarily benefit the community unless those methods can be deployed within the time and budget constraints of a commercial organisation.

In order to answer the research question, a comprehensive understanding of the current state of the art of calibrating building energy models was needed. This enabled access to the theoretical techniques and tools which are currently available and which could be drawn upon in the synthesis of a practical implementation. In the following, a summary is presented of the different methodological approaches that were considered for this research.

2.6.11.1 Literature review

A literature review is a search for information relating to the research question. During the literature review the researcher attempts to identify an exhaustive list of literature associated with the research topic and critically evaluates the research to discover what information is already available, which might assist the researcher answer the research question.

This research started with a comprehensive literature review. The results of that review are contained earlier in this chapter.

2.6.11.2 Action research

In *action research* the researcher is involved in a practice with the aim of improving some aspect of its operation. Typically, the researcher will be involved in the operation of the organisation and will critically evaluate a change in the operation. The evaluation might take the form of some sort of qualitative or quantitative analysis that would then be analysed to determine the extent to which the change has been successful.

While action research might be appropriate for investigating how well a new process for calibrating building energy models has been adopted, it would not have satisfied the need to develop and investigate the process itself. Before the success of an implementation can be judged, the process needs to be developed to a point where a successful deployment could be expected.

Action research was not applied in the development of this thesis.

2.6.11.3 Case studies

A *case study* is the examination of an example with the intention of identifying something which is specific to that example.

Flyvbjerg (2006) argues that case study research is important because, in contravention to traditional thought:

- Theoretical knowledge is not useful to society unless it can be applied and a useful application can be demonstrated within a case study.
- Even single case studies can identify unforeseen events which can lead to generalisations or disprove them.

Case studies have been used in this study to demonstrate the usefulness of optimisation in early stage design in Chapter 3, and to compare the efficacy of Monte Carlo and genetic algorithms in building energy model calibration in Chapter 4.

2.6.11.4 Evaluation research

Evaluation research is concerned with appraising or assessing the value, worth or practicality of something.

In a commercial environment, there is a constant need to ensure that practices are not only effective, but also efficient so as to maintain the commercial viability of the enterprise. While not all enterprises operate with the goal of producing profit, all businesses must operate within the restrictions of their cash flow. Therefore, in a commercial setting, one the of drivers for the selection of a process for calibrating building energy models is the practicality with which it is to be implemented and practice of determining this practicality is an evaluation.

In this thesis, the words "practicality" and "efficiency" are used to represent a value associated with the process of applying optimisation to building energy models. In both cases, these terms represent the reduction in time and resources which engineers and building physicists will take to optimise a design or calibrate a building energy model to a degree of quality represented in quantitative terms. When a model is more practical or efficient, this means there is a reduction in the number or expense of resources (including engineering time) required to carry out the calibration to a point within the quantitative limits.

2.6.11.5 Experiments

> *"Experiment n. test or trial (of); procedure adopted on chance of its succeeding. For testing hypothesis etc., or to demonstrate known fact."* (Sykes, 1982)

Experimentation was used extensively in this thesis to test hypotheses which might answer the research question.

Experiments were conducted as computer simulations using combinations of values for parameters which describe buildings to determine the effect on the accuracy of the simulation.

2.6.11.6 Conclusions on methods

Useful research, as might be carried out by a candidate for a Ph.D. includes producing knowledge which is useful to practitioners. This includes the application of *episteme* in the development of *techne* and study of the results of *phronesis*.

To achieve this, a number of techniques were useful. The overall approach has been one of evaluation research.

A review of the literature has been used to establish the current *episteme* and *techne*. Case studies illustrate risks associated with heuristic methods, limitations of a LHC Monte Carlo search, and power of a self-adaptive genetic algorithm.

Experiments, in the form of computer simulations, were used to determine if *DesignBuilder*™'s optimisation tool based on the Non-dominating Sorting Genetic Algorithm 2 (NSGA2) could justify the time taken to carry out the optimisation. Experiments were conducted to identify the influential parameters in commercial building energy models and to assess the practicality of calibrating models using a Monte Carlo search and using Self-Adaptive Differential Evolution.

Chapter 3 Application of Optimisation to Building Energy Models in Early Stage Design

3.1 Introduction

A commercial application that uses the genetic algorithm NSGA2 for optimisation of *EnergyPlus™* based models is available, but has only been applied in a limited number of cases in a commercial environment. While the analysis tool has been developed, there was still work required to develop, design and cost templates, which were necessary to produce credible results. At the start of this study, there was also no evidence that a design which has been optimised using NSGA2 would demonstrate significant savings over common practice.

This problem was rephrased as the following research question to enable practitioners to determine if additional engineering is justified:

> "*Does multivariable optimisation using NSGA2 yield savings significant enough to justify the engineering time which needs to be devoted to* the *optimisation process?"*

A case study approach was used to test this process.

3.2 University of Northampton Creative Hub

In 2015, the *University of Northampton* was in the process of extending its campus to include an additional six buildings. The designs for the buildings had been developed to RIBA Stage 3, where upon a contract for its construction was put up for tender. The design then underwent a value engineering exercise to attempt to refine the costs to match the University's budgetary constraints.

This presented an excellent opportunity to carry out a case study of the application of a parametric optimisation using *DesignBuilder™*.

Of the six buildings, a medium sized multi-function building: *The Creative Hub*, was chosen for the case study because it best represented a typical, modern university building.

3.2.1 Author's role in this research

The research detailed in this chapter was conducted by the author of this thesis. The work was carried out entirely as an academic exercise after the design had been developed beyond Stage 2 as a commercial service. Except where noted below, planning of the research, the heuristic optimisation work, construction of the *DesignBuilder™* and *EnergyPlus™* models, the optimisation process and the analysis of the results were all conceived and executed by the author. The results were presented at the 15th annual IBPSA conference (Polson, Zacharis, Lawrie, and Vagiou (2017) by Oliver Lawrie, after the author left his previous position with Arup. Evan Zacharis produced the paper from content and results in this chapter and Dora Vagiou and Oliver Lawrie helped to get the *DesignBuilder™* software running.

3.2.2 Building

Figure 9. The Creative Hub and the University of Northampton.

The Creative Hub at the University of Northampton as shown in Figure 9, is a five-story building with a floor area of 10,000 m^2. The building was designed to house a variety of spaces including:

- a café and full kitchen facilities;
- 3D printing workshop;
- research laboratories;
- teaching spaces;
- photographic studios;
- student workspaces;
- rehearsal and performance spaces;
- television studios;
- information and communication technology workshops.

The building has the normal circulation and services spaces, which include:

- corridors;
- toilets;

- stairwells;
- lifts;
- storerooms;
- cleaners’ cupboards;
- electrical and mechanical plant areas.

There are two substantial atria, which also provide return air paths from some of the internal spaces. A small portion of the building was to be left for a future fit-out as a destination restaurant.

3.2.3 Building fabric

The location of the exterior wall types specified on seven drawings provided by Couch Perry Wilkes Limited as part of the Stage 3 documentation were used to invite construction tenders. Each drawing contained a key that summaries the wall type associated with the label shown on the drawing.

The details of the construction are given in Appendix D.

3.2.4 Services

Heat was expected to be provided from a site-wide district hot water system, which was to supply Low Temperature Hot Water (LTHW) at between 85°C (Winter) and 70°C (Summer) and return it at a maximum temperature of between 55°C (Summer) and 45°C (Winter). LTHW was to be supplied from a campus Combined Heat and Power (CHP) plant.

Space heating within the building was designed to be provided via a combination of radiators and underfloor heating.

The majority of the cooling was designed to be provided by two air-cooled packaged chillers. Two Variable Refrigerant Flow (VRF) direct expansion systems were to be provided to a television suite and to Information and Communication Technology (ICT) rooms. Cooling was designed to be provided via all-air systems and via chilled beams. Minimum fresh air systems and kitchen makeup air were to be tempered.

A combination of strategies were designed for the ventilation services. Student workspaces and cafes were to be ventilated using a mixed-mode displacement and natural ventilation strategy. The television studio, 3-D workshop, performance space and teaching spaces were to be served with all-air systems.

All ventilation air handlers were shown to be provided with hygroscopic heat recovery wheels. LED lights with lighting control were specified for the building. Domestic hot water was to be provided using heat from the district heating system via a plate heat exchanger.

Occupancy schedules were based on defaults used when assessing University buildings as part of the National Calculation Methodology (NCM) to demonstrate compliance with Building Regulation: Part L (Parliament, 2000).

3.2.5 Legislative and sustainability and requirements

As a building designed for England, it had to comply with the English Building Regulations including Approved Document Part L. The building also required the calculation of an Energy Performance Certificate (EPC). In this case, the client has specified that the building be designed to achieve an "A" rating on its EPC.

At the previous design stage, a calculation was carried out using Integrated Environmental Solutions (IES) *Virtual Environment* (VE) software version 2014.2.0.0, which predicted a Target Emission Rate (TER) of 18.0 $kgCO_2/m^2$ and a Building Emission Rate of 14.6 $kgCO_2/m^2$. (Couch Perry Wilkes, 2015). This also corresponded to a predicted "A" rating for the EPC.

The employer's requirements included a requisite that the Creative Hub achieve a *Building Research Establishment Environmental Assessment Methodology* (BREEAM) rating of *Excellent*. The BREEAM methodology includes a number of options for how the overall score can be achieved. At early design stages, it is usual to formulate "budgets" during a pre-assessment which then provide targets for the various designers. For this building, a budget of eight credits for *Section ENE01: Reduction of CO_2 Emissions* was assumed. As part of the BREEAM system, there is also a pre-requisite requirement that, in order to achieve a rating of *Excellent*, the building needs to be awarded at least six credits for ENE01.

3.3 Optimisation

3.3.1 Parameters for optimisation

DesignBuilder™ is commercial building energy simulation software that provides a graphical user interface for *EnergyPlus*™. The version 4.x series of releases contains an application of the Non-dominated Sorting Genetic Algorithm 2 (NSGA2) (Deb, Pratap, Agarwal and Meyarivan, 2002) which adds an optimisation function to parametric analysis capabilities contained in previous versions.

A model which is developed for use in the simulation of the energy consumption of a building is defined by parameters which represent physical aspects of the building. Values for those parameters are used to define the geometry, construction, services and operation of the building. Simulation of a building to accurately represent the actual energy consumption is heavily reliant on the selection of values that best represent the building. When a building is being designed, and the form and operation of the building are undefined, the design problem is to devise the geometry, construction services and operation to meet the client's objectives. These objectives can be abstracted as the selection of parameters and values which, when appropriately used in a simulation, will predict a set of outputs that will meet the client's specification.

One of the key steps in the optimisation process is to select parameters, which represent aspects of the building design that would benefit from optimisation and a suitable range of values, which should be applied to those parameters.

DesignBuilder™ includes over 120 parameters (*DesignBuilder™*, 2016). From these the following parameters were selected for optimisation:

- external wall construction;
- external roof construction;
- glazing construction;
- lighting system;
- HVAC system for each of zones A, B, C, D and E.

Shading was omitted from the analysis to speed the simulation time, put more emphasis on the glazing selection and allow computational time for multiple HVAC system zones to be assessed.

Options for each of these parameters were developed and are described in detail in subsequent sections.

3.3.2 Constraints

The design of a building is also subject to constraints. For example, it would be of little benefit to have a building that operated with very little energy input, but which had internal temperatures that were either too high or too low to be acceptable to building occupants.

Constraints may be contained in a client's brief; however, in the experience of this engineer, it is more usual for the engineers to propose what they consider to be practical and appropriate conditions and seek confirmation from the client. These constraints are usually based on recommendations from professional organisations such as the *Chartered Institute of Building Services Engineers* (CIBSE).

The Building Regulations contain restrictions for the amount of time that the internal conditions exceed temperature limits. These were applied as constraints during the optimisation exercise.

The concept consultants had specified that the building must meet the requirements of *TM52: The limits of thermal comfort: Avoiding overheating in European buildings* (Fergus, 2013). TM52 provides a methodology for assessing discomfort due to overheating in buildings. TM52 is based on an *adaptive comfort model*, which assumes that as seasons move from cooler to hotter, people adapt to the higher temperatures. As outdoor temperatures rise, people are able to tolerate higher indoor temperatures than they would if they were acclimatised to cooler outdoor temperatures. TM52 sets three criteria, of which two must be met in order to claim compliance with the standard.

In TM52, a threshold temperature is calculated. The threshold temperature is a rolling mean of the previous month's outdoor dry-bulb temperature.

The three criteria are:

- *Criterion 1*: The internal temperature must not exceed the threshold by more than 1K for more than 3% of the occupied hours per year.
- *Criterion 2*: A daily weighted value, which is intended to reflect the severity of overheating, must be less than 6 (dimensionless) in any day.
- *Criterion 3*: The maximum temperature in the occupied space must never exceed 4K above the threshold temperature.

DesignBuilder^{TM} does not explicitly provide TM52 evaluation criteria, however TM52 uses the calculations described in BS EN 12521 (BSI, 2007). *DesignBuilder*^{TM} can carry out the BS EN 15251 calculations and define the exceedance values from TM52.

In practice, the author has found that it is usual to design for TM52 Criteria 1 and 3 to pass and for Criterion 2 to fail, so the optimisation simulations were constrained to pass *Criteria 1* and *3*.

3.3.3 Optimisation target

Building simulation can be used to provide estimates of a whole range of potentially useful outputs. This might be the internal temperature of a room over the course of a month or the energy consumed by an air handler in the production of cooling. In this case study, there was concern about the capability of the simulation software to identify potential cost savings which might result from an advantageous combination of building elements.

DesignBuilder™ is a tool that provides options for a range of outputs intended to cater to many of the problems that might be encountered by a professional building services engineer. It provides a number of optimisation targets from which a suitable selection must be made.

In optimisation studies, the target of the optimisation is called the *objective*. *DesignBuilder™* allows for over 100 design objectives (*DesignBuilder™*, 2016).

At this stage in a project, it is usual for there to be a strong emphasis on the capital cost of the project. It is common to carry out *Value Engineering* exercises to examine the scope of the project to identify opportunities to reduce the cost of the construction. Cost reduction can be particularly important to a contractor who is bidding for the construction of a building. Reducing the capital cost can result in savings for the client, which improve the contractor's probability of being awarded the contract, or can translate into profit for the contractor.

There is an obvious opportunity to use optimisation to balance the operating and capital costs for a building so the decision was made for this doctoral project to use capital and energy cost as the optimisation targets.

3.4 Multi-disciplinary approach

The commercial built environment involves a wide range of specialists, each of whom bring their own practice knowledge. A typical project would have:

- *Mechanical engineers* who are responsible for providing a comfortable environment within the sustainability aspirations of the client.
- *Electrical engineers* who are responsible for distributing electrical power and providing adequate lighting within the sustainability aspirations of the client.
- *Facade designers* who help the architect design the fabric of the building including the specification of glazing.
- *Quantity surveyors* who are responsible to estimating the cost of construction.
- *Architects* who would lead the design, devise the geometric arrangement of the building and assign spaces according to the client's programme.
- *Structural engineers* who would determine the method for supporting the building under various load conditions.

A building design team is also likely to have: *fire engineers, acoustic consultants, public health engineers* and *project managers*. The application of optimisation would ideally draw on all of that expertise.

For this case study, a team of engineers and quantity surveyors devised options for the optimisation process, as would be normal practice in a commercial environment.

Options for the external wall and roof construction were based on the architect's original specification but expanded by mechanical engineers in consultation with the quantity surveyor.

Options for the glazing construction were based on a market survey carried out by facade engineers and the architect's frame design. The options were then refined in consultation with a quantity surveyor.

Small volunteer teams of electrical and mechanical engineers were responsible for formulating alternative lighting and HVAC designs.

Each team produced summary documentation, which was used to provide the inputs to the energy model.

3.5 Parameter options

3.5.1 Limits to the extent of options considered

The optimisation process is well adapted to deal with physical properties that can be expressed as numerical values, but does not deal with values such as aesthetics, safety or operability. As a result, these inputs need to be constrained differently.

The optimisation of the Creative Hub needed to include limits on the degree to which the design could be varied. These limits also serve to constrain the number of alternative options, which were included in the optimisation process.

The extent of options was also limited by the time available to: formulate options and estimate their cost; the processing time which would be required to search the parameter space, and the capability of the evaluation software: *DesignBuilder™*.

The design was constrained by only varying parametric values of concepts already proposed by the architects. For example, the basic form and constructions were retained and only the insulation thicknesses were varied.

3.5.2 External wall construction

The external wall constructions were defined in the architect's specification and reflected in the previous engineer's *Building Regulations United Kingdom Part L* (BRUKL) report. As previously discussed, the options for alternative solutions are constrained by aesthetic considerations that do not lend themselves to mathematic optimisation. For this case study, this issue was addressed by limiting the options for exterior wall construction to variations in the thickness of the insulation layer in the existing building constructions.

A junior mechanical engineer was tasked with calculating the thickness of insulation that would be required to modify the overall heat transmission (U-Value) of the wall and roof constructions. The result was a range of construction alternatives for which the cost could be estimated by the quantity surveyor and optimised within the building energy model given in Table 2

The constructions for the glazing on stud walls in Types 03 and Type 06 are effectively combinations of the two glazing systems (Type 1 *Reglit* and Type 5 Curtain walling) and the opaque constructions (Types 02, 04 and 07). Since there is little difference between Types 02 and 04, and the basic U-Value specification is the same: either 0.2 W/m^{2}K or "to the energy evaluator's requirements" (which was also 0.2 W/m^{2}K), the opaque constructions have been approximated by two build-ups: one with mineral fibre and one with polyurethane.

External Wall Reference	***Construction***	***Insulation***	***Glazing system***	***Stud wall insulation***
Type 01	Glazing	-	*Reglit*	-
Type 02	Opaque wall	Mineral fibre	-	-
Type 03	Glazing on Stud wall	-	*Reglit*	Mineral fibre
Type 04	Opaque wall	Mineral fibre	-	-
Type 05	Glazing	-	Curtain walling	-
Type 06	Glazing on Stud wall	-	Curtain walling	Mineral fibre
Type 07	Opaque wall	Polyurethane	-	-
Type 08	Louvre	-	-	-

Table 2. Summary of exterior wall and glazing types specified in the Stage 3 design.

Where the construction is documented as glazing on stud wall, the stud wall insulation was modelled as the same construction as the opaque wall with mineral fibre insulation. For modelling purposes this simplified the exterior construction parameters down to four constructions:

- Opaque wall insulated with mineral fibre;
- Opaque wall insulated with polyurethane;
- *Reglit* glazing;
- Curtain wall glazing.

The options for the two glazing solutions are discussed in the glazing section.

Initially, each of the two final exterior wall constructions were developed with a range of U-Values of between 0.15 W/m^{2}K and 0.35 W/m^{2}K in increments of 0.05 W/m^{2}K. However, insulation is most cost-effectively obtained when bought in standard thicknesses. The insulation thickness, which corresponded to the initial range were calculated and the nearest size thicknesses were selected. The final U-Values were then recalculated and the costs were estimated. Part L of the Building Code also has maximum limits for U-Values, which further reduced the range to 0.15 W/m^{2}K and 0.30 W/m^{2}K. The costs and build-ups for the exterior wall constructions are given in Table 3 and Table 4below.

Option	***Nominal U-Value W/m^{2}K***	***Calculated thickness mm***	***Practical thickness mm***	***Wall cost £/m^2***	***U-Value W/m^{2}K***
Type 02a	0.10	294	210	1480	0.099
Type 02b	0.15	177	140	1390	0.145
Type 02c	0.2	119	100	1320	0.197
Type 02d	0.25	84	75	1300	0.254
Type 02e	0.3	60	60	1290	0.307

Table 3. Wall Construction and costs for Wall Type 02 with U-Values of 0.15 W/m^{2}K to 0.30 W/m^{2}K.

Option	*Nominal U-Value W/m²K*	*Calculated thickness mm*	*Practical thickness mm*	*Wall cost £/m²*	*U-Value W/m²K*
Type 04a	0.10	318	210	1570	0.099
Type 04b	0.15	201	140	1500	0.145
Type 04c	0.2	143	100	1430	0.197
Type 04d	0.25	108	75	1380	0.254
Type 04e	0.3	84	60	1360	0.307

Table 4. External Wall Construction and costs for Wall Type 04 for U-Values of 0.15 W/m²K to 0.30 W/m²K.

3.5.3 Roof construction

A similar process was applied to the roof constructions. In the case of the roof, there were only two construction types. The plant room roof construction is a simple low-cost product, whereas the main roof needed to be suitable for carrying a variety of loads. Since the application of the plant room roof was limited and was unlikely to offer significant savings, the plant room roof construction did not warrant incorporation into the optimisation process.

Again, a junior mechanical engineer was tasked with providing the table of options for various thickness of insulation in Table 5, which could be used as alternative constructions in the optimisation.

Option	*Nominal U-Value W/m²K*	*Calculated thickness mm*	*Practical thickness mm*	*Wall cost £/m²*	*Actual U-Value W/m²K*
Roof a	0.10	205	200	250	0.104
Roof b	0.15	122	130	210	0.145
Roof c	0.2	80	100	190	0.197
Roof d	0.25	55	75	190	0.254
Roof e	0.3	38	60	180	0.307

Table 5. External Wall Construction and costs for the roof constructions for U-Values of 0.15 W/m2K to 0.30 W/m2K.

3.5.4 Glazing construction

The Arup Facades team has a confidential document that contains a summary of glazing types, which are available in the market. The document contains a chart shown in Figure 10. Transmission properties of common available glasses. that plots the transmission properties of coated glasses, which are commercially available. The document is commercially sensitive so is not reproduced fully, but it still shows a general relationship between visible light transmission and total solar energy transmission (G-Value).

The author was not involved in the research and production of this glazing study or in the grouping of the categories. This work was carried out by a team of engineers in Arup Facades.

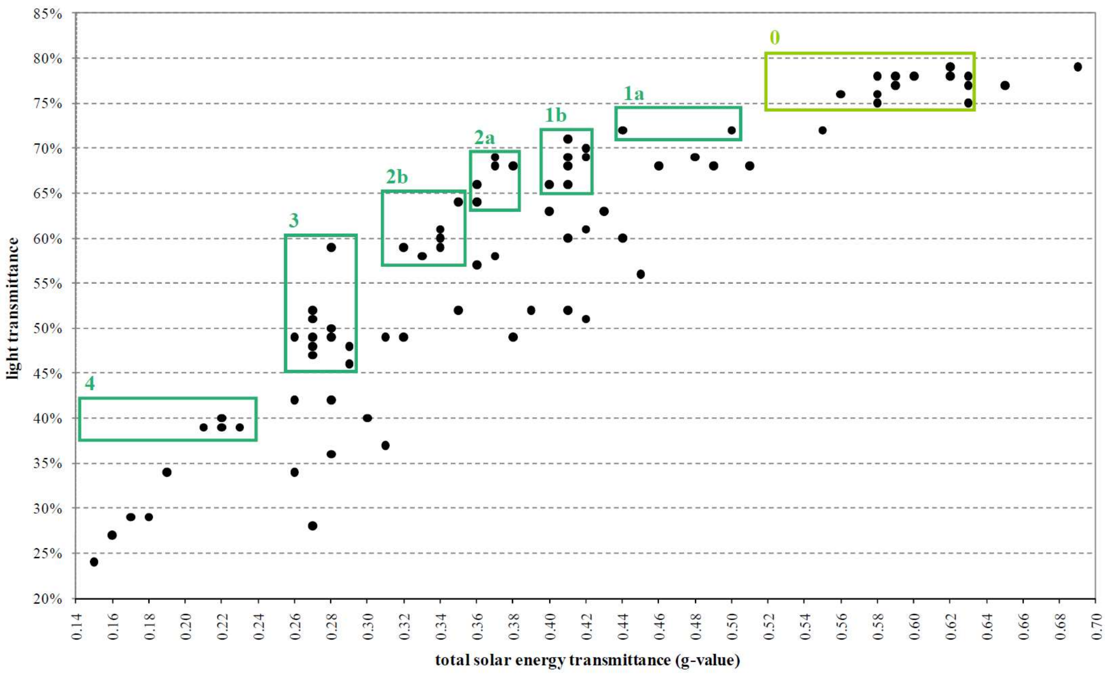

Figure 10. Transmission properties of common available glasses.

The glasses are grouped into seven categories that represent a general increase in glazing performance. The seven categories which were taken from the study are given in Table 10.

Category	***Description***	***G-Value***	***Visible light transmission***
0	Low emissivity	0.52-0.65	0.75-0.81
1a	Selective clear a	0.44-0.50	0.72-0.74
1b	Selective clear b	0.39-0.42	0.65-0.69
2a	Selective standard a	0.36-0.38	0.63-0.65
2b	Selective standard b	0.31-0.35	0.58-0.67
3	Selective dark	0.25-0.29	0.46-0.60
4	Selective darker	0.14-0.24	0.38-0.42

Table 6. Summary of properties for categories of glass in Arup study.

An enquiry was made to a number of glazing suppliers with a request to supply a specification and budgetary costs for a glass that would match each of the seven categories.

The options for representative glazing solutions are contained in Table 7 and Table 8.

Category	*Product name*	*Glazing configuration*	*Cost provided (£/m2)*
0			
1a	Pilkington OptiFloat Bronze	OptiFloat 6mm / 16mmAr / OptiTherm S1 Low-e 6mm	60
1b	Pilkington Optifloat Grey	OptiFloat 6mm / 16mmAr / OptiTherm S1 Low-e 6mm	60
2a	Pilkington Suncool 70/35	Suncool 6mm / 16mmAr / Clear Float 6mm	80
2b	Pilkington Suncool Silver 50/30	Suncool 6mm / 16mmAr / Clear Float 6mm	80
3	Pilkington Suncool Blue 50/27	Suncool 6mm / 16mmAr / Clear Float 6mm	80
4	Pilkington Suncool 30/16	Suncool 6mm / 16mmAr / Clear Float 6mm	85

Table 7. Representative glazing constructions and cost.

Category	**Products name**	**Total solar energy transmittance (G-Value)**	**Light transmittance (LT)**	**Thermal transmittance (U-value) [W/m^{2}K]**
0				
1a	Pilkington Optifloat Bronze	0.41	0.32	1.0
1b	Pilkington Optifloat Grey	0.37	0.31	1.0
2a	Pilkington Suncool 70/35	0.37	0.69	1.0
2b	Pilkington Suncool Silver 50/30	0.31	0.49	1.0
3	Pilkington Suncool Blue 50/27	0.28	0.49	1.1
4	Pilkington Suncool 30/16	0.18	0.4	1.1

Table 8. Glazing properties for selected representative glasses.

These details were then supplied to the quantity surveyor who used the architect's original specification to build up costs for the complete glazing solution, including the frame and curtain wall construction.

3.5.5 Lighting solution

Four potential lighting solutions were defined based on:

- T5 fluorescent tubes;
- T5 fluorescent tubes with daylighting controls;
- LED lighting;
- LED lighting with daylight controls;

The options for representative glazing solutions are contained in Table 9.

Option	Product name	Description	Cost
A1	Zumtubel Mellow Light V LED catalogue No 42182661	Open plan LED lighting	£79/m^2
A2	Zumtubel Mellow Light V LED catalogue No 42182661 with lighting control	Open plan LED lighting with daylight control	£84/m^2
A3	Zumtubel - Mellow Light V T16 catalogue No 42922727	Open plan fluorescent lighting	£70/m^2
A4	Zumtubel - Mellow Light V T16 catalogue No 42922727 with lighting control	Open plan fluorescent lighting with daylight control	£75/m^2

Table 9. Specification and cost for selected lighting solutions.

3.5.6 HVAC solution

Heating Ventilation and Air Conditioning (HVAC) systems can be divided into *natural ventilation* systems, which provide ventilation directly via openings in the facade and *mechanical ventilation* systems, which provide ventilation using mechanical plant. There is a third category called *mixed mode* in which maximum use is made of natural ventilation, but which is supplemented by mechanical ventilation under conditions that make natural ventilation impractical.

Mechanical ventilation systems can be divided into *all-air* systems and *minimum fresh air* systems. All-air systems provide heating and cooling using the ventilation air, while in minimum fresh air systems, only the ventilation required to control the level of carbon dioxide (CO_2) in the space, is ducted into the building's spaces.

At the volumes provided in minimum fresh air systems, air does not have sufficient heat capacity to be able to provide sufficient heating or cooling to spaces, so minimum fresh air systems need to be supplemented with additional heating and cooling systems. Typically, these include:

- Fan Coil Units (FCUs) are boxes that contain a small fan, a cooling and/or heating coil and a filter, which usually used chilled water and Low Temperature Hot Water (LTHW) to cool and heat the air.
- *Chilled beams* are devices that provide cooling (although some can also provide heating) by allowing air to convect directly against a cooling surface.
- Direct expansion (DX) units are a variation of the FCU, which can also use the direct expansion and condensation of refrigerants.
- Variable Refrigerant Flow (VRF) are another variation of DX units allow for evaporation and condensation across a network of FCUs. The amount of heat removed from or rejected into a room is controlled by varying the flow of the refrigerant, which is piped around the building. These have the advantage that heat removed from one space during cooling can be used to heat an adjacent space.
- *Radiators* are devices that combine convective and radiant energy transmission into a room using heat from a LTHW system.
- *Radiant Panels* also use LTHW but transmit most of their heat via long-wave radiation. Radiant panels are more expensive but have an advantage because they are usually ceiling mounted and therefore do not take up wall or floor space.
- Under Floor Heating (UFH) systems use pipes embedded into the slab of a floor to warm the structural floor of the building and conduct heat into the air.

All-air systems can be divided into the following categories:

- Variable Air Volume (VAV) systems provide heating or cooling to a space via air, which is conditioned in an Air Handling Unit (AHU) to fixed temperatures. This is typically 12 °C for cooling and 32 °C during heating. The amount of heating or cooling is controlled by varying the amount of heat provided to the space via VAV boxes. VAV systems make better use of cool outdoor air when it is available at an outdoor air temperature, which is at or below the supply air temperature. This means that the air does not need to be mechanically cooled before being supplied to space. Because the amount of air pumped around the building varies with the loads, VAV systems use less fan energy than the constant air volume systems described below.

- Constant Air Volume (CAV) systems provide heating or cooling to a space via air, which is conditioned in an Air Handling Unit (AHU). The amount of air fed to the rooms is fixed and the temperature in the space is controlled by varying the temperature of the air supplied by the AHU. CAV systems use more fan energy but sometimes a constant flow of air is required, such as in association with kitchen extraction systems or where the air is being supplied into a room via jets. In this context there needs to be sufficient velocity to ensure that the air reaches the furthest regions of the space.
- *Displacement* is a variation of the VAV system but in which supply air is delivered at very low velocities. Displacement systems supply air at higher temperatures than typical VAV systems, so there is a greater proportion of the year when air can be directly supplied from the outside of the building without the need for mechanical treatment.
- VAV with *Terminal Reheat*. VAV systems supply air for both temperature control and ventilation. Usually the heating and cooling loads predominate so the ventilation requirements are provided serendipitously. However, in rooms with high occupancies like meeting rooms and lecture theatres, satisfying the ventilation requirements can lead to over-cooling in the space. In this case, re-heat batteries are used to reintroduce some heating to offset the overcooling. Re-heating can also be required when the VAV control boxes cannot provide sufficient turndown to supply spaces with a large range of loads.

The Heating Ventilation and Air Conditioning (HVAC) solution for the Creative Hub was summarised in the engineer’s design documentation by a set of eight treatment drawings. There was one drawing for each of the four floors for ventilation and one for each floor that described both the heating and cooling strategies.

From an inspection of the drawings, the ventilation strategies did not naturally align with the heat and cooling strategies and a combination of methods was expected to be provided according to the use of the space and location within the building. There were nine ventilation types and seventeen heat and cooling systems shown on the drawings. The large number of HVAC systems described was due in part to the inclusion of natural ventilation solutions, which needed to be supplemented with mechanical systems when natural ventilation was impractical. It is not unusual to need to define ventilation systems separately from heating and cooling systems, but despite the inclusion of mixed-mode ventilation, it was unusual to have so many different types of systems in one building of this size.

In the version used, *DesignBuilder*™ was limited to twelve parameters for optimisation. This meant that at most, there could only be twelve types of zone where options for combinations of systems could be chosen. This would need to decrease to allow simultaneous optimisation with other parameters such as wall construction, roof construction, floor construction, lighting system and glazing choice.

It was possible that the optimisation process might consist of a series of optimisations; however, this would place limits on the parameter space from which solutions could be drawn.

One of the main attractions of optimisation is that it promises to allow the simultaneous evaluation of the effects that different parameter classes would have on each other. For example, the selection of the glazing could increase the energy demand for cooling by allowing more solar gain into a space. However, allowing more solar gain could decrease the amount of energy required by reducing the need for lighting. The advantage of optimisation should be that all the positive and negative effects are evaluated simultaneously and a range of optimal solutions can be established in terms of cost and energy consumption.

As the number of solutions was unusually high, and because of the constraints of the software, it was clear that the HVAC solutions needed to be rationalised. This rationalisation was also likely to have benefits in terms of value engineering for the project even before any optimisation analysis was carried out.

A list of spaces was draw up and the types of ventilation, heating and cooling system for each space was identified from the treatment drawings. Some of the definitions of the HVAC system were overly complicated and effectively required the same type of design approach as other systems, which could be rationalised and treated as the same. A summary of the systems contained in the original combination of treatment drawings is provided in Table 10.

Ref	Natural Ventilation Solution	Mechanical Ventilation Solution	Heating Solution	Cooling Solution
1	None	Constant Air Volume	By air system	By air system
2	None	Displacement	Radiators	By air system
3	None	Foul extract	Radiators	By air system
4	None	Foul extract	UFH	By air system
5	None	Minimum fresh air	VRF	VRF
6	None	None	DX	DX
7	None	None	None	None
8	None	None	Radiators	None
9	None	VAV	By air system	By air system
10	None	VAV	Radiant panels	By air system
11	None	VAV	Radiators	By air system
12	None	VAV + process extract	Radiators	Chilled beams
13	Secure ventilators	Displacement	Radiators	Air system
14	Secure ventilators	Displacement	Radiators	Chilled beams
15	Secure ventilators	Displacement	Reheat batteries	Air system
16	Secure ventilators	Displacement	UFH	Air system

Table 10. Summary of heating ventilation and air conditioning strategies taken from treatment drawings after systems requiring the same design approach had been simplified.

3.5.7 Rationalization of space treatment prior to optimisation

Some of the systems in Table 10 include a requirement for supplementary heating or cooling, which could have resulted in control problems, or clearly did not add value to the design by their inclusion. For example, one area was required to be treated with a Variable Air Volume (VAV) system with additional heating required by radiators. In this case, the design of the VAV system would have the capability to providing all the heating for the space and the additional expense of providing radiators along with all the piping, valves, pumps and controls could be immediately saved.

Some parts of the building such as staircases, plant rooms and back-of-house corridors are only used infrequently and therefore did not need to be treated. Toilets draw air from adjacent spaces and are only provided with a small amount of supplementary heating to offset fabric losses. Information and Communication Technology (ICT) rooms have clear requirements for treatment, which lead to the provision of specialist systems. All of these areas and the related treatment designs were excluded from the optimisation study because either, they were already minimalist systems that could not be further simplified (and therefore reduced in cost), or had complex requirements which required a specialist solution.

The First Floor Exhibition Space was described as having secure ventilators, and an underfloor heating system. However, the space does not have any external walls so there was nowhere to place secure ventilators and there is no heat loss for the underfloor heating to compensate. For this space, the secure ventilators and underfloor heating system were deleted.

The Recording Studio and Leather Workshop were to be provided with displacement heating systems and radiators. The heating provided by the radiators could be supplemented by increasing the volume of the displacement system dependent on the temperature of the air, which can be supplied via the system. In these spaces an exercise was required to determine if the heating for the space could be provided by the displacement system alone.

The Rehearsal Studio, Product and Interiors, Communication and Illustration, Fashion Space and Foundation Art Spaces were all to have a combination of secure ventilators, displacement ventilation and radiators. It might appear that radiators are required for heating while the system is operating with natural ventilation; however, secure vents were only to be provided for summer cooling. As the ventilators are manually operated, the designers assumed that they would not be used in winter because occupants were unlikely to open the ventilators as this would overcool the space. In these spaces an exercise was required to determine if the heating for the space could be provided by the displacement system alone.

Graphics, Games Technology, IT Research and Media Journalism Space are treated using a combination of secure ventilators, a displacement system, radiators and chilled beams. Chilled beams are fundamentally incompatible with manual natural ventilation. While it is possible that the occupants could be trained to ensure that the ventilators are closed when cooling is required, experience would indicate that this is unlikely to happen. In this case, the secure ventilators seemed redundant and could be value-engineered out. It may have also seemed excessive to provide both displacement ventilation cooling and chilled beams; however, displacement ventilation has limited cooling capacity and this space contains high gains from computers. It also seemed incongruous that additional cooling capacity is required because of the high heat loads but that additional heating is to be provided to supplement the displacement system when the space will invariably operate in a cooling mode. In these spaces the secure ventilators and radiators were deleted.

The Performance Space has been provided with a displacement ventilation supply with additional heating provided by console fan coil units. However, black-out curtains will interfere with both the low level displacement supply and the console units. Instead, the design was revised so that supplementary heating could be provided by a reheat battery.

The air for the Performance Space was expected to be supplied by the same Air Handling Unit (AHU) that supplied the VAV system to the 3D Workshop below it. This was not practical because the supply conditions for the displacement system (18°C) are different from the supply conditions for the VAV system (12°C). This was further complicated by the requirement for the VAV system to supply make-up air for process extraction systems, which may or may not run. If the process extraction systems are operating then the process make-up demand is likely to exceed the internal cooling load and the VAV will over cool the space. Terminal reheat is usually installed to compensate for this, but this would be especially wasteful given that the large volumes of air are simply exhausted from the building. The systems in the Performance Space and 3D workshop were changed to VAV. Terminal reheat was provided to the Performance Space to ensure that high ventilation demand would not lead to over-cooling.

The displacement system fresh air demands were checked to ensure that the system would be capable of meeting the fabric component of the CIBSE heating loads. Initially, it was assumed that all the heating would be provided within the minimum fresh air flow with a maximum differential temperature of 8K. It quickly became obvious that in some areas, an increase in the airflow would be required to enable a displacement ventilation system to meet the heating loads. However, the increases in air required are small enough that a displacement ventilation system could be considered to be a practical alternative. The calculations confirming that the performance, of the simplified and rationalised system, would be adequate, are given in Table 11.

Space	***Occupancy (occupants)***	***Air flow (m^3/s)***	***Heating capacity (kW)***	***Area (m^2)***	***Volume (m^3)***	***Air change (ac/hr)***	***Heat from lighting (kW)***	***Total heating (kW)***	***CIBSE fabric load (kW)***	***Factor for ventilation increase required***	***Final Air change (ac/hr)***
Recording Studio	10	0.12	1.152	26.6	63.84	6.8	0.13	1.285	1.04	0.8	5.5
Leather Workshop	15	0.18	1.728	110	264	2.5	0.55	2.278	2.8	1.2	3.0
Rehearsal Studio	30	0.36	3.456	110	264	4.9	0.55	4.006	2.44	0.6	3.0
Product and Interiors	30	0.36	3.456	262	628.8	2.1	1.31	4.766	7.5	1.6	3.2
Communication and Illustration	35	0.42	4.032	322	772.8	2.0	1.61	5.642	9.48	1.7	3.3
Fashion Space	30	0.36	3.456	203	487.2	2.7	1.02	4.471	6.3	1.4	3.7
Foundation Art Spaces	100	1.2	11.52	386	926.4	4.7	1.93	13.45	14	1.0	4.9

Table 11. Comparison of heating loads against CIBSE standards for spaces can be provided by displacement ventilation system only.

The designs were rationalised down to the nine types of system given in Table 12.

Ref	***Natural Ventilation Solution***	***Mechanical Ventilation Solution***	***Heating Solution***	***Cooling Solution***
0	Facade opening	None	Radiators	None
1	None	Displacement	By air system	By air system
2	Secure ventilators	Displacement	By air system	Chilled beams
3	None	Minimum fresh air	VRF	VRF
4	Secure ventilators	Displacement	Radiators	By air system
5	Secure ventilators	Displacement	UFH	By air system
6	None	VAV	By air system	By air system
7	None	Minimum fresh air	Fan coil units	Fan coil units
8	None	Minimum fresh air	Radiators	Chilled beams

Table 12. Summary of heating ventilation and air conditioning strategies taken from treatment drawings after removal of space where HVAC optimisation was to have no benefit and after systems were rationalised.

3.5.8 Preliminary load estimation

Some HVAC systems have limits on the cooling capacity that they can realistically be designed to achieve.

- Passive chilled beams are limited to about 100 W/m^2 (CBCA, 2012).
- Active chilled beams can be used to cool loads up to about 167 W/m^2 (CBCA, 2012).
- Displacement ventilation systems are limited to about 35 W/m^2 (Abbas, 1999) although underfloor supply systems which allow for some mixing increase this limit to 80 W/m^2 (Arup, 2004).

Before these systems could be added to the list of alternatives, and because this was a live project, an intermediate engineer was asked to run a simulation to estimate the cooling loads in each of the spaces. Only two spaces had predicted loads above 60 W/m^2; these were the Performance Control Room (234 W/m^2) and the Pattern Cutting Workshop (277 W/m^2). Both of these spaces needed to be provided with special conditioning and were excluded from the optimisation.

A series of solutions were developed for spaces that could collectively be grouped by zone. The zones were labelled O, A, B, C, D and E and referred to combinations of options for HVAC as summarised in Table 13. The locations of the zones are shown in Appendix D.

Zone and treatment options	***O***	***A***	***B***	***C***	***D***	***E***
0 Minimal Treatment	✓					
1 Displacement		✓	✓	✓	✓	✓
2 Secure vents, chilled beams and displacement			✓			
3 Minimum fresh air and variable refrigerant flow		✓	✓	✓	✓	
4 Secure vents radiators and displacement				✓	✓	
5 Secure vents under floor heating and displacement					✓	
6 Variable air volume		✓	✓	✓	✓	✓
7 Minimum fresh air and fan coil units		✓	✓	✓	✓	
8 Minimum fresh air, radiators and chilled beams		✓	✓	✓	✓	

Table 13. Summary of options for heating ventilation and air conditioning strategies

3.5.9 Costs for HVAC systems

A professional quantity surveyor provided cost estimates for the alternative HVAC systems. These costs were associated with the *DesignBuilder*™ construction templates for use by *EnergyPlus*™ to compile costs for the project.

The costs that were provided were for the equipment and its installation only and excluded power, controls, building management system, ancillary works, builder's work, main contractor's preliminaries, overheads, profit, risk allowances or contingencies.

The costs per square meter of floor area are shown in Table 14.

System	***Cost***	***Notes***
Underfloor heating	£40/m^2	Excludes central plant and associated distribution
Secure ventilators	£100/m^2	Budget quotation from ADS Limited associated with their FLW 28 product
Perimeter heating only	£160/m^2	Pump, radiators, gas boiler, insulation etc.
Displacement	£275/m^2	Centralised system including floor grilles
Minimum fresh air with Variable Refrigerant Flow	£300/m^2	Assumed to be a 4-pipe system
Variable Air Volume	£345/m^2	Centralised system with no local heating or cooling within the VAV units
Minimum fresh air with Fan Coil Units	£365/m^2	4 pipe units
Minimum fresh air with chilled beams	£395/m^2	Ventilated active chilled beams

Table 14. Summary of cost for options for heating ventilation and air conditioning strategies.

From the costs provided above, the costs for the system options in Table 15 were compiled.

Ref	*HVAC solution*	*Total cost*
0	No treatment	£0/m^2
1	Displacement	£275/m^2
3	Minimum fresh air and variable refrigerant flow	£300/m^2
6	Variable air volume	£345/m^2
7	Minimum fresh air and fan coil units	£365/m^2
2	Secure vents, chilled beams and displacement	£495/m^2
5	Secure vents under-floor heating and displacement	£495/m^2
4	Secure vents radiators and displacement	£505/m^2
8	Minimum fresh air, radiators and chilled beams	£555/m^2

Table 15. Summary of costs for heating ventilation and air conditioning strategies.

3.6 Baseline results

Once the model had been constructed, a simulation was carried out to establish the baseline and to prepare the model for the optimisation.

The simulated energy use was 829,000 kWh and the estimated cost of the building was £14,957,000.

3.6.1 Results of Optimisation

The results of the simulations were plotted as a scatter diagram using Excel in Figure 11. The points on the Pareto Front were plotted as an additional series so they could be highlighted in a different colour. The results from the reference design were also included as a single data point.

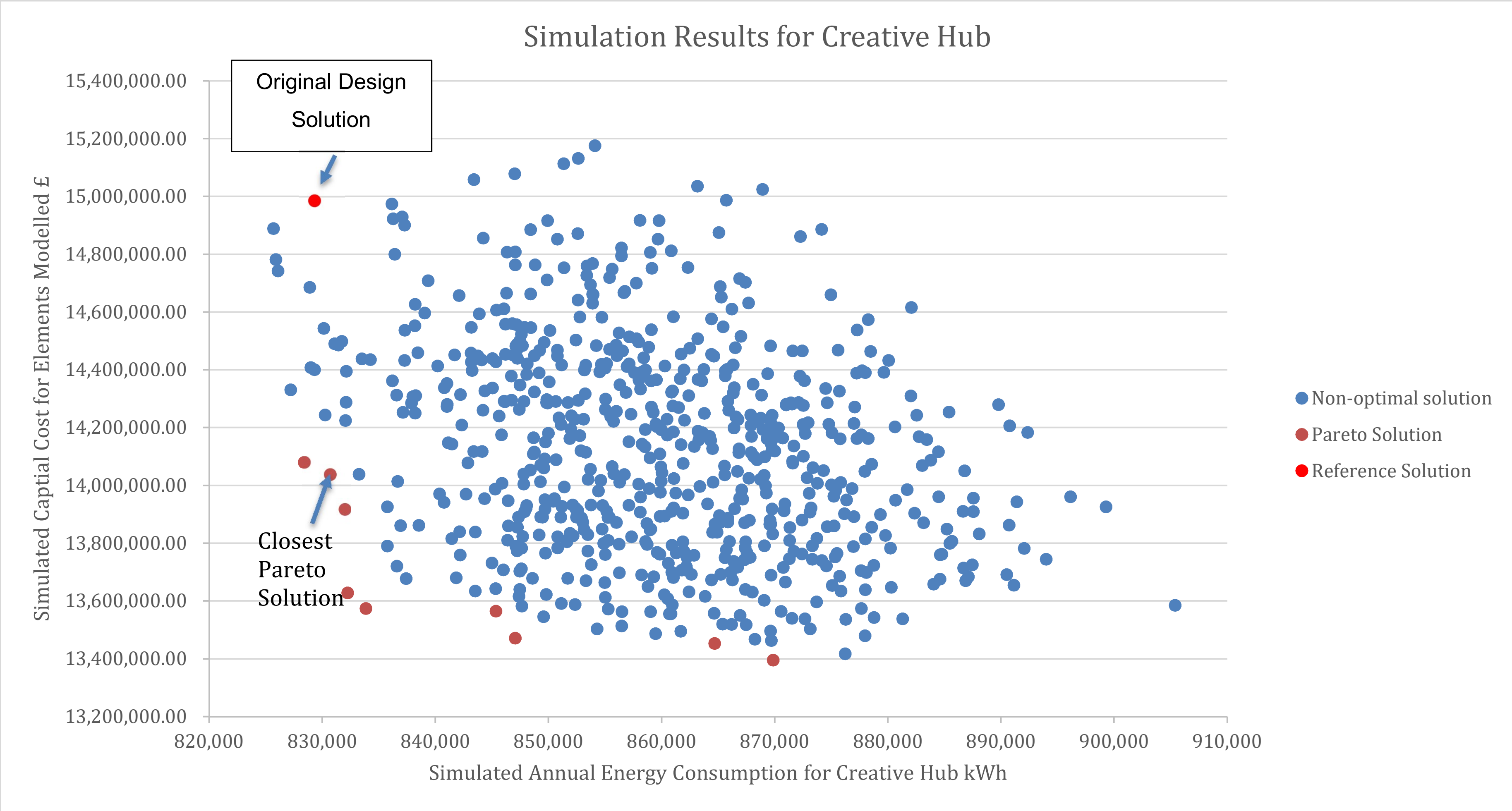

Figure 11. Results of optimisation simulations of the Creative Hub

The Pareto-efficient points which are shown as Series 2 represent a significant reduction in cost for the same energy performance.

The difference between the construction and the systems are summarised in Table 16 below.

Parameter	***Reference Design***	***Pareto solution***
Simulated annual energy consumption	829,327 kWh	835,030 kWh
Simulated construction cost	£15,000,000	£14,600,000
External wall construction Type 4	0.197 W/m²K	0.254 W/m²K
External wall construction Type 2	0.197 W/m²K	0.254 W/m²K
Flat roof construction	0. 197 W/m²K	0. 197 W/m²K
Lighting template	LED with linear/off control	LED no control
Glazing type	1a Pilkington Optifloat Bronze	2a Pilkington Suncool 70/35
HVAC Zone A	1 Displacement heating and cooling	6 VAV
HVAC Zone B	2 Secure vent, displacement heating and chilled beam	1 Displacement heating and cooling
HVAC Zone C	2 Secure vent, displacement heating and chilled beams	1 Displacement heating and cooling
HVAC Zone D	5 Secure vent, UFH, displacement	1 Displacement heating and cooling
HVAC Zone E	6 VAV	1 Displacement heating and cooling

Table 16. Comparison between Reference (non-optimised) and Closest Pareto Efficient Solution for the Creative Hub Case Study Building.

3.7 Implications of optimisation study

This case study clearly demonstrated the benefits of carrying out an optimisation on the early design stage design that had been developed by others.

Some savings could have been made if the heuristic rationalisation had been carried out, even without the optimisation, but overall the process outlined in this chapter clearly demonstrate that a simpler, more cost effective solution could have been produced.

It could be argued that the savings found are relatively small compared to the overall cost of the project (around 2.7%). However, the magnitude of the savings of £400,000, would have been large compared to the cost of the engineering time required which was around £15,000.

The next chapters will present data from three case studies where optimisation is applied to the calibration of building energy models.

Chapter 4 Assessment of applications of optimisation to building energy model calibration.

4.1 Heuristic calibration of Institute of Life Science Building 1

This chapter contains a description of the work carried out, and resulting findings, from a case study based at the Institute of Life Sciences Building 1 (ILS1) at Swansea University. It demonstrates the challenges of using BMS data for a heuristic calibration of a building energy model.

Initially, the investigation into methods for calibrating building energy models in a commercial environment started with an assumption that models would be best calibrated using a heuristic method. The case study method was selected to test the practicality of obtaining data from the building management system of building, which had been completed and was being used.

The object of the case study in this chapter was to determine how much useful data could be obtained from the building, which could then be used to calibrate a building energy model of the building. The longer term goal would then be that of discovering how this information might be used in combination with existing methods to provide a practical method for calibrating building energy models in a commercial environment.

Specifically, the objectives of the case study were to:

- Produce an *EnergyPlus™* model of a building which could predict energy use for comparison with metered consumption.
- Obtain data about the energy consumption of the building which could then be used to assess the accuracy of the building energy model.
- Obtain data on the operation of the building from the building's existing building management system which could then be used to improve the quality of the building energy model.

4.1.1 Institute of Life Sciences Building 1

The Institute of Life Sciences Building 1 (ILS1) is a laboratory building completed in 2006 to provide laboratory, office and teaching space at the University of Swansea. The building was designed for around 200 staff and has a total treated floor area of 5,400 m^2 over seven stories (Boyce, H., Austin, B., 2009). The building features a central atrium which runs full height through the building. Heating and cooling are provided from ground source heat pumps using network electricity. A minimum fresh air system provides ventilation to the building and heating and cooling are provided by fan coil units in laboratory, classroom and office spaces. Specialist extraction air is provided for fume cupboards. The building also contains a Category 3 (Cat 3) Laboratory which provides a high degree of security for experiments that deal with dangerous organisms.

A comparison of the rendered *DesignBuilder*^{TM} model and a photograph taken on site is given in Figure 12

Figure 12. A comparison between ILS1 and DesignBuilderTM Model.

The building is controlled by a *Building Management System* (BMS). Access to the BMS can be made through a campus-wide *Human Machine Interface* (HMI) via computers on the campus *Local Area Network* (LAN). The HMI provides a series of operator screens that enable users to make changes to the settings on the BMS and to set up logs which record data from the instruments in the building. At the time of the investigation (early 2013) access could be made to the BMS from outside the campus using the web-based remote tool *LogMeIn* (logmein.com, 2015). *LogMeIn* provides a relatively simple interface that allows a user to operate an onsite computer, using a computer, keyboard and mouse that is located at another site, and connected to the internet.

4.1.2 Results of ILS1 Investigation

Despite care being taken to ensure that a complete recording was being taken, most of the data were lost due to a failure of the server which was outside the control of the author.

Following the failure of the server, nearly two years of data were lost. No data were recovered from back-up drives. It would appear that the problem was that, while back-up drives were available to restore information held prior to the system crash, the recording of new data did not recommence. This is a risk that is not usually taken into consideration when designing building management systems, but should be considered for future installations.

The risk of data loss could have been mitigated by the author with more regular backups of the database being taken throughout the period when data was assumed to be being collected. More regular checks would have also uncovered impact of the crash earlier. This is certainly a recommendation for future work.

The only data available for analysis came from an earlier copy of the database. A copy of the database was made early in the investigation to confirm that the reading from the building were being recorded and that a system was in place to copy the database when the time came for analysis. This copy contained under three months of data.

This data was analysed in some depth to see if useful information could be obtained. The results of that analysis is contained in Appendix A3.

4.1.3 Discussion of Results

There must be sufficient information about the actual performance of the building to be able to calibrate a building energy model. The heat meter readings for ILS1 were also missing from the database. This was a critical failure, which effectively meant that there was insufficient data to calibrate the building energy model.

Just under 12 weeks of hourly data were obtained for 1322 data channels. Of these, 15% were missing or blank. Of the remaining 1114 logs 47% were potentially erroneous.

A large number of logs contained long periods of full-scale readings which were not expected. Closer examination showed that these periods of full-scale occurred at common times which indicates a common cause.

Similarly, the meter recordings stopped after a relatively short period. This fact, and the complete loss of the heat meter data, meant that there was insufficient data to calibrate the model and another way to investigate the research question needed to be found.

Following the failure of the calibration of ILS, it was apparent that another method of calibrating building energy models would be required which would not necessarily rely on extensive BMS monitoring.

4.1.4 Conclusions from ILS1 case study

The database was capable of being loaded and queried; however, there were no data associated with the lighting systems and data relating to other systems had significant gaps and showed signs of containing errors.

Even with modern BMS systems, the collection of data is not a simple task. Once access has been gained to a building, the BMS may not be robust, and even when it appears to be operating correctly, has been shown to omit data.

A heuristic method, based on the accumulation of data by a building management system, was not suitable for calibrating the building energy model because data was not reliable recorded. Future work should ensure regular checks are made on the accumulation of data. Building management systems that are going to be used for the collection of data should have robust functionality that ensures that data collection continues after there is a system crash.

4.2 Case Study: Sensitivity analysis of an *EnergyPlus™* model

As described in the previous chapter, the attempt to calibrate a building energy model using heuristic methods failed as a result of the loss of data from the building management system. While a heuristic investigation could have proceeded using data gathered on-site using data loggers or blink tests, this would have been impractical due the engineering time which would have been required. Instead, focus was shifted to methods of calibrating building energy models using a deterministic method.

Building energy models are defined by a set of parameters which notionally correspond to engineering concepts. These engineering concepts are an attempt to describe the physics of buildings. For example, walls may be described by geometric coordinates and the heat transfer coefficient of the materials that comprise the wall. The heat transfer coefficient is an application of physics found to be useful when attempting to predict the relationship between the properties of a surface and the heat flowing across it.

In heuristic calibration techniques, the modeller might use their experience of observing the construction of buildings. Observing the effect of reducing or increasing the heat transfer coefficient, they might seek to change the value of the heat transfer coefficient to better reflect the wall in the constructed building. Their decision as to the appropriate value might be supported by a site investigation into the construction of the wall, where holes are made in the wall to visually inspect the as-built construction.

In a deterministic calibration technique, the selection of appropriate values is made by searching the parameter space for values which result in the least divergence between simulated and measured energy use. Since the energy model is only a representation of the physics that is being applied to the building, and both the representation in the modelling code and the physics represent additional abstractions, it could be argued that more appropriate selection of values for parameters could compensate for some of the inherent errors in the modelling process.

This chapter contains the results of the sensitivity analysis which formed the first step in applying a deterministic approach to an *EnergyPlus™* building energy model.

4.2.1 Number 8 Fitzroy St, London

Arup operates a building at Number 8 Fitzroy St in London, in which special attention has been paid to the recording of energy use. If the quality of the data was adequate, then this would at least provide the essential element for energy model calibration: that is, data about the actual energy consumption of a building against which the predictions of the building energy model can be compared.

At the same time a method was required which could be applied with minimum input from engineers, but which would enable a model to be modified so that the predicted energy consumption would fall within the requirements of ASHRAE 14.

A deterministic method based on a parametric analysis followed by a Monte Carlo search of the parameter space for suitable values was then adopted. It was decided that the method be applied using Number 8 Fitzroy St as the second case study. The results of that case study are contained in the following chapters.

4.2.2 EnergyPlus™ model

An *EnergyPlus™* model was constructed to represent the Arup building at 8 Fitzroy St in London using *DesignBuilder™* 3.4 as shown in Figure 13.

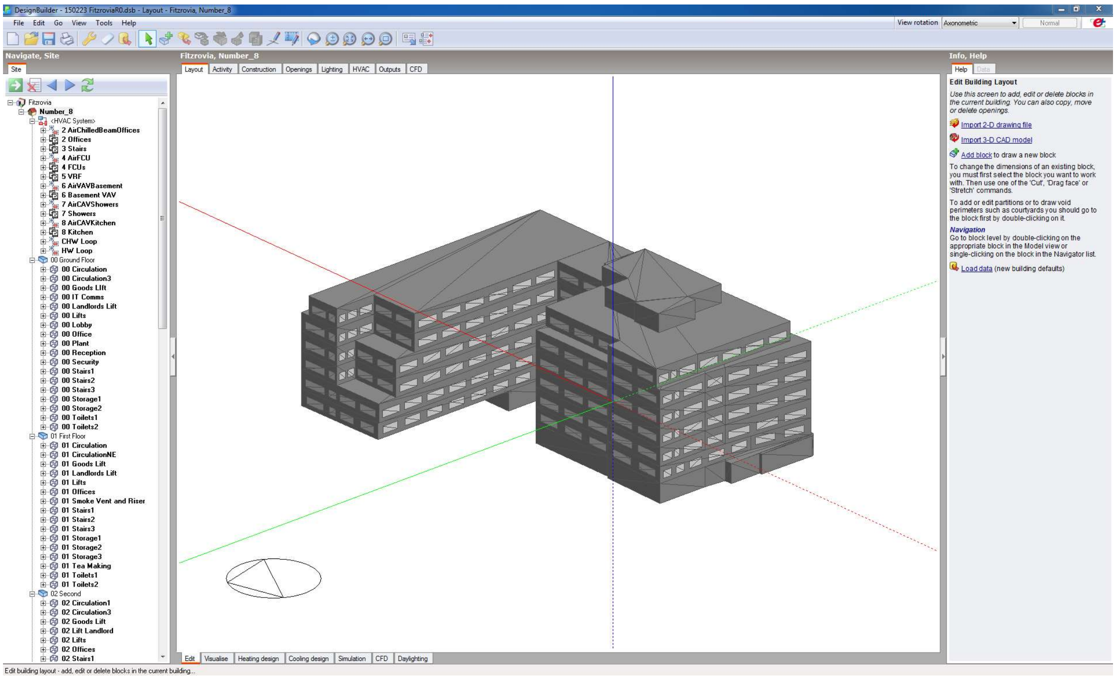

Figure 13. DesignBuilderTM 3.4 model of 8 Fitzroy St, London.

8 Fitzroy St was selected because a full set of design and construction documentation existed for the building and a full set of hourly meter readings was available against which the model could be calibrated.

Number 8 Fitzroy St (Fitzrovia) is a six-storied office block in central London as shown in Figure 14. It has a basement which includes a sound studio, a kitchen and large meeting halls, and there is an atrium which runs up through the whole building.

Figure 14. 8 Fitzroy St, London

Most of the accommodation in Number 8 is open plan, but it also includes a number of closed meeting rooms which are available for confidential discussions and team meetings.

The building is served by a minimum fresh air system and chilled beams. The facade has high performance solar excluding glazing and was intended to be a showcase for good engineering services design.

4.2.3 Evaluating the Difference between Simulated and Measured Energy Consumption

A complete set of energy meter readings for 2013 was obtained from the facility manager for 8 Fitzroy St. The data were supplied in Excel spreadsheets which contained ½ hourly meter readings.

The first task was to check that the dates used in the simulation were aligned with the actual date under consideration.

The first day in January 2013 was a Tuesday and was a bank holiday in the United Kingdom. A visual inspection of the daily energy consumption showed a clear pattern of one day with low energy consumption followed by three days of normal consumption, then two days of limited consumption and a further five days of normal consumption; as can be seen in Figure 15, this was as expected.

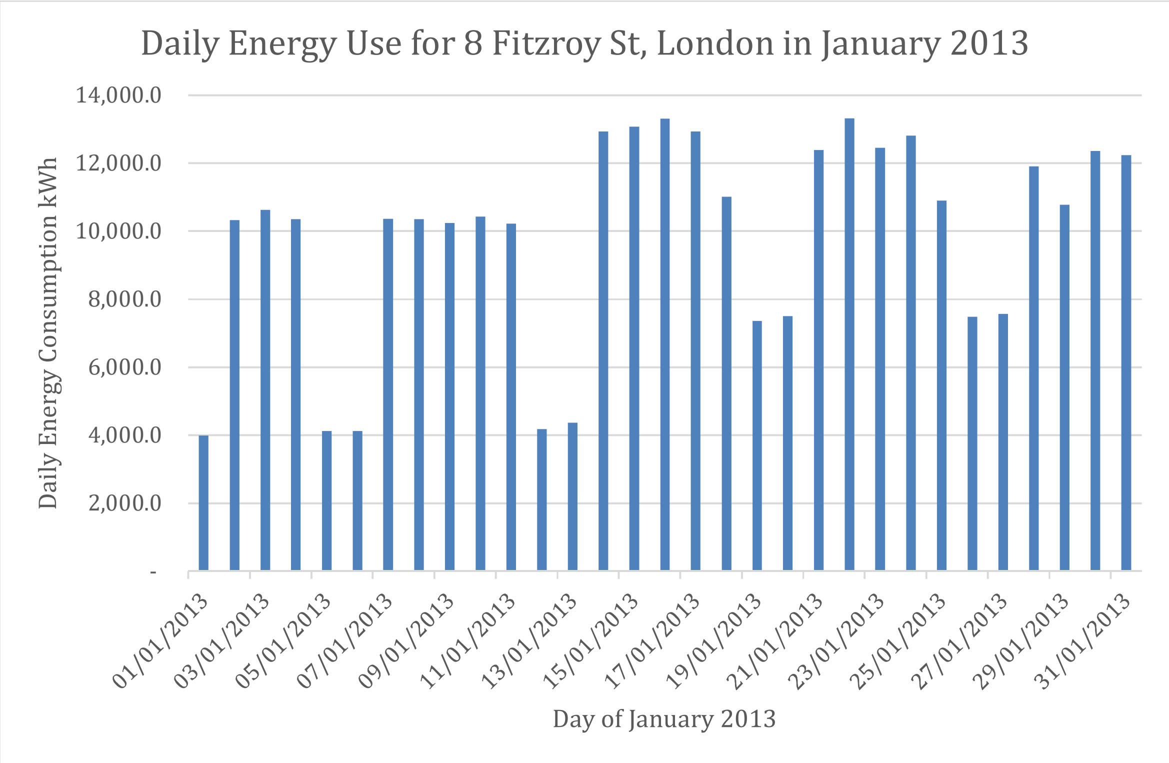

Figure 15. Measured Daily Energy Consumption for 8 Fitzroy St, London in January 2013.

The first day of the simulated energy use shown in Figure 16 was also a Tuesday, however the original activity schedules in *DesignBuilder™* did not treat the 1st of January as a Bank Holiday so the simulated energy use shows substantial energy consumed, whereas the meter data do not.

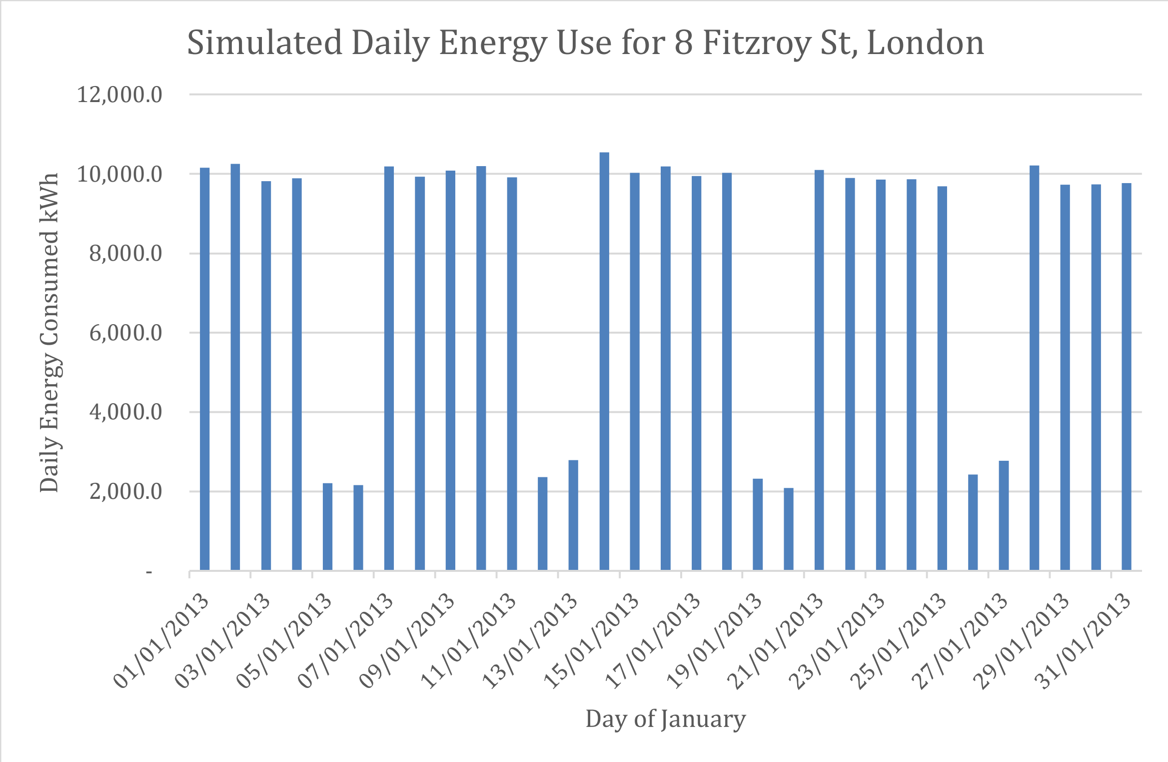

Figure 16. Simulated Daily Energy Consumption for 8 Fitzroy St, London in January.

Once it had been confirmed that the simulation energy consumption data aligned with the actual days of the week, the measured and simulated energy consumptions were compared for the month of January 2013. The superimposed data are shown in Figure 17.

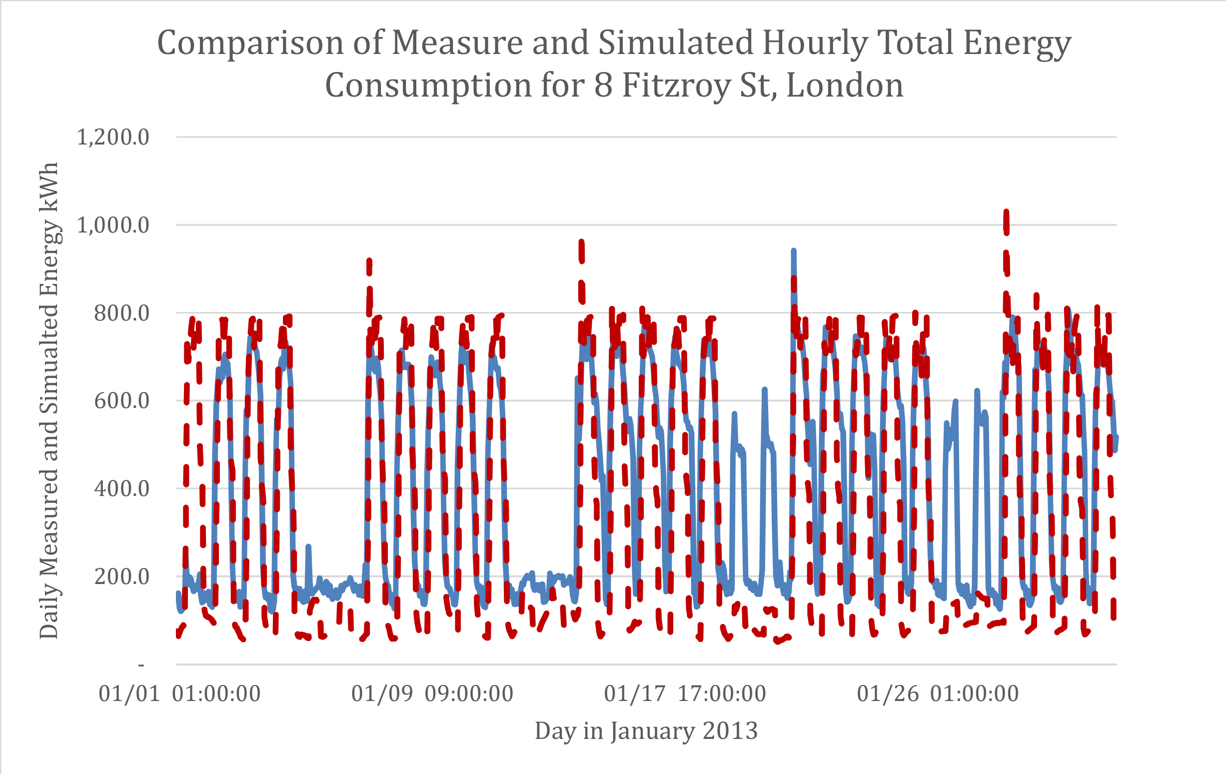

Figure 17. Comparison of Measure and Simulated Hourly Total Energy Consumption for 8 Fitzroy St, London in January 2013

From inspection, simulated and metered energy use correlated by day but that there was a significant underestimation of the amount of energy that was being consumed in weekends in the second half of the month. This was likely to be due to staff returning to work after the Christmas break.

The Normalized Mean Bias Error ($NMBE_{hourly}$) and Coefficient of Variance for Root Mean Square Error ($CVRMSE_{hourly}$) were calculated using the formulae provided in ASHRAE 14.

Under the requirements of ASHRAE 14, a model can be considered calibrated if the NMBE and $CVRMSE_{hourly}$ are within 10% and 30% respectively. A comparison of the level of calibration between the requirements of ASHRAE 14 and the results for 8 Fitzroy St are given in Table 17.

	ASHRAE 14 maximum allowable	Un-calibrated simulation
$NMBE_{hourly}$	10%	14%
$CVRMSE_{hourly}$	30%	41.6%

Table 17. Comparison of the level of calibration between the requirements of ASHRAE 14 and the results for 8 Fitzroy St.

Table 17 shows that the design model which was produced solely using design information, would not be classified as calibrated under AHSRAE 14.

4.2.4 Automatic evaluation of $CVRMSE_{hourly}$ and $NMBE_{hourly}$ based on hourly measurements

Under ASHRAE 14, $CVRMSE_{hourly}$ and $NMBE_{hourly}$ can be evaluated on either an hourly or monthly basis. Evaluation on an hourly basis was chosen as the more rigorous test for calibration.

Initially an *Excel* spreadsheet was used to calculate the hourly $CVRMSE_{hourly}$ and $NMBE_{hourly}$ for the un-calibrated model. While this was not particularly onerous for the results of one simulation, repeating the analysis for thousands of simulations which can be run from *jEPlus*, would not have been practical. Instead a simple tool was developed using the Excel programming language *Visual Basic for Applications* (VBA). This script cycles through the results of multiple simulations produced by *jEPlus*, evaluates the $CVRMSE_{hourly}$ and $NMBE_{hourly}$ and stores the results in a CSV file for later evaluation.

There was hope that the work carried out in this thesis would be applied to a number of buildings with some benefit to the Ph.D. candidate’s employers, so the script was written by a graduate engineer under the supervision of the candidate.

In summary, the process that the script follows is:

- *jEPlus v1.5* creates a job file for each simulation which contains an IDF for the model containing all the values for the parameters for each iteration.
- *jEPlus* executes the *EnergyPlus*™ simulation and the results are stored in a file called *Eplusout.csv*.

- The VBA evaluation script cycles through the job files, calculates the $CVRMSE_{hourly}$ and $NMBE_{hourly}$ compared to the metered energy file and stores the two values against the name of the job file in another CSV file called *Results.csv*.
- The results are inspected using *Excel*.

This script was also used to evaluate the results of the main Monte Carlo search to find the values which best represent a calibrated model which is described in more detail below.

4.2.5 Calibration Process

This deterministic process of calibrating the building energy model can be broken down into two steps. A test is made of the relative influence that the parameters have on the simulated energy use. Then a search is made of the influential parameter subspace for values which produce the best fit between simulated and metered data. A Latin Hypercube Monte Carlo search was performed because of the ease of implementing the search algorithms.

This thesis examines the practicality of applying a calibration methodology in a commercial environment. Once the decision on the method of calibration is established there are a number of questions that need to be answered about the details of its implementation.

- What is the minimum dimension of the influential parameter space that must be searched in order to produce a calibrated model?
- How should inputs for the Monte Carlo search be distributed and what range should they be distributed over?

There is also room to improve the process which is used to determine the influential parameters. In sensitivity analysis the nominal values for all the parameters in the energy model are varied by a set amount and the relative effect on the simulated annual energy consumption is reported. The most influential parameters are determined to be the ones which most greatly influence the simulated energy use.

The first parametric test *jEPlus v1.5* was used to compare the influence of reducing the value of each parameter by 20% on the simulated annual energy use of the model of 8 Fitzroy St.

However, the overall calibration process is concerned with the influence a parameter has on improving the goodness of fit between simulated and measured energy use. This implies that it would be more appropriate to test a parameter's influence on $CVRMSE_{hourly}$ and $NMBE_{hourly}$ than on annual energy consumption.

At the end of the process, the parameters with the greatest influence on the simulated energy consumption can then be read from a spreadsheet.

Manual editing of the *EnergyPlus™* Input Definition File (IDF) produced a list of 2480 parameters to be evaluated. Each parameter was evaluated using *jEPlus* by varying the value of the parameter by -20%. *jEPlus* produced a summary file which was imported into Excel. The difference between the annual energy consumption and the annual energy consumption with each decreased value for the parameter of interest was calculated and the parameters were sorted based on the relative magnitude of the deviation.

4.2.6 Results

There were 44 parameters for which a 20% decrease in the value of the parameter from the nominal (design) value resulted in a change in the simulated annual energy consumption of more than 1%. A list of the 20 most influential parameters is given in Table 18.

Ref	Relative Effect	Nominal Value	Parameter description
1	5%	3.4	Chiller baseline coefficient of performance {W/W}
2	5%	0.933884	Chiller performance bi-quadratic coefficient
3	4%	1.15	Cooling sizing factor
4	3%	0.7	Building fan efficiency
5	3%	1	Air distribution effectiveness in cooling mode {dimensionless}
6	3%	1	Air distribution effectiveness in heating mode {dimensionless}
7	3%	1	Heating sizing factor
8	3%	0.1	Chiller minimum part load ratio
9	3%	-0.058212	Chiller performance bi-quadratic coefficient for x
10	3%	0.008	Outdoor air flow per person {m3/s-person}
11	3%	0.222903	Chiller performance bi-quadratic coefficient
12	2%	600	Building fan developed pressure {Pa}
13	2%	0.00450036	Chiller performance bi-quadratic coefficient for x^2
14	2%	14	Cooling design supply air temperature {C}
15	2%	0.65	Sensible effectiveness at 100% heating air flow {dimensionless}
16	2%	43541	3rd Floor office electrical gain (kW)
17	2%	32656	Lighting Level {W}
18	2%	0.04	Condenser fan power ratio {W/W}
19	1%	-0.001215	Chiller performance bi-quadratic coefficient for x*y
20	1%	18.6	Wetbulb or dew point at maximum dry-bulb {C}

Table 18. First 20 parameters with an effect of greater than 1% on simulated annual energy consumption when the value of the parameter is decreased by 20%

4.2.7 Discussion of the results

The parameters in Table 18 can be grouped according to the class of input where they are documented in the *EnergyPlus™* IDF.

The most influential parameters describe:

- Design day conditions used to size cooling equipment;
- Ventilation rate per person;
- Sizing factors (factors of safety);
- Ventilation supply temperature;
- Occupant density;
- Lighting energy density;
- Electrical equipment energy density;
- Fan efficiency;
- AHU and FCU fan developed pressure;
- Hot water part load ratios;
- Chiller performance: COP, Unloading ratio, and Condenser fan power ratio;
- Chiller performance curve parameters.

This suggests that greater attention is warranted in the selection of values for these parameters at the design stage.

4.2.8 Errors and incomplete simulations

*EnergyPlus*TM runs sub-routines which are designed to identify errors in input data. When these are identified, *EnergyPlus*TM identifies a "fatal" error and terminates the simulation. When some of values were reduced by 20%, a fatal error was produced and the simulation terminated.

On inspection, there were only four parameters that produced fatal errors when reduced by 20%. These were:

- Ratio of Frame-Edge Glass Conductance to Center-Of-Glass Conductance;
- Ratio of Divider-Edge Glass Conductance to Center-Of-Glass Conductance;
- Basin Heater Setpoint Temperature {C};
- Maximum Part Load Ratio.

*EnergyPlus*TM required these parameters to have values not less than their nominal value. Variation of these parameters did not make sense from an engineering point of view and were discarded from further analysis.

4.2.9 Effect of parameters on CVRMSE and NMBE

Examining the sensitivity of the annual energy consumption to changes in values of input parameters is useful. However, the focus of calibration should be on the sensitivity of

$CVRMSE_{hourly}$ and $NMBE_{hourly}$ to changes in values of input parameters since these are the measures that are being affected. This gives rise to the question:

What is the relative effect of changes to values of input parameters on $CVRMSE_{hourly}$?

This was evaluated by calculating the $CVRMSE_{hourly}$ and $NMBE_{hourly}$ for the revised parameter values in the previous exercise and ranking the parameters by the change in $CVRMSE_{hourly}$ or $NMBE_{hourly}$.

For this experiment, attention was focused on the 44 parameters identified which resulted in a deviation from the nominal simulated annual energy consumption of more than 1%.

A batch of 44 simulations was run using *jEPlus v1.5*. Once the simulations were complete, the *Excel* script, described in Section 4.2.4, was used to calculate the $CVRMSE_{hourly}$ and $NMBE_{hourly}$ for each parameter whose value had been varied by 20% from nominal. Then the calculated $CVRMSE_{hourly}$ and $NMBE_{hourly}$ were compared against the $CVRMSE_{hourly}$ and $NMBE_{hourly}$ for the simulation based on nominal values and the parameters were ranked by impact.

It is important to note that, at this stage in the evaluation, the emphasis was not on looking for improvements i.e. reductions, in $CVRMSE_{hourly}$ as the parametric runs only considered a change in the values of the parameters – not necessarily a better informed value.

The relative impact of varying the values selected for parameters is compared in Table 19. The parameters were ranked in order of their relative effect on the three valuation criteria:

- Impact on annual energy consumption;
- Impact on $CVRMSE_{hourly}$;
- Impact on $NMBE_{hourly}$.

The table was examined to see how much the parameters moved in ranking depending on the evaluation criteria.

The relative rank of the influence of parameters changes depending on the method used to evaluate their influence: annual energy consumption, $NMBE_{hourly}$ or $CVRMSE_{hourly}$, so the relative shift in rankings between evaluation criteria was also calculated. Three columns in Table 19 are included which show the change in the ranking of the parameter if the criteria are shifted from annual energy consumption to $NMBE_{hourly}$, from annual energy consumption to $CVRMSE_{hourly}$, or from $NMBE_{hourly}$ to $CVRMSE_{hourly}$. These changes in rank have been colour coded to highlight where there are large changes in rank between evaluation criteria. Green indicates relatively small changes. Red indicates large changes.

Parameter	Nom. value	Rank Energy	Rank NMBE	Rank CV RMSE	Rank change Annual & NMBE	Rank change Annual & CVRMSE	Rank change NMBE & RMSE
Building fan efficiency	0.70	4th	4th	1st	0	3	3
Outdoor air flow per person {m3/s-person}	0.01	9th	8th	2nd	1	7	6
Building fan developed pressure {Pa}	600	11th	10th	3th	1	8	7
Cooling design supply air temperature {C}	14	13th	12th	4th	1	9	8
Air distribution effectiveness in cooling mode	1.00	5th	5th	5th	0	0	0
Air distribution effectiveness in heating mode	1.00	6th	6th	6th	0	0	0
Chiller model bi-quadratic coefficient for y	0.05	34th	33rd	7th	1	27	26
Sensible effectiveness at 100% heating air flow	0.65	14th	13th	8th	1	6	5
Zone design electrical load {W}	26,370	24th	14th	9th	10	15	5
Cooling sizing factor	1.15	3rd	3rd	10th	0	7	7
Chiller model bi-quadratic constant	0.93	2nd	2nd	11th	0	9	9
Wetbulb or dewpoint at maximum dry-bulb {C}	18.6	19th	18th	12th	1	7	6
5th Floor office electrical load {W}	36,551	36th	23th	13th	13	23	10
3rd Floor office occupancy	217	25th	24th	14th	1	11	10
Zone design level {W}	26,618	40th	27th	15th	13	25	12
Chiller reference coefficient of performance {W/W}	3.40	1st	1st	16th	0	15	15
Chiller minimum unloading ratio	0.25	23th	22th	17th	1	6	5
July ground temperature {C}	18.00	39th	38th	18th	1	21	20
4th Floor office design electrical load {W}	42,529	31st	30th	19th	1	12	11
Chiller model bi-quadratic constant	0.22	10th	9th	20th	1	10	11

Table 19. Colour coded relative changes to rankings of important impactful dependant on sensitivity test applied

4.2.10 Interpretation of Results

Table 19 shows that parameters can change significantly in perceived importance depending on the criteria used to evaluate their significance. The rank of parameters changes significantly depending on whether their impact is based on annual energy consumption, $CVRMSE_{hourly}$ or $NMBE_{hourly}$.

It was clear that a more rigorous approach to the ranking of parameters needed to be developed. This is addressed in the next section.

4.2.11 Wider Search

The search methods applied up to this point used relatively crude methods to defining alternatives. While the selection of a value of 20% less than the nominal value, has some precedent in the literature (O'Neill, Eisenhower, Yuan and Bailey, 2011), other values have also been used, and there is little reason for one value to have precedence over another.

Although, the evaluation of the impact of a parameter by examining the impact on $CVRMSE_{hourly}$ or $NMBE_{hourly}$ obviously makes more sense, the selection of a value of 20% less than the nominal value is still relatively arbitrary.

From a purely mathematical point of view, searching the complete parameter space for values which would best allow a simulation to fit metered data would be useful. However, it must be recognised that the parameters have a basis in physics and the values are estimates selected by engineers who are attempting to find values for the parameters, which reflect their significance in engineering. From this point of view, it is attractive to attempt to search for values that are in the vicinity of the nominal values, which were selected for the design simulation.

The test was to search the parameter space in the vicinity of the nominal values more thoroughly, and to evaluate the impact of the changes in values in terms of $CVRMSE_{hourly}$ and $NMBE_{hourly}$. This was done using multiple test values for each parameter.

A normal distribution of values was chosen for each parameter. The workstation that was available to run simulations using *jEPlus* could run 48 simulations in parallel, so 48 values were chosen for each parameter. The values were chosen using *Excel's* random number generator with the nominal value used as the average and a standard deviation, which equated to 20% of the nominal value.

Under this scenario, the most influential parameter is defined as the parameter for which a normal distribution of input values results in the greatest improvement in $CVRMSE_{hourly}$ or $NMBE_{hourly}$.

For this test, 48 values were selected for 44 parameters that required 2,112 simulations. The simulations were managed using *jEPlus v1.5.*

The most significant variables, and the values which gave the 10 best $CVRMSE_{hourly}$ and 10 best $NMBE_{hourly}$, are given in Table 20 and Table 21.

Rank (CVRMSE)	Parameter Name	Nominal Value	Optimised Value	NMBE	CVRMSE
1st	Building fan efficiency	0.7	0.25938	-6.96094	38.43549
2nd	Cooling design supply air temperature {C}	14	20.47179	-0.06407	39.045
3rd	Building fan pressure developed {Pa}	600	930.2557	8.777236	39.75568
4th	Sensible effectiveness at 100% heating air flow {dimensionless}	0.65	0.919353	8.909079	39.80055
5th	Air distribution effectiveness in heating mode {dimensionless}	1	0.635638	7.784365	40.49807
6th	Outdoor air flow per person {m3/s-person}	0.008	0.011227	9.607789	40.66102
7th	Chiller performance model bi-quadratic coefficient for Y^4	0.0468684	0.026661	15.84212	40.68146
8th	Air distribution effectiveness in cooling mode {dimensionless}	1	0.728771	9.942595	40.70818
9th	3rd Floor office electrical Load {kW}	43541.284	26445.46	17.31707	40.81638
10th	July ground temperature {C}	18	26.51575	12.31716	41.02204

Table 20. Ten most significant parameters and their impact on $NMBE_{hourly}$ and $CVRMSE_{hourly}$ ranked by $CVRMSE_{hourly}$.

Rank (NMBE)	Parameter	Nom	Value	NMBE	CVRMSE
1st	Cooling design supply air temperature {C}	14	20.47179	0.06407	39.045
2nd	Air distribution effectiveness in cooling mode {dimensionless}	1	0.485328	2.414793	40.80838
3rd	Cooling sizing factor	1.15	1.90835	3.310484	43.32882
4th	Chiller performance model bi-quadratic coefficient for x*y	-0.001215	0.000769	4.103332	43.07508
5th	Baseline chiller coefficient of performance {W/W}	3.4	2.206225	4.469356	42.9538
6th	Building fan efficiency	0.7	0.399432	4.665463	38.83837
7th	Zone air distribution effectiveness in heating mode {dimensionless}	1	0.635638	7.784365	40.49807
8th	Building fan developed pressure {Pa}	600	930.2557	8.777236	39.75568
9th	Sensible effectiveness at 100% heating air flow {dimensionless}	0.65	0.919353	8.909079	39.80055
10th	Chiller performance model bi-quadratic coefficient constant	0.933884	1.172571	9.044068	41.89553

Table 21. Ten most significant parameters and their values and their impact on $NMBE_{hourly}$ and $CVRMSE_{hourly}$ ranked by $NMBE_{hourly}$.

Six parameters appear in both tables; this is notable because, independent of whether the term "influential" is defined by $NMBE_{hourly}$ or $CVRMSE_{hourly}$, these parameters must qualify as influential. Furthermore, the top five parameters ranked by $CVRMSE_{hourly}$ all also appear in the top 10 for $NMBE_{hourly}$.

At this stage it appeared that a decision should be made to focus on pursuing $CVRMSE_{hourly}$ or $NMBE_{hourly}$.

4.2.12 CVRMSE or NMBE

$NMBE_{hourly}$ is a measure of the error between the simulated and actual data. $NMBE_{hourly}$ is the average of the errors divided by the average of the observations.

$CVRMSE_{hourly}$ is a measure of the dispersion of the error between the simulated and actual data. $CVRMSE_{hourly}$ is the standard deviation of the errors divided by the average of the observations.

Both $NMBE_{hourly}$ and $CVRMSE_{hourly}$ are necessary to eliminate allowing certain types of errors to be classed as acceptable. If $NMBE_{hourly}$ was the only measure, large variations in simulated estimates would be acceptable, as long as the total error above and below the simulated energy consumption balanced. If $CVRMSE_{hourly}$ is the only measure, then large offsets with little variation would be acceptable.

In the Monte Carlo Sensitivity Analysis, there were 121 solutions already identified that reduce the $NMBE_{hourly}$ below the 10% threshold defined by ASHRAE 14 whereas the best combination of value and parameter for $CVRMSE_{hourly}$ only resulted in a decrease from 41.6% in the uncalibrated model to 38.4% in the revised model. This suggests that meeting the $CVRMSE_{hourly}$ criteria is more stringent than meeting the $NMBE_{hourly}$ criteria and implies that if $CVRMSE_{hourly}$ is met, then $NMBE_{hourly}$ will follow. $CVRMSE_{hourly}$, was selected as the determining factor because it is harder to achieve than $NMBE_{hourly}$ but that a check would also be made of $NMBE_{hourly}$ to ensure that once a set of values has been obtained, that the solution also meets the $NMBE_{hourly}$ criteria.

4.3 Latin Hypercube Monte Carlo Search for Calibration of an *EnergyPlus™* Model

A series of simulation runs were made to determine how many parameters would need to be included in a Latin Hypercube Monte Carlo search to find a solution that meets the criteria of ASHRAE 14.

The searches were formulated based on the results of the Monte Carlo Sensitivity test results of a parameter's influence on $CVRMSE_{hourly}$.

Since the workstation used was capable of running around 2000 simulations overnight it made little sense to test the influence of each parameter with a total number of simulations of less than 2000. Therefore, a series of 2000 simulations were carried out based on combinations of the most influential $CVRMSE_{hourly}$ parameters. First only one parameter was tested, then two, then three etc. The improvement in the best identified $CVRMSE_{hourly}$ was then plotted against the number of parameters used in the simulation. The NMBE was also calculated and is also displayed on the graph of the results.

The *EnergyPlus™* IDF files were modified manually using *Notepad++* and the simulations were manually organised in *jEPlus v1.5*.

Once the changes were made the IDF was saved for processing with *jEPlus*.

The first batch of simulations was run with all 2000 random values for Fan Efficiency. Later simulations were run with a Latin Hypercube sample from the total set of permutations.

The assessment was carried out by assembling all the necessary files in the results directory and running the Excel VBL macro.

Initially, there was a problem with running the script. When the script was first developed, it was designed to assess the output of parametric runs which were assembled for processing in *jEPlus* using the *Python* script. The names produced by the *Python* program have the form "J1", "J2", "J3"… etc. so the first iteration of the VLB script read the names of the folders in the output directory and looped through the folders with names J followed by a series of numbers: 1 to the total number of files in the directory. When the parametric runs are assembled in *jEPlus* the names of the output folders were produced by *jEPlus,* which uses a different algorithm and produces different names. The names of the *jEPlus* out folders have the form "EP_G-T_0-W_0-P1_n", where n is the sequential number of the run, so the script could not be simply applied to the new set of results. The script was modified so it would read in all the names of the output folders irrespective of the format.

4.3.1 Results of Monte Carlo Searches

Once the *EnergyPlus™* simulations were complete, the *Excel* script was used to calculate $CVRMSE_{hourly}$ and $NMBE_{hourly}$ which for 2000 files took around 13 minutes.

The results of the series of simulations are given in Figure 18.

As the number of parameters was increased from one to ten, there was a steady reduction in $CVRMSE_{hourly}$. However, as more parameters were added, the $CVRMSE_{hourly}$ rose and fell but did not drop below 30%, which would be required for the model to be considered calibrated to ASHRAE 14.

It was apparent that adding additional parameters to the search space did not yield better calibrated models.

It is interesting to note that the addition of each parameter did not necessarily decrease the $CVRMSE_{hourly}$. This could be due to a flaw in the sensitivity analysis or could be due to the random nature of the Monte Carlo simulations.

Overall, the trend was towards a value just short of the 30% target. With 200 simulations and around 10 parameters the value of $CVRMSE_{hourly}$ drops to around 33% and greater numbers of parameters produce a minimum figure of 32%. This likely represents the lowest value that can be achieved without the application of weather or occupancy data.

4.3.2 Omissions and weaknesses of the process

Areas where the process is open for criticism are:

- The analysis does not examine the influence of the *Energy Plus Weather* (EPW) file on output from the simulations.
- The analysis does not examine the influence of operating schedules on the output from the simulations
- The analysis could use a wide range of values for the deviation of the input instead of 20%.
- The influence of values representing temperature in degrees Celsius are skewed by a universal variation of 20%.

The process used for the parametric optimisation is far from perfect, however the test in a commercial environment is fitness for purpose.

4.3.3 Future work

Since the model did not achieve a $CVRMSE_{hourly}$ of below 30% more simulations might need to be carried out to more thoroughly search the parameter space. The number of simulations used previously was 2000 because this was a feasible number to run in a few days. With a dedicated PC there was a possibility to run many more calculations over a correspondingly larger time frame. This is discussed in more detail in Chapter 5.

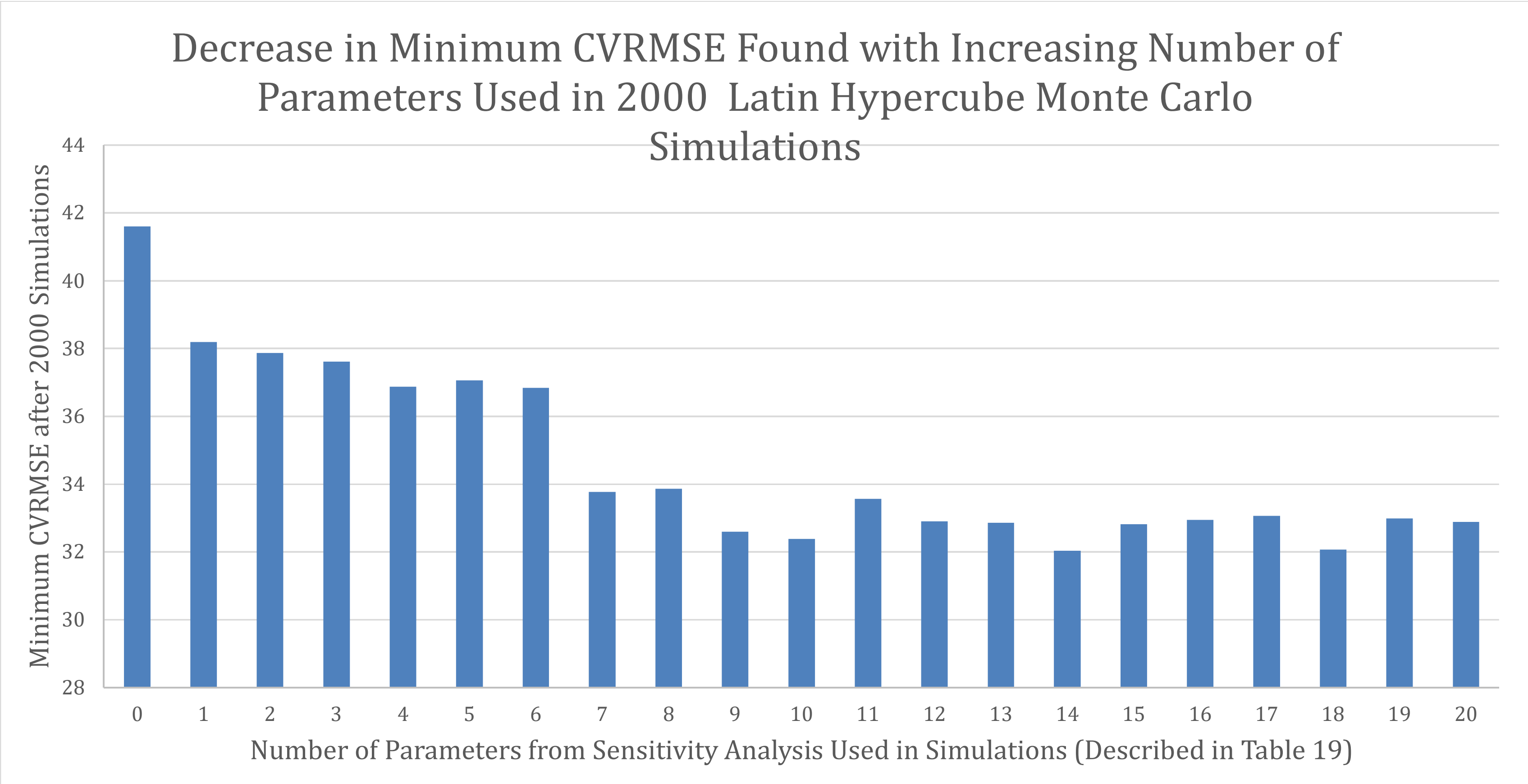

Figure 18. Decrease in minimum $CVRMSE_{hourly}$ found with increasing number of parameters used in 2000 Latin Hypercube Monte Carlo simulations.

4.4 Case Study: Calibration of an *EnergyPlus™* Model using Differential Evolution

In the previous chapter, the calibration of a building energy model was shown to be improved by employing a Latin Hypercube (LHC) Monte Carlo sampling approach. However, Monte Carlo is known to be a computationally intensive method in optimisation problems. Evolutionary algorithms have been shown to provide a more efficient search of the parameter space because they use information obtained from early searches to guide the areas of focus towards more promising regions of the parameter space.

The results of the LHC Monte Carlo search were next compared with those based on a differential evolution model.

Differential evolution has already been described in the literature review. This chapter will describe the process by which differential evolution was applied to the calibration of a building energy model.

4.4.1 Process development overview

Work at the University of Sheffield has previously been used to apply a Self-Adaptive Differential Evolution (SADE) algorithm in the analysis of Generalised Extreme Value (GEV) Distributions. While the analysis of GEV distributions are outside the scope of this thesis, the optimisation procedure used in the exploration of GEV distributions transposes readily to the minimisation of divergence between measured and modelled data.

The script (Worden and Manson, 2012), developed for the GEV study, was written in *Matlab™*. This script was modified to run the processes necessary to perform the optimisation. The SADE process has already been described in the literature review, and was modified to call *EnergyPlus™* to perform simulations using inputs representing vectors in the parameter space.

Once the modifications were complete, a test was carried out to ensure that the script was operating correctly. The test procedure consisted of simulating a simple building: “House Example 1” and using the output data as a baseline representing measured data. A limited number of parameters (four) were then perturbed to represent a design model and the calibration process was executed to ensure that the SADE process converged on the baseline data.

Once the process was shown to be operating correctly, the SADE script was expanded to include the 20 parameters examined previously and the process was set to run on the *EnergyPlus™* IDF for Arup’s Fitzrovia building.

4.4.2 Model to test correct operation of SADE script

In the time since the original model of Number 8 Fitzroy St was produced, *DesignBuilder™* had been updated to Version 5.4.9.021, which runs *EnergyPlus™ Version 8.6.0*.

DesignBuilder™ comes with a number of templates including a simple residential building called *House Example 1*. *House Example 1* is a two-storey semi-detached building which is fairly typical of residential British housing. It has medium weight construction, pitched roofs and double glazed windows. The building is heated using natural gas, but not comfort cooled. A rendered illustration of the building, taken from the *DesignBuilder™* GUI, is given in Figure 19.

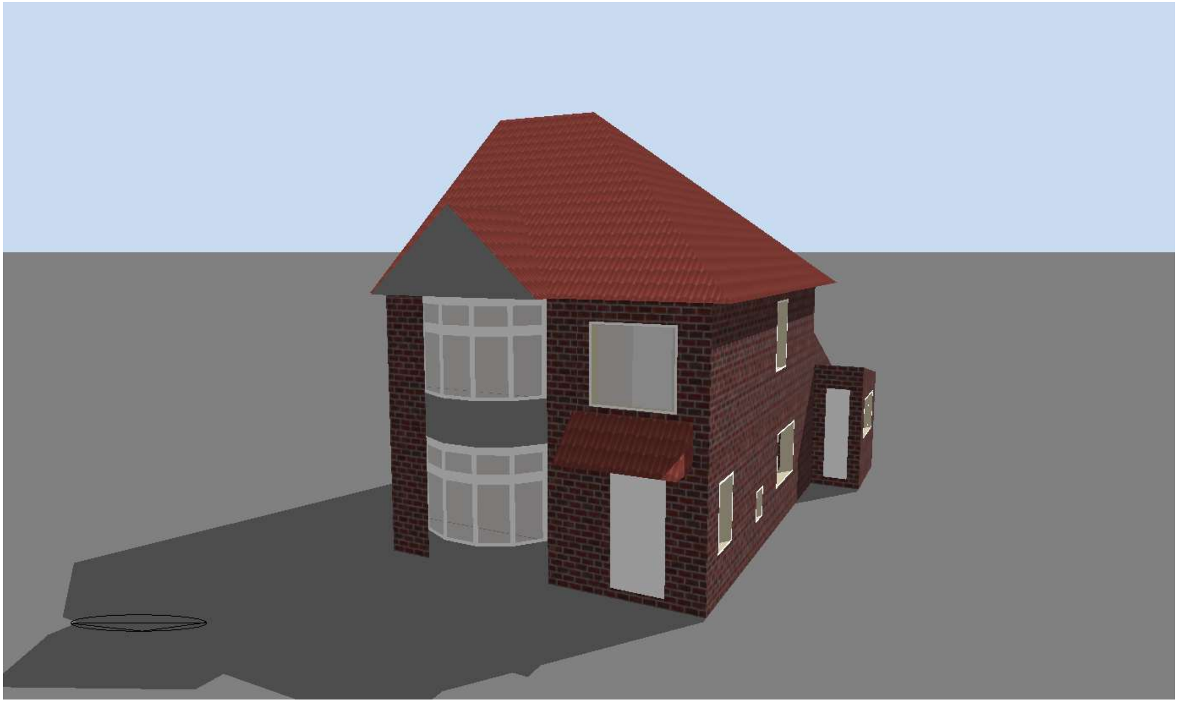

Figure 19. Test building "House Example 1".

The IDF was checked to ensure that it could be run correctly using a command line interface. The IDF that was produced by *DesignBuilder™* and the associated weather file was copied from *DesignBuilder™*'s working directory to *EnergyPlus™*'s program directory. A windows command shell was opened and *EnergyPlus™* was executed from within the *EnergyPlus™* directory.

There are a number of other arguments that are accepted when running *EnergyPlus™*, including a path to the input file (in.idf) and the weather file (in.epw); however, the programme looks for a weather file in the same directory as the executable file by default so running from within the program directory was the most expedient.

4.4.3 Testing Powershell commands

The process of running the differential evolution algorithm followed a similar process to the one that *jEPlus* uses to manage parametric analysis. The values of parameters of interest are replaced by searchable strings. The SADE algorithm then searches the input file and replaces the strings with values from the parameter space which are to be tested. The difference between the Monte Carlo method and SADE methods is that for Monte Carlo the values are selected randomly from a Latin hypercube, whereas SADE generates new values influenced by the success of previous simulations.

Powershell commands were used to execute *EnergyPlus™* from within *Matlab™* and to call the post processing program to produce the results file.

Once the string substitutions were made into the IDF, a simple check file was written using *Notepad++*. The check file was comprised of the series of searchable strings representing the influential parameters and the default values which should yield the baseline. The *Matlab™* script was used to substitute values for the variables using *Microsoft Powershell* commands. Checks were made that the script ran correctly by inspecting the resulting modified IDF.

Preliminary runs failed to execute correctly because the operating system delayed returning the revised IDF. This was fixed with a workaround to add a 5 second pause after each action in the *Matlab™* code.

There were some initial problems with obtaining a full year of test data. This was tracked down to the default setting in *DesignBuilder™* which was set to model the operation of the example building over the design summer period, instead of a full year. Once this was discovered and changed within *DesignBuilder™*, and the simulation re-run, a full year of baseline data was obtained for the test.

A remaining problem was that each time a *Powershell* command was given, a new command shell was opened but not closed. This led to a build-up of open command shells which needed to be closed manually once the script had completed. Eventually this was solved by calling *killtask.exe* after each *Powershell* operation.

There was also a problem with running the script in *Windows 7*. The script was developed on a *Windows 10* laptop which was in everyday use, but the intention was to run the SADE calibration on a *Windows 7* desktop which could be left doing simulations without being disturbed. When the test script was originally copied to the desktop computer, the *Powershell* commands didn't execute. When the desktop was upgraded to *Windows 10* the script ran correctly.

4.4.4 Generation of baseline data

A baseline of data was needed so that there would be something for the SADE program to check against. The SADE script could then be tested to see if it was capable of re-discovering the values that had been used in the generation of the test case. This was produced using the *EnergyPlus™* utility: *ReadVarsESO.exe*, which comes bundled with *EnergyPlus™*. *ReadVarsESO* is a post processing facility which enables users to process the output files from *EnergyPlus™* (eplusout.eso and eplusout.mtr) into a more usable form. The requirements for the new output file are saved in a file called eplusout.csv, which can be used as an input for the calculation of $CVRMSE_{hourly}$.

The results of simulation were copied in the *ReadVarsESO* post-processing directory and *ReadVarsESO* was used to compile the hourly energy consumption for the test model.

4.4.5 Changes to SADE *Matlab™* script

Changes to the GEV SADE script were made to adapt it to delete the GEV functions, execute *EnergyPlus™* simulations, post-process the results and evaluate the cost function ($CVRMSE_{hourly}$).

SADE simulations are run in populations which are grouped into generations. Once a defined population of simulations has been executed, the SADE algorithm is applied to the generation to produce a new generation which is used for the next population of simulations.

The SADE algorithm also requires a number of hyper-parameters to be estimated. These are:

- Initial ranges for parameter values;
- Population size (number of simulations in a generation);
- Number of generations (number of times the genetic algorithm is to be executed).

4.4.6 Testing the modifications to the SADE script

The process to check that the modifications to the SADE script were operating correctly was as follows:

- Produce a baseline model (as above);
- Nominate four influential parameters;
- Record the default values for the parameters;
- Modify the IDF by replacing the values of the influential parameters with searchable strings;
- Run the SADE algorithm to search for values of the influential parameters;

- Check that the values obtained by the SADE agree with the default values used to generate the baseline set.

The four initial changes that were made to the Input Definition File (IDF) are given in Table 23.

A test was run to check that the differential evolution algorithm was performing correctly. The test was set up with a population of ten running over ten generations. The simulations ran successfully and the test took 2 hours and 9 minutes to run.

The SADE search for the values used in the baseline are given in Table 22. The final value of $CVRMSE_{hourly}$ was -0.66%, so it was immediately obvious that there were some problems with the script. In addition, the SADE script produces a graph of the convergence of the cost function with the number of generations, which is given in Figure 20. The values are increasing, whereas the algorithm is expected to minimise the cost function and the values of the cost function are negative, which should be impossible. This demonstrated that the algorithm was not operating correctly, even within the limited bounds of the initial settings.

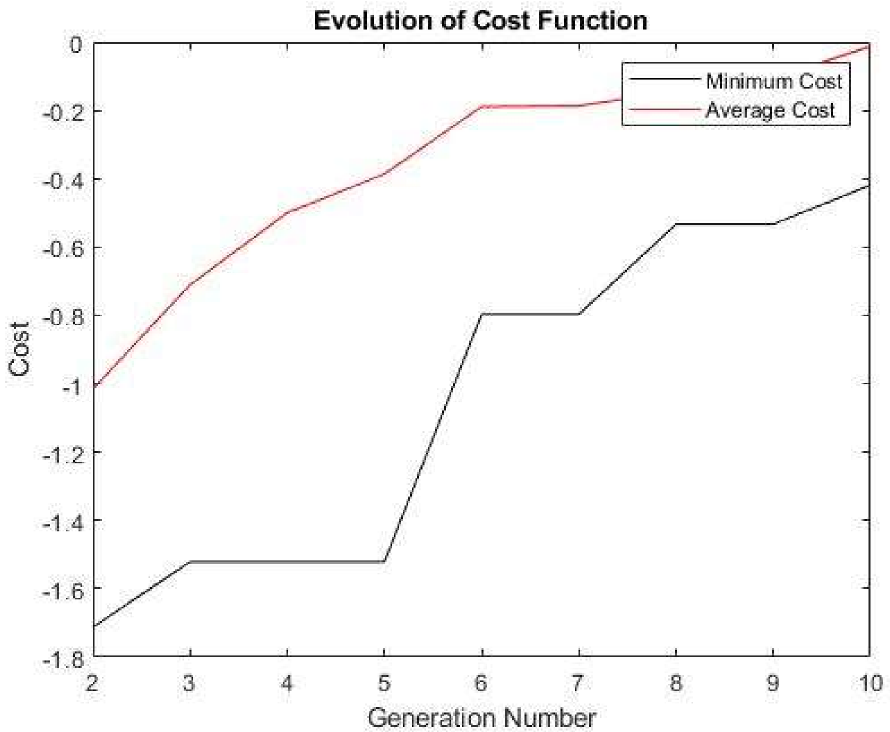

Figure 20. Convergence of CVRMSEhourly with generation number for the test of the modified SADE MatlabTM script.

Description	***Variable name***	***Comment in IDF***	***Original value***	***Search range***	***Final value***
Ground floor living room design lighting level	VARS1	! Watts per Zone Area	15	14 to 16	15.4813
Ground floor living room design equipment level	VARS2	! Watts per Zone Area	3.9	3 to 5	4.3851
Ground floor living room design ventilation rate	VARS3	! Natural Ventilation Rate	0.10453	0.05 to 0.25	0.0788
Design winter outdoor temperature	VARS4	! Max Dry Bulb {C}	-4.4	-5 to -3	-4.6228
$CVRMSE_{hourly}$			(0)		-0.658

Table 22. Results of initial testing.

A review of the code revealed that a flag for optimisation was set to maximise and that the script was selecting the incorrect column in an intermediate results file which was empty. This meant that the cost function was being incorrectly evaluated.

In the course of trying to find the source of the errors, a series of simulations were carried out to check that the cost function did not have peculiar characteristics. A sensitivity test was carried out on each of the variables. The cost function was found to behave independently to the two variables: *Ground floor living room design ventilation rate*; and *Design winter outdoor temperature.* These were substituted with two variables that were tested and confirmed to have an influence on the cost function.

The test was repeated with a broader range. Previous experience had shown that the population size for SADE should be 5 to 10 times the number of parameters that are being searched. Consequently, for four parameters the population size was set to 20.

Initially, a test of 10 generations was carried out to confirm that the corrections had correctly identified the bugs.

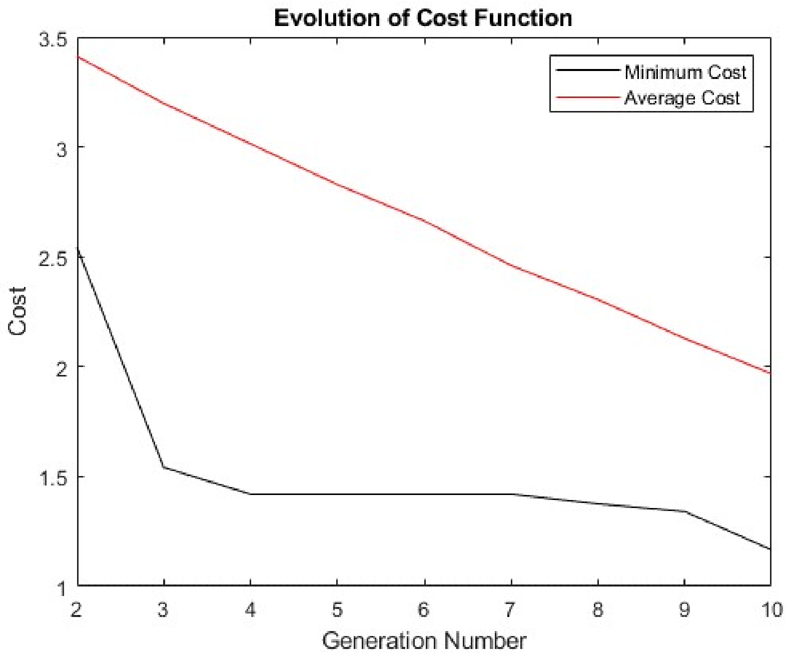

Figure 21. Successful convergence of the test simulations after 10 generations.

To enable a good comparison with the results from the previous chapter, which applied a search of up to 2000 simulations, the number of generations was set to 100.

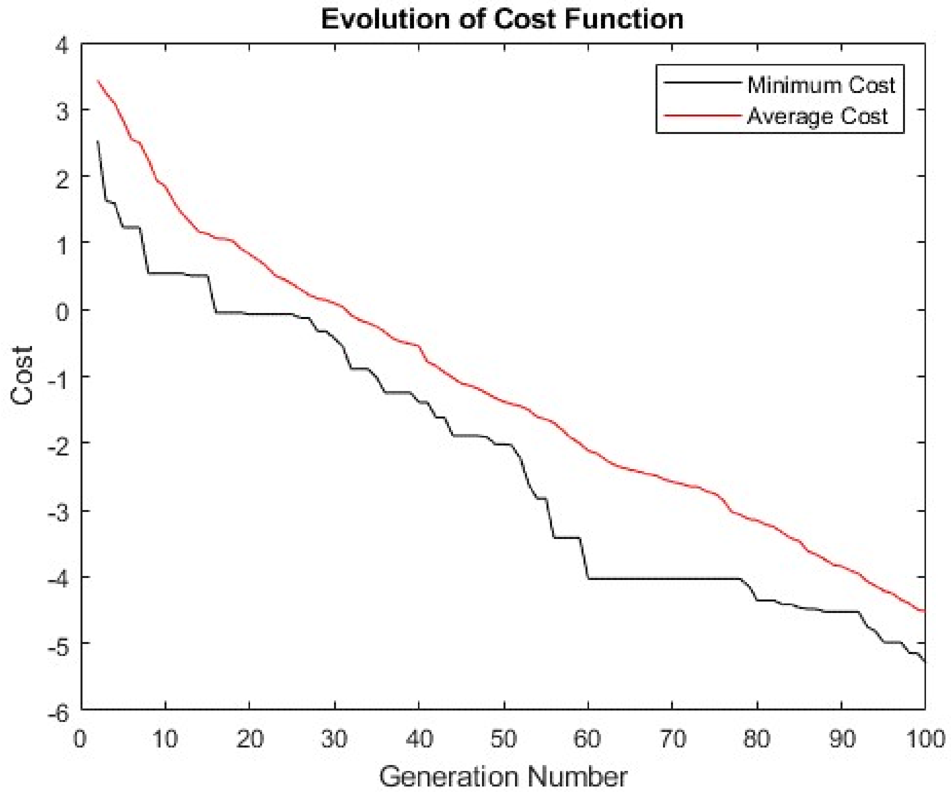

Figure 22. Evolution of cost function in final test.

4.4.7 Correct Operation of the SADE script on "Example House 1"

The values obtained while testing the SADE script agreed very well with values obtained from the preliminary simulation as shown in Table 23. This is important as it demonstrated that the script was operating correctly by being able to find the correct values of the variables from a global search.

One point which might result in some confusion, is that the graphs above show the cost function running into negative values. SADE is set to produce graphs with log values. In this case the cost function was not negative but was very small.

Parameter	***Original value***	***Final test range***	***Initial test results (10 generations)***	***Final test results (100 generations)***
Ground floor living room design lighting load	15	0 to 40	21.2017	15.0099
Ground floor living room design equipment load	3.9	0 to 40	0	3.8872
Kitchen add-on equipment load	2.16	0 to 40	0.0439	2.1705
Front bedroom equipment load	3.58	0 to 40	0	3.5775
$CVRMSE_{hourly}$	(0)		3.2079	0.0050

Table 23. Final Results of Testing Demonstrating Correct Operation of the SADE Script on the Test Model, Example House 1.

4.4.8 Application to Fitzrovia model

Once it was determined that the adapted SADE script was running correctly and calibrating the test model, House Example 1the *EnergyPlus*™ model of Number 8 Fitzroy St was applied.

The original model to be tested was produced using *DesignBuilder*™ 3.2.0 so the IDF was written in a format compatible with *EnergyPlus*™ 7.2.0.

A decision needed to be made as to whether to upgrade the model from *EnergyPlus*™ 7.2.0 to *EnergyPlus*™ 8.6.0. On the one hand, all the previous work had been carried out based on *EnergyPlus*™ 7.2.0. On the other hand, *EnergyPlus*™ had been rewritten from FORTRAN into C++ for *EnergyPlus*™ 8.6.0, which promised a significant reduction in processing time. Therefore, it was decided to attempt an upgrade.

The conversion of the IDF to *EnergyPlus*™ 8 was not straight forward. The first approach was to try to upgrade the IDF using *EP-Launch*. The IDF appeared to be upgraded without errors, however the simulation crashed due to fatal errors when any attempt was made to run a simulation. It was assumed that this was because of an issue with the reformatting utility so an attempt was made to go back to the original design model in *DesignBuilder*™ and use that to upgrade the IDF.

DesignBuilder™ 5.4 was used to update the original Fitzrovia model from *DesignBuilder™ 3.2,* but again the annual simulations failed to run. After some investigation, it was found that the latest implementation of *EnergyPlus*™ contained some improvements that meant that additional set point managers needed to be added to the model to replicate the control over the chiller and the boiler. These set point managers could have been manually added into the IDF, which was updated by *EP-Launch*; however, in the end it was easier to make the changes in *DesignBuilder*™. Once the additional set point managers had been added, the simulation executed successfully.

To be consistent with the previous work had been done using *EnergyPlus*™ 7.2.0, and despite the longer processing time, the decision was made to continue the analysis using *EnergyPlus*™ 7.2.0.

4.4.9 Greedy algorithm

A greedy algorithm is one that simplifies the search of the parameter space. The advantage is that the space can be searched more quickly, but the disadvantage is that it runs the risk of ignoring potential solutions.

Since the original design model was based on sensible assumptions, it makes some sense that a calibrated model would have values which are in the vicinity of the assumed values. The results of the sensitivity analysis provided a ranking of the parameters so the algorithm was designed to run with the most sensitive parameters being optimised first.

Since the algorithm had been shown to operate correctly for a search of four parameters, SADE was used to search the most sensitive parameters in groups of four up to twenty. This also has the advantage of following the Monte Carlo stepwise assessment of the number of parameters that needed to be included to achieve calibration.

4.4.10 Final SADE calibration runs

The Fitzrovia model was altered to include 20 searchable parameters over five models (four parameters per model). Initial ranges in the vicinity of the design values were specified for the parameters and a series of five optimisation were run. After each optimisation, the best values of the previous optimisation were substituted into the model for the next run.

4.4.11 Additional changes to script

Running the larger number of generations initially failed because *Matlab™* was proceeding with the analysis of results before the *PowerShell™* executable was finished running. The original script had a timer which allowed sufficient time for *EnergyPlus™* to complete a simulation and return a results file. The new Fitzrovia *EnergyPlus™* file took significantly longer to run and steadily increasing the timer became impractical. Eventually, the code was changed to include a timer and a loop which checked for a complete output file.

The handling of failed simulations was also improved. If an input into *EnergyPlus™* violates some internal error checking metric, the program will terminate and record a severe error. The *Matlab™* script was updated to handle the terminated simulations and the script then ran through the required number of generations.

4.4.12 Results of SADE calibration process

After 2,000 simulations, the SADE *Matlab*^{TM} script produced a lower $CVRMSE_{hourly}$ than any of the LHC Monte Carlo attempts, although the process did not yield a result which met the ASHRAE 140 criteria for calibration.

4.4.13 Convergence

When the script has completed a predetermined number of generations, it produces a graph of the cost function, which can be used to assess the proximity of the cost function to the overall minima. The graphs are contained in Figure 23 to Figure 27.

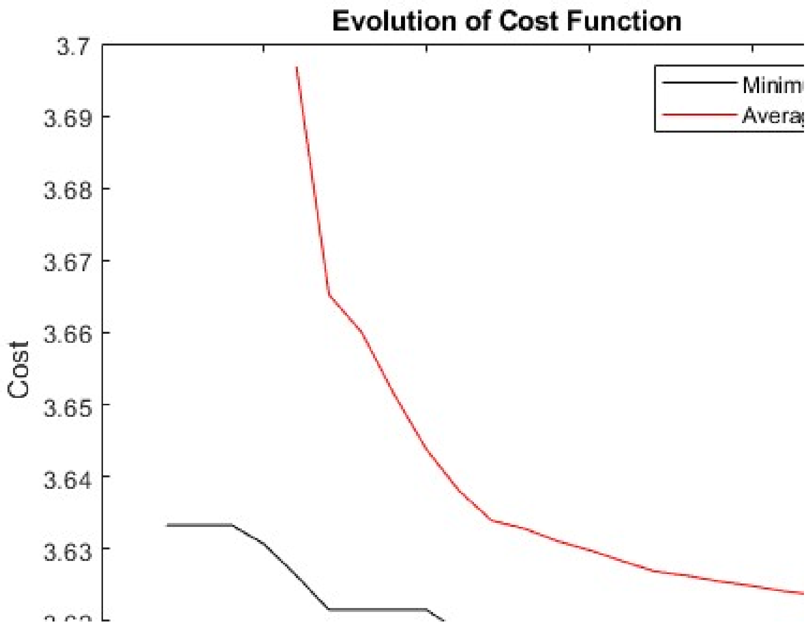

Figure 23. Results of Greedy SADE Optimisation on Variables 1-4.

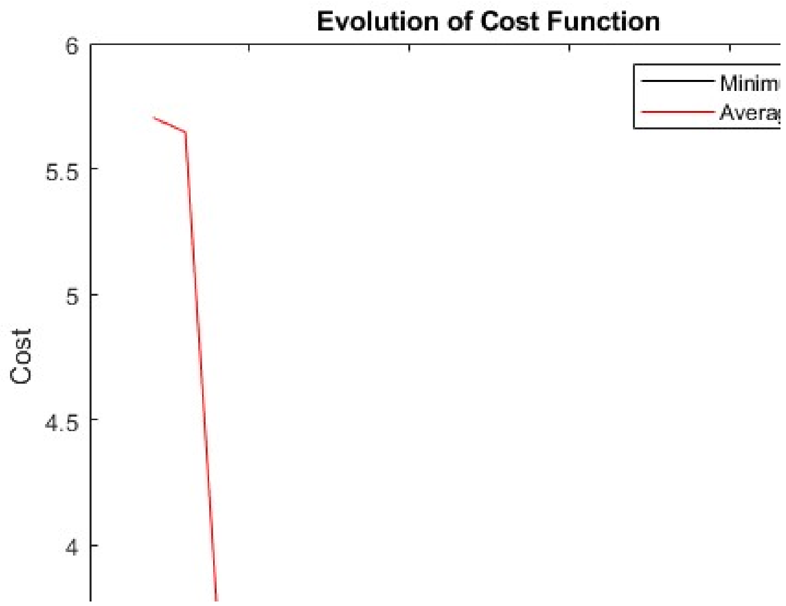

Figure 24. Results of Greedy SADE Optimisation on Variables 5-8.

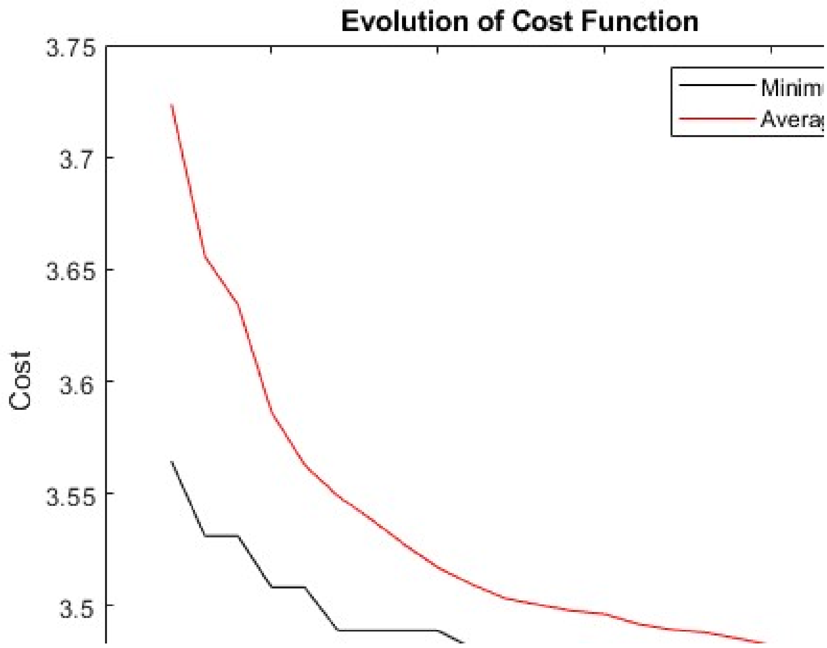

Figure 25. Results of Greedy SADE Optimisation on Variables 9-12.

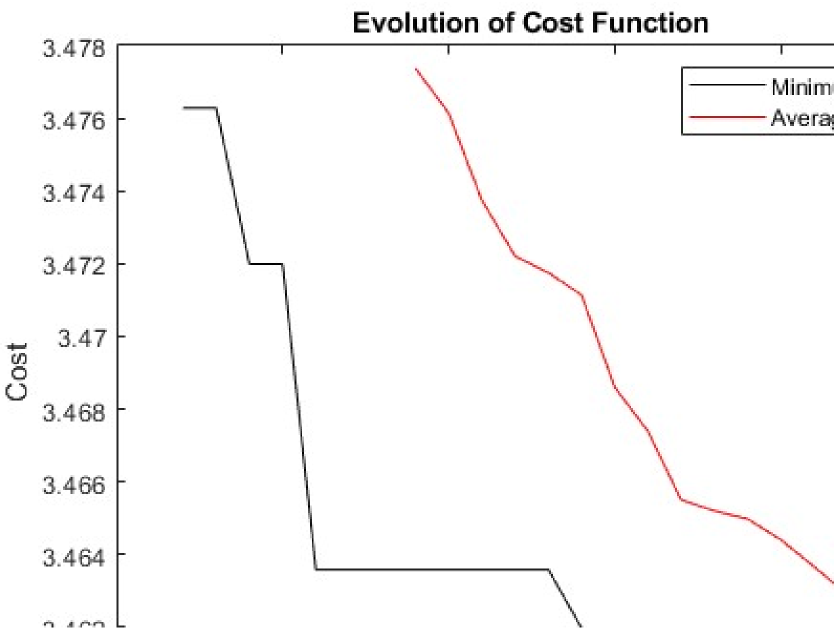

Figure 26. Results of Greedy SADE Optimisation on Variables 13-16.

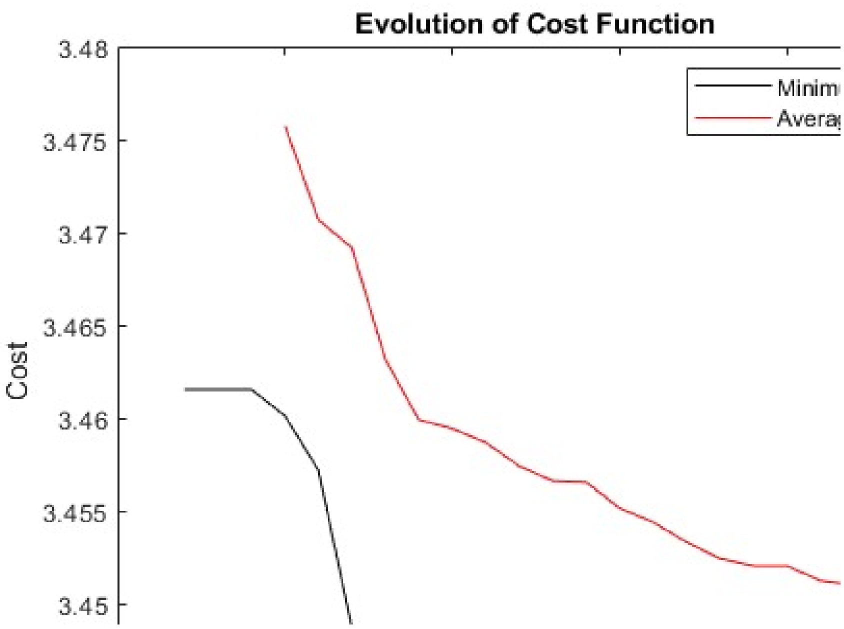

Figure 27. Results of Greedy SADE Optimisation on Variables 17-20.

The graphs show the average cost function and the minimum cost function for each generation. Where the two lines converge (Figures 24 and 25) the algorithm can be assumed to have found the minima. Where the lines do not converge the population contains solutions which are not yet optimal and there is room for further optimisation of the solution.

Despite the sensitivity testing indicating that the model was most sensitive to variables 1 to 4, the greatest gains were made by the optimisation of variables 5-8 as shown in Figure 20.

Overall the process produced an improvement in the value of $CVRMSE_{hourly}$, however the advantage of the SADE algorithm was small compared to the Monte Carlo approach.

4.4.14 Results

A comparison of values obtained for the Monte Carlo and SADE approaches are contained in Table 24 with the original design values for reference.

Parameter name in EnergyPlus^{TM} Input File	***Nominal Value***	***Monte Carlo***	***SADE***
Building fan efficiency	0.7	0.48	0.5
Zone cooling design supply air temperature	14	8.5	10
Building fan pressure rise (Pa)	600	935	1200
Sensible effectiveness at 100% heating air flow	0.65	0.48	1.0
Zone air distribution effectiveness in heating mode	1.0	0.50	1.0
Outdoor air flow per person (m^3/s.person)	0.008	0.0132	0.0137
Air cooled chiller biquadratic coefficient for y^4	0.046	0.024	0.023
Zone air distribution effectiveness in cooling mode	1.0	0.55	0.83
3rd Floor office electrical load (kW)	43.5	19.8	0
July ground temperature (°C)	18	20.9	40
1st Floor office electrical load (kW)	44.5	54.6	27.5
3rd Floor office number of people	217	255	0
4th Floor office electrical load (kW)	42.5	41.4	21.3
Wet bulb or dew point at maximum dry-bulb	18.6	16.2	40
5th Floor office electrical load (kW)	36.5	37.8	28.6
Air cooled chiller biquadratic minimum value for y	24	35	32.5
Ground floor office electrical load (kW)	36.6	30.0	14.1
Air cooled chilller minimum unloading ratio	0.25	0.59	0.31
4th Floor office number of people	212	428	0
1st Floor office number of people	222	341	493

Table 24. Comparison of assumed values and values found by 20 parameter Monte Carlo and SADE optimisation processes.

The results in Table 24 reveals some anomalies. In the SADE search, some of the values for the parameters have converged on unlikely values. From an engineering viewpoint, the zero values for occupancy of the Third and Fourth Floors, and the 40°C values for the outdoor ground temperatures are not credible. However, the modelling and calibration processes are robust and their correct operation has been demonstrated using a rigorous process.

The explanation for these apparent anomalies values lies in the nature of the modelling process itself. The model is only a representation and the decision to do the optimisation without measured weather data or occupancy schedules has resulted in an underdetermined system. This leaves room for the optimisation process to find values that compensate for the error in the model.

It might be argued that proceeding on this basis was a fool's errand, but the fact that the final results are so close ($CVRMSE_{hourly}$ = 31.4, compared with 30.0 to be considered calibrated), to producing a fully calibrated model should serve as a warning. Where these models are used as the basis for financial models, then this type of deterministic approach could be used to bend the results in the favour of one of the parties.

4.4.15 Conclusions from Differential Evolution Case Study

Self-Adaptive Differential Evolution (SADE) has been shown to be marginally more effective than Latin Hypercube Monte Carlo (LHMC) for searching the parameter space for optimal values which would enable a model to be considered calibrated. While the *EnergyPlus™* model was not able to be calibrated the final result was very close to the ASHRAE 14 value of $CVRMSE_{(hourly)}$ of 30.

Chapter 5 Discussion and Conclusions

5.1 Background

The background chapter of this thesis explains that there is overwhelming evidence that the production of greenhouse gasses, including carbon dioxide in particular, is due to human influences. Greenhouse gases are causing changes to the climate including an increase in average surface temperature. It is imperative that the global production of carbon dioxide is rapidly reduced.

Buildings are responsible for the production of around 35% of global carbon dioxide. Reduction in the carbon dioxide produced by buildings can thus have a significant impact on the total carbon dioxide produced.

In many countries, building energy modelling plays a significant role in the design and refurbishment of buildings. Many design decisions are made based on the results of these models. Better models would result in a sounder basis for decisions.

The energy simulation of buildings is an imperfect science. Where engineers lack the detailed information to produce a credible model, they rely on practice knowledge to make assumptions that inform the models. By studying the results of computer models and comparing them with measured data, engineers can learn to make better assumptions.

The increase in available computational power allows multiple energy simulations to be run and the use of optimisation to both improve designs and help calibrate models. Designers can test a range of designs. In mathematical terms, the designer can use computer models to search the space of design variables, which will enable them to best satisfy the design problem being studied. In this thesis, a number of optimisation techniques have been applied to improve the quality of results from building energy models.

5.2 Literature review

A comprehensive literature review was conducted to examine the current state of the art in the application of optimisation to building energy modelling.

The literature review shows that optimisation in building energy modelling has the following two main applications; these are:

- Design stage optimisation: the comparison and selection of design alternatives to best satisfy the constrained objectives of the design team.
- Model calibration: the revision of models to minimise the divergence between the predictions of design models and the data obtained from buildings in use.

While the idea of design stage optimisation has been around for some time, there has been a lack of accessible design tools to facilitate a systematic approach. *EnergyPlus^{TM}* is a building simulation engine developed by the United States Department of Energy (DOE) to predict a range of values useful to building designers and which is well tested in the academic literature. *DesignBuilder^{tm}* software provides a Graphical User Interface (GUI) and an interface for running *EnergyPlus^{TM}* simulations. *DesignBuilder^{tm}* has recently included an optimisation tool which uses a Non-dominated Sorting Genetic Algorithm 2 (NSGA2) to inform the selection of design parameters using optimisation. However, there has been a clear lack of case studies which demonstrate that the application of rigorous optimisation using building energy models is worth the engineering commitment involved with their application.

This gives rise to the first research question in this study:

> *"Is the use of DesignBuilder^{TM}'s NSGA2 optimisation tool worth the time and effort that is required to model and optimise a building energy model?"*

As has been shown in this thesis, the answer to this question has been clearly answered. The engineering time required to produce a building energy model and compile the necessary costing data is more than offset by the savings identified by optimisation.

Calibration of building energy models is essentially the minimisation of some quantification of error between the predictions of the building energy model and measured data obtained from a building in operation. It is an optimisation problem where the engineer is seeking to optimise the selection of parameters to be used in the model, in order to minimise the divergence.

The literature review reveals there is a clear broad scholarly output on the calibration of building energy models, with the methods falling into three basic categories.

- Heuristic methods rely on the engineer's knowledge and understanding of buildings and the influence that parameters describing the building have on the output from the models. Models are calibrated by using additional data from the building in use to revise the model.

- Deterministic methods treat the problem as a mathematic exercise in which the input parameters to the building energy model are assumed to be represented by an input vector and the suitability of the result can be measured by a cost function. The calibration is a search of the input vector space for the optimum input vector.
- Stochastic methods treat the performance of buildings in terms of the statistics surrounding the input and output vectors. Statistical distributions are assigned to the input parameters and these distributions are propagated through the building energy model. Bayesian statistics can then be applied to the results to optimise the selection of the optimal input vector and bread the output prediction vector.

The application of these methods has been studied by a number of authors with varying degrees of rigour. One of the main problems with many of the papers reviewed is a lack of an agreed measure to determine if the building energy model is sufficiently calibrated. It could even be argued that failing to quote the degree of calibration to an agreed metric is a means of obfuscating poor results.

In energy performance contracting, those seeking to fund changes to a building by demonstrating savings via a building energy model can use a model which has been agreed with a body representing funding agencies. The American Society of Heating and Refrigeration Engineers (ASHRAE) has published *Standard 140-2017 – Standard Method for Test for the Evaluation of Building Energy Analysis Computer Programs*, which quantifies suitable measures for calibration in terms of Normalised Mean Bias Error (NMBE) and Coefficient of Variance of Root Mean Square Error ($CVRMSE_{hourly}$). Compliance with ASHRAE 140 would be a suitable method for assessing the degree of calibration of a building energy model or cost function in optimisation terms.

The research question associated with this work was:

> *"Which of the calibration methodologies is best suited to application by engineers who are working in practice?"*

5.3 Optimisation in early stages of design

Early design stage decisions often have substantial impact on the overall cost and operating efficiency of a building. *DesignBuilder*^{tm} enables designers to construct a Pareto curve which represents a range of optimised solutions, which can be used to inform a building development team of the best practical options to develop. Designs that have been developed without access to optimisation tools can be refined and improved to increase energy performance for a given construction cost, or reduce cost for a given energy performance.

Case studies can offer substantial evidence which can be used to demonstrate improvements in the methods of engineering practitioners. A case study using *DesignBuilder™*'s application of NSGA2, was used to show that savings, which were far in excess of the cost of the optimisation process, would have been able to be made if the process had been used in the early design phase.

Another case study used the Northampton University building *Creative Hub*. This is a novel application of optimisation, as this building had not previously been optimised using NSGA2. Optimisation studies are limited by computer processing power. Compromises in the level of detail in the building energy model needed to be made to enable a study to be carried out in a practical timescale.

The optimisation process cannot be carried out in isolation from external influences. Where the optimisation problem might be described as finding the minimum cost for a range of energy demand targets, the possibility of space overheating needed to be considered. In this test case evaluation, the requirements of TM52 were able to be incorporated into the optimisation process.

This thesis shows that the implementation of the optimisation process required a multidisciplinary approach. In particular, information was required from: mechanical engineers who described the Heating Ventilation and Air Conditioning (HVAC) requirements; electrical engineers who described the lighting and general power requirements; and quantity surveyors who provided a range of costs for construction options. Glazing information also needed to be obtained from facades engineers.

The process of reviewing a preliminary design in detail and producing a building energy model revealed some shortcomings in the existing design, which were not due to the implementation of optimisation *per se*. However, it is evident that design scrutiny will yield results.

The non-optimised (reference or base case) solution was found to be relatively energy efficient. When plotted on the output from the optimisation study with energy efficiency on the horizontal axis and cost on the vertical axis, the base case was not far to the right of the Pareto efficient solutions. However, the base case was substantially above (more expensive) than the Pareto curve, which indicated that substantial savings could have been made without sacrificing energy efficiency.

The capital cost savings that could have been made without sacrificing energy efficiency were estimated at £400,000. This compares very well with the consultancy cost of constructing an additional building energy model and providing the detailed costs for the various design options which was around £15,000. It should also be noted that as constructing and running the model is repeated, the process is likely to become more refined, which would result in lower costs.

While this result is an isolated case study, this is a substantial finding. Demonstrating these potential savings could change the way early stage design is conducted.

5.4 Building Energy Model calibration

Early stage design is not the only application where optimisation can be useful. This thesis has shown that optimising the values that define a building energy model of a completed building could be useful. In the second part of this thesis, a series of representative calibration processes were compared for suitability in a commercial environment.

5.4.1 Heuristic calibration

A new building energy model was constructed using *DesignBuilder*^{tm}. The model was not able to be calibrated, but the construction of the model and investigation of the *EnergyPlus*^{TM} files created by the software, enabled the author to become proficient with the software. On site checks of the model revealed changes to the building layout that were not recorded on the “as-built” drawings.

The work of this thesis shows that the building energy model of the Swansea University’s *Institute of Life Science Building 1* (ILS1) could not be calibrated because of the loss of data which resulted from a crash in the Building Management System’s server.

The BMS system was not fit for the purpose of calibrating a building energy model because:

- The data collection system was not robust enough to restart the collection of data after a system crash;
- No-one checked the operation of the BMS, which also meant that a number of heating and cooling water control valves were permanently driven fully open or fully closed.

In the execution of the work of this thesis, the database of the ILS1 BMS logs was found to be able to be interrogated using SQL to obtain information on the operation of the building without interference in the operation of the building.

Despite early checks that the database was recording correctly, when an attempt was made to retrieve information after a year of operation, the BMS had stopped recording after only four months. Since a full year's data on energy consumption was required to provide a calibrated model, the data obtained were not suitable for the calibration of the building energy model.

In addition to the cessation of data collection, there were periods where the data were only recorded late in the collection period and other periods where data were missing or *"dropped"* from the records; with these events often coinciding.

While the data obtained are not suitable for use in the calibration of a building energy model, the work carried out showed that there were a number of interesting trends that could have been investigated in future academic work, or to improve the performance of the building. A close examination of the data revealed that several points were recorded at 100% and others which had long periods at 0%. These data corresponded to the set points for control valves providing cooling and heating to individual spaces. There are a number of possible explanations, but the most likely is that there was a control valve which was stuck open (for example: on the heating circuit) and that the corresponding valve on another circuit (for example: on the cooling circuit) had been driven fully open in an attempt to maintain the room temperature set point.

The new evidence presented in this thesis that "using building management system data in the calibration of a building energy model was not practical", supports anecdotal evidence from experienced building services engineers.

This thesis contains practical lessons which are useful for future investigations. The most important (and perhaps obvious in hindsight) is to regularly check that the metering system is continuing to record data. A procedure for retrieving, interrogating and processing data from a *TAC Vista* BMS was developed during this study, which could be applied in future work.

From the work carried out it is obvious that buildings involve complex control operations and they do not necessarily operate as designed. Therefore, there is a clear finding that using BMS data collection using the system installed at the ILS1 could not be relied on for the calibration of a building energy model.

This work also reinforces findings (Bordass and Leaman, 2005) that post occupancy assessment is underutilised in modern construction practices. Building owners and operators should insist that their buildings are fully tested, including data acquisition and storage equipment.

5.4.2 Sensitivity Analysis

Treatment of the calibration of a building energy model as a purely mathematical exercise opens up a range of algorithms which are available to be applied.

From the literature review, it was noted that deterministic calibrations typically begin with a sensitivity analysis to refine the number of variables which it is practicable to optimise.

The case study of Arup's London building, Number 8 Fitzroy St., obtained data on energy consumption. A building energy model was constructed, again using *DesignBuilder*^{tm} software, so that an *EnergyPlus*^{TM} model could be produced.

Initial checks confirmed that the energy consumption data and the predictions of the model agreed to some extent, but an evaluation of the $NMBE_{hourly}$ and $CVRMSE_{hourly}$ confirmed that the initial model was not calibrated.

An initial count of the number of variables in the *EnergyPlus*^{TM} Input Definition File (IDF) was around 2000 individual variables. Of these, about 500 variables were data on the properties of glazing options, which were available for use in *DesignBuilder*^{tm}, but were found not to be necessary to the correct operation of the building energy model.

The literature review also revealed that other researchers had used annual energy consumption in their sensitivity analysis, so an initial sensitivity analysis was carried out to find the parameters which had the most influence over annual energy consumption. With a 20% variation of input value, there were 50 parameters that had an influence over annual energy consumption of greater than 1%.

However, the objective in calibration is not to reduce annual energy consumption, but to reduce the divergence between modelled and measured predictions. A novel approach was to carry out a sensitivity analysis which measured the impact of input values on $CVRMSE_{hourly}$ and $NMBE_{hourly}$ rather than annual energy consumption. The research question: *"Does carrying out sensitivity analysis based on* $CVRMSE_{hourly}$ *or* $NMBE_{hourly}$ *produce a different order in the sensitivity of modelling parameters from annual energy consumption?"* was investigated.

This thesis identified the novel finding that there is a clear difference in the impact of the input variables if $CVRMSE_{hourly}$ or $NMBE_{hourly}$ is used as the cost function, compared to annual energy consumption. There was also a difference in impact between sensitivity based on $CVRMSE_{hourly}$ and $NMBE_{hourly}$, and later work revealed a low value of $CVRMSE_{hourly}$ would be harder to achieve and so is more appropriate as a cost function.

It can be concluded that, based on the sensitivity work carried out in this thesis, the calibration of building energy models should use $CVRMSE_{hourly}$ or $NMBE_{hourly}$ as the basis for evaluating the impact of building energy model parameters, not annual energy consumption.

5.4.3 Deterministic Calibration

The work of this thesis isolated a set of the most 20 influential parameters from a new building energy model, based on their influence on $CVRMSE_{hourly}$.

Computer simulation time was found to have a significant impact on the number of options which could be evaluated in a commercial environment. With a simulation time of around 15 minutes each, around 2000 Latin Hyper Cube (LHC) Monte Carlo simulations could be made over a period of a few days on a 4-core i7 desktop computer running eight hyperthreads. Obviously a more powerful machine would be able to run more simultaneous simulations, but the timescale would only improve by around a factor of six for a 24-core machine running 48 hyperthreads.

A series of simulations were carried out to determine if there was a minimum number of parameters that could be optimised within 2000 simulations. A novel finding was that as the number of parameters used in the simulation increased, the minimum value for $CVRMSE_{hourly}$ obtained from 2000 LHS Monte Carlo simulations fell as solutions were found which better fitted the metered data. At the same time the $NMBE_{hourly}$, which had satisfied the requirements of ASHRAE 140, rose and fell but remained within the 10% limit.

The $CVRMSE_{hourly}$, which started out at around 42%, fell to a limit around 32% after ten parameters were included in the 2000 simulations.

When more than ten parameters were included, the $CVRMSE_{hourly}$ rose and fell but did not drop below 32% after 2000 simulations.

Another ad hoc group of simulations was also conducted using ten parameters, but with 5000 simulations. Again, the $CVRMSE_{hourly}$ did not drop below 32%. This does not represent a large improvement in calibration.

5.4.4 Differential Evolution

A new self-adaptive differential evolutionary (SADE) algorithm was applied to an *EnergyPlus™* building energy model. A new test procedure based on a *DesignBuilder™* template was developed, which after some preliminary problems showed that the algorithm operated correctly.

A greedy application of the SADE algorithm found better solutions to the calibration problem than the LHC Monte Carlo approach. After 2,000 simulations the best LHC Monte Carlo approach found a $CVRMSE_{hourly}$ of 32.0%, whereas the SADE algorithm found a value of 31.4%. This difference is small and indicates that both methods identified solutions that were around the limit that was able to be achieved without making changes to the occupancy schedules or weather files.

While both of these results are tantalisingly close to the $CVRMSE_{hourly}$ of 30% required under ASHARE 140, the results of this research cannot be used to claim that a building energy model was able to be calibrated through a purely deterministic process.

5.4.5 Wider Implications of the study

Data collection systems of the type installed at the Swansea ILS1 need to be more robust to be able to collect and store data for the purposes of building energy model calibration. Data servers are not 100% reliable and data collection systems need to be able to protect data in the case of a crash and resume data collection automatically on restart.

Site engineers need to be vigilant about the collection of data. Data needs to be checked regularly for cases which might indicate system faults such as stuck valves.

The commissioning and handover of buildings remains an important and often overlooked stage in building construction. Professional bodies need to prioritise the engineering resources allocated to early years of the operation of the building to diagnose operational problems and collect accurate and complete data.

Both Monte Carlo and SADE deterministic approaches to calibrating building energy models can be used to manipulate input variables. This study has shown that there is flexibility to redefine input values using sophisticated algorithms for the calibration of a model, which opens a vulnerability to exploitation. In other words, the input parameters of a building energy model can be manipulated to fit the constraint of producing a calibrated model. It follows then, that it should be possible to add constraints such as maximising profitability. Where the building energy model is to be used as the basis of a payment system, such as privately funded public buildings, then the funding authorities need to be alert to the potential for the manipulation of such models.

5.5 Future Work

This research has laid a foundation for future work in a number of applications.

5.5.1 Application of Non-dominated Sorting Genetic Algorithm 2

The finding that NSGA2 could be productively applied to early design stage work is a significant finding and can be used to demonstrate that, where resources are applied to the optimisation of designs, the resulting savings can more than pay for the design effort required to carry out the optimisation. However, the building services industry is slow to adopt new technology and further case studies are required to strengthen a rationale for making this type of optimisation routine.

5.5.2 Institute for Life Science Building 1

While the results of the investigation into the use of BMS data for the calibration of building energy models was disappointing, the discovery of data indicating incorrect operation of the building warrants further investigation. Academic work should focus on the process of implementing systems for the recording and retrieval of operating data.

Commercially, there is work to be done to ensure the correct operation of the building. The data that was able to be collected indicated a number of potential failures in the operation of the building. These need to be worked thorough rigorously, diagnosed and remedied.

5.5.3 Northampton Creative Hub

The Northampton Creative Hub was completed in 2017 and has had three years of operation. A study should be undertaken to compare the operational performance of the building against the original design predictions.

5.5.4 Monte Carlo Sensitivity Analysis

It is clear that the Monte Carlo sensitivity analysis based on CVRMSE used to determine the order in which the Monte Carlo and SADE algorithms yields additional information, has not been fully exploited in this study. Both the Monte Carlo and SADE procedures each require an initial range, which will yield the lowest value for the cost function to be discovered. The best value from the Monte Carlo sensitivity analysis was used to inform the ranges for the Monte Carlo approach, but were not employed for the SADE search.

The next stage in future research, would be to create a tool to automatically interrogate an EnergyPlus input file, identify and parameterise key values, and run a Monte Carlo sensitivity analysis.

5.5.5 LHC Monte Carlo Calibration Process

The LHC Monte Carlo approach was useful because it provided a benchmark for the effectiveness of a search with only 2,000 simulations. Monte Carlo is more effective when very large numbers of simulations are possible. In this application, SADE was a more effective search tool, but there is much work to be done to refine and apply the process, which is discussed in the following section.

5.5.6 Self-Adaptive Differential Algorithm Process Development

In future work, SADE should use the results of the Monte Carlo sensitivity test to determine suitable initial ranges.

There will always be room to apply these optimisation scripts in different ways. The hyper-parameter approach, which was used to develop differential evolution into SADE itself, needs to optimise:

- The number of parameters in the greedy application;
- The population size in each generation;
- The number of generations required to converge on an optimised solution.

There is differing informal advice on the selection of these values, which will only be determined rigorously as experience in applying SADE grows.

The *Matlab*™ script employed in this study is unreliable and does not make good use of the parallel processing that is available in modern PCs. Immediate changes to the script would include:

- Recording of all the values in the most recent generation so that if the script crashes (as often happens), the script can be restarted from the last successful complete generation, rather than re-starting the search from the beginning.
- Parallel processing so that more of a population of simulations that are carried out in each generation are executed simultaneously, rather than in series, as is done in the current implementation.

In the longer term, it would be sensible to develop SADE into a format, perhaps similar to jEPlus, to enable the power of the optimisation process to be applied to a wide range of analytical programs. SADE should be rewritten in a more robust programming language like Python, Java or C.

5.5.7 Implications for the building services consulting industry

Optimisation has the potential to significantly improve building design and building energy model calibration.

Savings in building costs due to optimistaion have been shown to greatly outweigh the cost to carry out optimisation studies. Building services engineers should work with quantity surveyors to define and quantify useful design parameters. Engineers should use modern optimisation software to produce building services designs that are energy efficient and make best use of the resources available.

Where building models are required to be calibrated, optimisation techniques such as SADE should be used to refine model parameters.

5.6 Reflection on PhD process

Undertaking research into “real-world” building design and performance is challenging. Assessing data is problematic, many clients do not want their buildings to be investigated and data is often missing or erroneous even when access is allowed. Buildings are just not a tightly engineered product. This difficulty in collecting empirical data has led researchers to focus their efforts on purely theoretical modelling, particularly in the non-domestic sector. This in turn has led to an increasing performance gap between modelled and measured performance.

Research requires balancing the aspirations of answering research questions with the resources available. The two biggest challenges were finding time to conduct and document the research and obtaining computing resources to carry out the optimisation processes. The conflicting demands of working as a consulting engineer and carrying out doctoral research meant that the research was spread over a greatly extended timescale, but meant that more reflection time went into selecting an appropriate course of research. Similarly, the lack of processing capacity meant that time was spent trying to assemble a Beowulf cluster, which further delayed obtaining results. The limited processing capacity gave additional impetus to finding an optimisation method that could be executed most efficiently.

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Appendix A Multi-Objective Optimisation in Early Stage Design. Case Study: Northampton University Creative Hub Building.

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Multi-Objective Optimisation In Early Stage Design. Case Study: Northampton University Creative Hub Building

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Abstract

The aim of this paper is to investigate optimum design options for the early design stage of a building that would not only result in achieving low carbon status, but could also have a reduced construction capital cost.

During the last decade, there has been an increasing interest in using optimisation algorithms in the building design process. However, in real-world building design complications, the optimisation problem consists of at least two conflicting objectives, e.g. minimising energy demand whilst keeping the construction cost low without compromising the user's comfort. In this case study, a commercial variant of the well-known genetic algorithm NSGA II was used to identify a set of optimal solutions. DesignBuilder software was utilised to create the base model and run the multi-objective optimisation, with two objectives; energy consumption and capital cost.

The optimisation results represent the design balance between capital cost and energy consumption. The design solutions that help maintain the comfort performance have been derived from a rationalisation exercise that was undertaken prior to this study and aligns thermal comfort with a defined industry guidance including minimising the quantified risk of overheating and excessive energy use for cooling.

Introduction

In order to achieve the 80% CO_2 reduction target by 2050, the UK government has signed and is legally bound by the UNFCCC Framework and Kyoto protocol agreements. In addition, the UK is forced under the EU proposal Directive to a 20% more energy efficient building infrastructure (Grubb et al., 2008).

The building sector is the largest user of energy in the European Union. Hence, the need to improve the design of new buildings is critical. In the UK, according to the national statistics (DECC, 2014), 30% of the energy consumption and 35% of the total electricity was consumed within the buildings sector.

Passive strategies, energy efficiency methods and innovative building services technologies, are well discussed and established within this research field. However, the decision making process to identify the best combination that would result in the best possible scenario is not a straightforward practice. There are numerous features, which need to be harmonised, such as: financial, social, legal and energy & environmental etc. (Asadi et al., 2012).

There is evidence in literature that the early stage design decisions for new builds will highly influence the building performance over at least the first 50 years of their lifetime (Negendahl et al., 2015).

In the building performance modelling research community, the term 'optimisation' has a different meaning to different researchers. The optimisation exercise is either treated as a technique to find a global optimum to a defined problem through sensitive and qualitative analysis alone (Heiselberg, 2009) or it is performed by implementing a numerical simulation and mathematical optimisation to derive the optimal solution to an objective problem (Nguyen, 2014). Furthermore, optimisation problems can be categorised as one-dimensional or multi-dimensional optimisation, depending on the number of design variables in action.

In this research work, optimisation is considered as a combination of a qualitative and quantitative analysis – rationalisation that leads to an automated process, which is entirely based on numerical simulation and mathematical optimisation. This method is usually automated by the combination of a building simulation program and an optimisation "machine" which contains an optimisation algorithm.

In particular, the authors approach is following the multi-objective optimisation that is proposed by Pareto. A solution is non-dominated when there is no other feasible solution that advances one objective without weakening the other one. The multi-objective algorithm product is a set of non-dominated solutions that is termed 'Pareto Front' (Machairas et al, 2014).

The Case Study Building

The University of Northampton located in the United Kingdom (UK) is in the process of extending its campus to include six additional buildings as shown on the architectural master plan in Figure 1.

Figure 1: Architectural master plan of the development. University of Northampton campus layout and selected building location.

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The design for the buildings had been developed to RIBA Stage 3, where upon completion, a contract for construction is issued typically based on competitive tender. The design then underwent a value engineering exercise to attempt to reduce the project capital cost to align with the client budget. This presented an excellent opportunity to undertake a case study of the application of a parametric optimisation using the updated DesignBuilder software. Of the six buildings, a medium sized multi-function building, The Creative Hub, was selected for this case study.

The Creative Hub at the University of Northampton is a five-story building with a floor area of 10,000 m^2; a 3D Revit generated design model representation is shown in Figure 2. The building architectural scheme reflects a variety of spaces, including breakout spaces, teaching facilities, rehearsal and performance spaces, as well as functional circulation and services spaces.

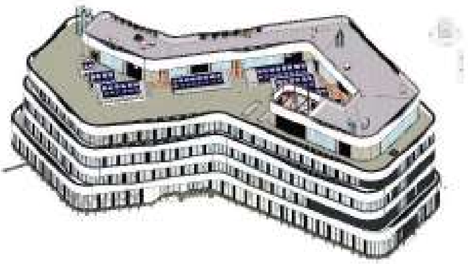

Figure 2: Creative Hub building 3D model.

Since the case study building is located in the UK, the design must comply with Building Regulations including Approved Document Part L2A (Building Regulations 2010). The building is also targeting an Energy Performance Certificate (EPC) rating of "A". The Target Emission Rate (TER) has been derived based on a dynamic model as 18.0 $kgCO_2/m^2$ while the resulting Building Emission Rate (BER) is 14.6 $kgCO_2/m^2$ which also reflects a predicted "A" rating for the EPC. In addition, The Creative Hub building is required to achieve a Building Research Establishment Environmental Assessment Methodology (BREEAM) rating of "Excellent".

The Optimisation Methodology

A thermal model was developed for the simulation of the energy consumption of the building and it is defined by parameters that represent physical aspects of the building. Variable values for those parameters were used to define building fabric construction, services, and operation of the building.

In order to explore a very large number of building variants in a relatively short time, the implemented approach contains the following:

(i) identifying the design variables to be optimised

(ii) describing the options and the range of variation for each parameter

(iii) running the energy simulation of the building in free-running mode using a simulation tool

The energy simulations of the building were run with the software EnergyPlus version 8.5 (Crawley et al, 2001) using DesignBuilder version 5.0.1.024 as an interface.

The optimisation run was achieved by using the DesignBuilder software through the non-dominated genetic algorithm NSGA-II (Deb et al., 2002). The optimisation module utilises an advanced evolutionary algorithm analysis platform to assimilate building performance design variables through a natural selection process to meet the design objectives. The optimum design solutions are identified and inherited to subsequent generations and continue to do so until the optimum design synergies have been determined based on the design constraints applied. In order to build up the optimisation run, the steps include:

(i) specifying the design variables, their variation ranges and the optimisation algorithm

(ii) examining the variants that minimise capital cost, considering the objective functions related to energy performance

As previously mentioned, one of the key steps in the optimisation process is to select parameters that represent aspects of the building design that would benefit from optimisation and a suitable range of variables that should be applied to those parameters (Fesanghary et al., 2012). In this study, a team of academics, engineers and quantity surveyors carefully selected design options translated in kWh/m^2 and £/m^2 for the following parameters:

1. External wall and roof construction
2. Glazing
3. Lighting system
4. HVAC (Heating Ventilation and Air Conditioning) system
5. Shading strategy

In combination with the following limitations:

a. The shape of the building and the façades to be retained as specified by the architect.
b. The layout of the building to be simplified by merging similar activity zones to decrease the computational time.

Design Variables

Within the optimisation function of DesignBuilder, the overall cost is based on the construction cost. This estimation is based on market prices in July 2016, and implemented into the software by the authors. This cost value includes the supply of materials and labour cost for installation with an additional contingency percentage, but excludes the main contractor's preliminaries, overheads, profit, design fees and VAT.

Rationalisation Prior to Optimisation

One of the main attractions of optimisation is that it assures the simultaneous evaluation of the effects of different conflicting design parameters. For example, increasing the glazing area could increase the energy demand for cooling by allowing more solar gain into a space. However, greater glazing area could decrease the amount of energy required by reducing the need for lighting and increasing the potential opportunity to apply natural ventilation and passive cooling strategies. The advantage of multi-objective optimisation is that all the parameters are evaluated simultaneously and a range of optimal solutions can be established in terms of the objectives: cost and energy consumption. In order for the optimisation process to identify the optimum solutions, the authors consider the "rationalisation prior to optimisation" exercise is critical to allow the algorithm to identify the Pareto optimal trade-off between conflicting design objectives such as capital cost and operational energy usage.

Rationalisation was applied by analysing the room operational requirements and identifying suitable environmental conditions in reference to CIBSE recommended design practices. This exercise informed the design team to allow the baseline building services systems to be defined in terms of Heating Ventilation and Air Conditioning (HVAC) and lighting systems. For example, for circulation spaces, the background heating and ventilation has been consistently applied as a zoning solution, as shown in Table 4.

Environmental Comfort Performance

Comfort performance analysis has been provided in reference to indoor environment design indicators specified in European Standard BS EN 15251 (British Standard Institute EN 15251, 2007) in terms of thermal criteria, air quality, humidity, lighting and acoustic performance. This applies to both the reference design and the optimisation study. Assessment of the internal environment is based on the thermal environment and resultant comfort performance for a mechanically heated and/or cooled building for a Category II application, which is defined as having a 'normal level of expectation adopted for new buildings' (BSI, 2007). It should be noted that detailed analysis related to comfort performance is not the focus of this study and is beyond the scope of this paper.

Building Fabric

The design variables related to the building fabric consisted of external wall construction, glazing, window to wall ratio and shading. In this particular building, the façade and hence the window to wall ratio was fixed and based on architectural specification as well as the shading which was based off the landscape architect specification. The external wall and roof constructions were specified in the architect's design specification with options for alternative solutions being constrained by aesthetic considerations.

For the case study, this resulted in the options for exterior wall construction to be limited to variations in the thickness of the insulation layer, constrained by Building Regulations compliance. Consequently, in this optimisation study, two types of external walls have been considered, an opaque wall construction with mineral fibre as the insulation media and an opaque wall with polyurethane insulation. The only variant is the thickness of the insulating layer. The overall costs and build-ups for the exterior wall constructions are shown in Table 1.

Table 1: External wall and roof construction variables and variation range

External wall and roof insulation	Commercial available thickness (mm)	Calibrated U-Value (W/m^2K)	Cost (£/m²)
Opaque wall Internal insulation – mineral fiber	210	0.099	1480
	140	0.145	1390
	100	0.197	1320
	75	0.254	1300
	60	0.307	1290
Opaque wall Internal insulation – polyurethane	210	0.099	1570
	140	0.145	1500
	100	0.197	1430
	75	0.254	1380
	60	0.307	1360
Roof Insulation - polyurethane	200	0.104	250
	130	0.145	210
	100	0.197	190
	75	0.254	190
	60	0.307	180

Initially, each of the two final exterior wall constructions were imported to the model with a range of U-Values between 0.15 W/m^2K and 0.35 W/m^2K and a step increment of 0.05 W/m^2K. However, in practise, insulation thickness is constrained by commercially available sizes. Consequently, the fabric U-values have been calibrated to reflect the commercial procurement with respect to cost and thermal performance for both the external walls and the roof construction.

Glazing consisted of 6 options with different U-values taking into account light transmittance (LT) and solar energy transmittance (G-value), details can found in Table 2.

Table 2: Glazing design variables and variation range

Glazing Description	g-value	LT - Value	Ug-Value (W/m²K)	Cost (£/m²)
(1a) Pilkington Optifloat Bronze	0.41	0.32	1.0	60
(1b) Pilkington Optifloat Grey	0.37	0.31	1.0	60
(2a) Pilkington Suncool 70/35	0.37	0.69	1.0	80
(2b) Pilkington Suncool Silver 50/30	0.31	0.49	1.0	80
(3) Pilkington SuncoolBlue 50/27	0.28	0.49	1.1	80
(4) Pilkington Suncool 30/16	0.18	0.4	1.1	85

For the lighting design, there are four different options which have been considered. T16 fluoresent open plan lighting and LED open plan lighting, both with and without daylight control. The cost of the options vary from 70 £/m² to 84 £/m² and are shown in Table 3.

Table 3: Lighting options and costs

Lighting solution	Total cost
(1) T16 fluorescent	£70/m²
(2) T16 fluorescent with daylighting control	£75/m²
(3) LED	£79/m²
(4) LED with daylighting control	£84/m²

HVAC systems can be divided into natural ventilation systems, which provide ventilation directly via openings in the façade and mechanical ventilation systems, which provide ventilation using mechanical plant. There is a third category called "mixed mode" in which maximum use of natural ventilation is made with supplementary assistance of mechanical ventilation under conditions where natural ventialtion alone is impractical due to design constraints.

In the current version of the DesignBuilder software, there is a limitation factor of ten parameters for optimisation. This means that at the absolute most, there could only be ten types of zoning where options for combinations of HVAC systems could be applied. This would need to decrease to allow simultaneous multi-objective optimisation with other parameters such as building fabric construction, lighting system and glazing selection.

Because of the number of solutions being high and the constraints of the software, it was clear that the HVAC solutions needed to be rationalized. This was also likely to have benefits in terms of value engineering for the project even before any optimisation analysis was carried out. Hence the zones were rationalised to six options: O, A, B, C, D and E, all with different combinations of HVAC systems. A system breakdown of these zones is shown in Table 4.

Table 4: Zoning of the HVAC solutions

Zone and treatment options	*O*	*A*	*B*	*C*	*D*	*E*
(0)Background heating and ventilation	✓					
(1)Displacement		✓	✓	✓	✓	✓
(2) Secure vents chilled beams and displacement			✓			
(3) Minimum fresh air and variable refrigerant flow		✓	✓	✓	✓	
(4) Secure vents, radiators and displacement				✓	✓	
(5) Secure vents, under floor heating and displacement					✓	
(6) Variable air volume		✓	✓	✓	✓	✓
(7) Minimum fresh air and fan coil units		✓	✓	✓	✓	
(8) Minimum fresh air, radiators and chilled beams		✓	✓	✓	✓	

Figure 3 below shows how the derived solutions were applied on the first Floor of the Creative Hub building as an indicative example of this exercise.

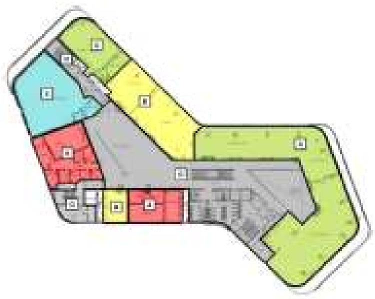

Figure 3. First Floor Ventilation system philosophy

The cost parameters of the selected HVAC systems for the optimisation run can be found in Table 5 below.

Table 5: Cost of the HVAC variables

HVAC solution	Total cost
No treatment	£0/m²
Displacement	£275/m²
Minimum fresh air and variable refrigerant flow	£300/m²
Variable air volume	£345/m²
Minimum fresh air and fan coil units	£365/m²
Secure vents, chilled beams and displacement	£495/m²
Secure vents under-floor heating and displacement	£495/m²
Secure vents radiators and displacement	£505/m²
Minimum fresh air, radiators and chilled beams	£555/m²

Table 6 indicates the solution space size as a product of all the parameters and their limitations after the rationalisation exercise the authors went through to minimise non-dominant solutions and to drive the dominant ones to the right direction towards a feasible design outcome. As it can be seen from this table, with a number of parameters and relatively small number of variations of each, the total number of possible designs for single building, increased very quickly to over 8,000,000. It is not common practise in the design industry for a team to search this solution space exhaustively, as a point-to-point search would last a very long time and could easily lock into a local suboptimum design. On the other hand, the amount of time taken by simulation tools to run the evaluations to find an optimum solution is high and a powerful computer is definitely required to perform these runs. In this particular research study, an optimisation run of approximately 5000 iterations of the discussed optimisation problem took approximately 180 hours to complete on an 8-core 3.50GHz Intel PC. This limits the use of simulation tools for real time control applications but at least it is obvious that it is a time effective solution in comparison with the value engineering exercises.

Table 6: Possible solutions space

Parameter	Options
External wall 02	5
External wall 04	5
Roof construction	5
Glazing	7
Lighting	4
HVAC Zone A	5
HVAC Zone B	6
HVAC Zone C	6
HVAC Zone D	7
HVAC Zone E	2
The solution space	**8,820,000**

Results & Discussion

The results output of the optimisation simulation performed in the DesignBuilder software is shown in Figure 4. The optimisation algorithm used in this study recalled only realistic solutions - those meeting the constraints - for the final Pareto set. Analysis of unrealistic solutions is also useful in providing information on areas of the solution space to avoid for future reference.

The 15 Pareto design solutions highlighted in red which form the Pareto Front, are the most practical solutions for capital cost vs site energy consumption. The reference design is highlighted in blue.

As shown in Figure 4, the engineered reference solution is close to the Pareto Front but there are other solutions that achieve the same energy consumption with a lower capital cost. Thus the optimisation successfully provides a superior solution than the actual reference design for the Creative Hub.

Table 7 summarises the design variable combinations of the reference case, the solution that achieves the minimum energy consumption, the solution that achieves the minimum capital cost and the selected practical solution from the Pareto Front. It demonstrates that although an improved building fabric performance achieves minimum energy consumption, a more average building fabric can be more cost effective providing a similar saving in energy.

LED lighting seems to dominate the Pareto solutions but the benefit of the daylight dimming in energy consumption is not cost effective. This could be the result of the building orientation and building form being pre-defined. In addition, the glazing type optimisation was applied on a building level, meaning daylight control would not have been utilised based on orientation.

A different glazing type than the reference case provides better results for the majority of the Pareto Front solutions. The HVAC system options for the reference case are in correlation with the minimum energy consumption solution while the displacement heating and cooling system seem to be the most efficient in the practical solution and most of the Pareto Front solutions as the results show in Table 8 in the Appendix.

The above points reveal that optimisation at an early stage in the design would have taken the building services design down a substantially different design path. The potential benefits of applying design optimisation to a project greatly outweigh the additional engineering design input required. Applying optimisation as a design tool is most beneficial during early design development stages where project specific objectives and constraints can inform design decisions and propagate through the design process. Since design solutions are typically informed based on cost as a primary driver, developing representative cost data and understanding and interpreting design cost synergies is critical.

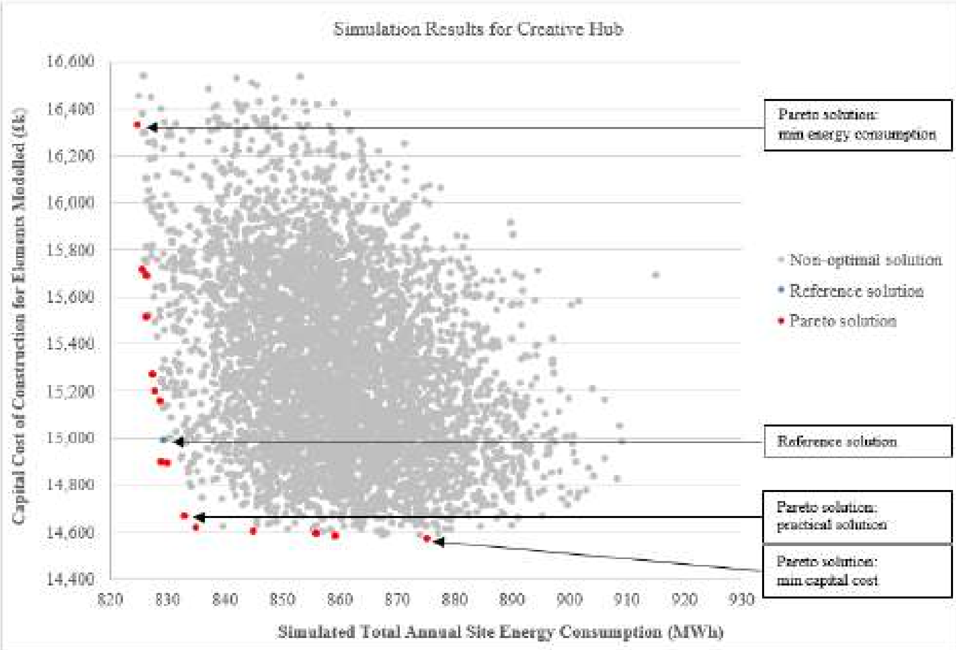

Figure 4: Results for optimisation simulations of the Creative Hub

Table 7: Summary of the key results for the reference and the selected Pareto solutions

Parameter	Ref Design	Pareto Solution		
		Min Energy Consumption	Min Capital Cost	Practical Solution
Simulated annual energy consumption (kWh)	829,327	824,767.74 (-4,559)	875,117.7 (45,791)	835,030.18 (5,703)
Simulated construction cost (£)	14,987,356	16,328,368 (1,341,012)	14,569,758 (-417.598)	14,619,173 (-368,183)
External wall construction Type 4 (W/m².K)	0.197	0.099	0.197	0.254
External wall construction Type 2 (W/m².K)	0.197	0.099	0.307	0.254
Flat roof construction (W/m².K)	0.197	0.104	0.307	0.197
Lighting template	LED linear/off control	LED no control	T16mm Fluorescent, no daylight control	LED no control
Glazing type	1a - Pilkington Optifloat Bronze	2a-Pilkington Suncool 70/35	2b-Pilkington Suncool Silver 50/30	2a-Pilkington Suncool 70/35
HVAC Zone A	1 Displacement heating & cooling	1 Displacement heating & cooling	1 Displacement heating & cooling	6 VAV
HVAC Zone B	2 Secure vent, displacement heating & chilled beam	8 Min FA, radiators, chilled beams	1 Displacement heating & cooling	1 Displacement heating & cooling
HVAC Zone C	2 Secure vent, displacement heating & chilled beams	4 Secure vent, displacement, radiators	3 Min FA + VRF	1 Displacement heating & cooling
HVAC Zone D	5 Secure vent, UFH, displacement	5 Secure vent, UFH, displacement	1 Displacement heating & cooling	1 Displacement heating & cooling
HVAC Zone E	6 VAV	6 VAV	1 Displacement heating & cooling	1 Displacement heating & cooling

Conclusion

Further simulations are needed in order to establish whether the practical solution accomplishes similar performance under Part L2A Building Regulations compliance and similar thermal comfort as the engineered reference case.

The optimisation results successfully provide a solution of lower capital cost whilst sustaining a comparable energy performance against the base reference solution. The final practical result of optimisation illustrates construction savings of 2.5% (£368,183) whilst maintaining a similar annual energy consumption (<0.01% difference of 5703KWh) in comparison with the reference design choice.

From this computational study, it can be concluded that am optimisation run should be done at an early stage of the design process to influence the major parameters affecting energy efficiency and capital cost. The optimisation module of the DesignBuilder software enables the user to run multiple combinations of design options that in common engineering practice would be very time consuming and commercially unsustainable. The optimum solutions identified can then be further interrogated if they are feasible to be applied in the building design. This optimisation process offers greater assurance from early stage design that that the best solution is implemented.

Acknowledgements

This work was financially supported by the Arup Group Ltd. through internal research funds. The authors would like to express their gratitude to Design Builder Software Ltd. for providing the necessary software products for the research project. The authors would like also to thank Karan Kapoor and Meng Chen for their contribution to this work.

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Appendix

Table 8: Reference and Pareto Front Results

Parameter	Ref. Design	Pareto Solution														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Simulated annual energy consumption (MWh)	921.9	824.8	825.7	826.2	826.4	827.4	827.8	828.7	828.9	829.9	833.1	835.0	845.0	855.9	859.2	875.1
Simulated construction cost (£M)	14.99	16.33	15.72	15.69	15.51	15.27	15.20	15.16	14.90	14.89	14.67	14.62	14.60	14.59	14.58	14.57
External wall construction Type 4 ($W/m^2.K$)	0.197	0.099	0.197	0.254	0.254	0.254	0.254	0.099	0.197	0.254	0.254	0.254	0.254	0.254	0.197	0.197
External wall construction Type 2 ($W/m^2.K$)	0.197	0.099	0.099	0.099	0.099	0.145	0.197	0.197	0.197	0.197	0.254	0.254	0.254	0.307	0.307	0.307
Flat roof construction ($W/m^2.K$)	0.197	0.104	0.104	0.104	0.145	0.104	0.104	0.104	0.104	0.104	0.145	0.197	0.307	0.254	0.307	0.307
Lighting template	4	3	4	3	3	3	3	3	3	3	3	3	4	3	3	1
Glazing type	1a	2a	2a	2a	2a	2a	2a	2a	2a	2a	2a	2a	2a	1a	3	2b
HVAC Zone A	1	1	1	1	1	1	6	7	1	1	6	6	1	1	1	1
HVAC Zone B	2	8	2	8	1	1	1	6	1	8	1	1	3	6	3	1
HVAC Zone C	2	4	1	1	1	6	1	1	1	1	1	1	1	1	1	3
HVAC Zone D	5	5	5	5	4	6	4	6	6	1	1	1	1	1	1	1
HVAC Zone E	6	6	1	1	1	1	6	6	1	1	1	1	1	1	1	1

Appendix B Background to the climate targets

Appendix B.1 Carbon dioxide

The measurement of the mass of carbon dioxide relative to air using an infrared absorption technique shows a clear continuing increase in the levels of carbon dioxide in the atmosphere. Similar results have been reported at Barlow, Alaska (Peterson, Komhyr, Harris, and Waterman 1982) and at Baring Head, New Zealand (Lowe, Guenther and Keeling 1979).

To establish atmospheric levels of carbon dioxide before direct measurement began in 1958, levels of greenhouse gases have been determined by other techniques including the examination of air bubbles trapped in Antarctic ice. Several studies (Raynaud and Barnola, 1985; Etheridge et al., 1996; Monnin et al., 2001) agree with the Mauna Loa results and allow the record of carbon dioxide in the atmosphere to be extended back for thousands of years, albeit with greater uncertainty.

These studies show an accelerating increase in the level of carbon dioxide in the atmosphere since the beginning of industrialisation around the end of the 18th century.

Appendix B.2 Other greenhouse gasses

Carbon Dioxide is not the only greenhouse gas. Wang et al., (1976) identified N_2O, CH_4, NH_3, NHO_3, C_2H_2, SO_2, CCl_2F_2, CCl_3F, CH_3Cl and CCl_4 as having strong infrared absorption bands in the region of 7 to 14 um, which despite their small concentrations, could have a significant effect on global warming. Lashof and Ahuja (1990) proposed the use of a “Global Warming Potential” relative to that of carbon dioxide, which has been largely adopted.

However, while many of these gases have been important to the building industry as refrigerants and as foaming agents in insulation, this thesis is primary concerned with the reduction of carbon dioxide. The study of relative levels of other greenhouse gases and their link with climate change is not explored further.

Appendix B.3 Other sources of greenhouse gases

Not all greenhouse gas production is anthropogenic (IPCC, 2007). Furthermore, there are natural processes which remove greenhouse gases from the atmosphere. Water vapour is a significant greenhouse gas which is introduced into the atmosphere by evaporation and carbon dioxide is ejected during volcanic activity. Carbon dioxide is removed from the atmosphere by vegetation, and other greenhouse gases break down in the atmosphere as a result of processes in the upper atmosphere. The planet has a very complex carbon system with very large non-anthropogenic sources and sinks.

The background to climate science has been thoroughly documented. A summary of background to the climate targets is contained in Appendix A1.

Appendix B.4 International Panel on Climate Change Target

There is international agreement now that to avoid the impacts of climate change, we will need to rapidly reduce our carbon emission over the next three decades, whereas carbon emissions have been rising over the last three. This is a major challenge and buildings which are responsible for roughly one third of carbon dioxide emissions will have to rapidly decarbonise globally.

Appendix B.5 Carbon dioxide contribution from buildings

Worldwide, in 2004, it was estimated that buildings account for 35% of primary energy use and 28% of the carbon emissions (Price et al., 2006). The improvement in the design, construction and operation of buildings therefore, represents a significant opportunity to reduce greenhouse gas emissions.

Appendix B.6 The international response and the Kyoto Protocol

In 1992, the international community responded to the threats associated with climate change by setting up a treaty to address Climate Change called the United Nations Framework Convention on Climate Change (UNFCCC).

The Kyoto Protocol to the United Nations Framework Convention on Climate Change (United Nations, 1998) is an international agreement intended to stabilise the concentration of greenhouse gas emissions. The countries signing up to the Protocol agreed to set binding targets for an initial period from 2008 to 2012. Targets were set in terms of a percentage of a base year, which for most countries was 1990. Under the initial agreement the United Kingdom committed to reducing greenhouse gases to 92% of 1990 levels by 2012.

In 2012 a second commitment period from 2013 to 2020 was agreed and recorded in the Doha Amendment. Under the Doha Amendment the United Kingdom committed to reducing greenhouse gases to 80% of 1990 levels (United Nations, 2013).

Appendix B.7 Current UK emission levels

The calculation of the collective impact of a combination of the various greenhouse gases is complex. The United Nations Framework Convention on Climate Change (UNFCCC) publishes *The Kyoto Protocol Reference Manual on Accounting of Emissions and Assigned Amount*. This manual documents the agreed method for the calculation of carbon dioxide emissions and quotes an estimate of the 1990 CO_2 equivalent produced in the United Kingdom as 3.4 billion tonnes

Appendix B.8 European Union legislation

The European Union (EU) has introduced legislation to control the use of energy in buildings and, as a member, the United Kingdom is obliged to adhere to European parliamentary regulations. These regulations include:

- eco-design of energy using products (EuP) Framework Directive 2005/32/EC;
- Directive 2009/28/EC on the promotion and use of energy from renewable sources (Renewable Energy Directive);
- Directive 2010/31/EU on the energy performance of buildings (the Energy Performance of Buildings Directive).

Under the European Directives, the United Kingdom is required to develop legislation to regulate building energy use which includes the use of theoretical models.

Appendix B.9 UK legislation

The United Kingdom has undertaken to reduce the production of greenhouse gasses to zero by 2050 under the Sixth Carbon Budget (Institute for Government, 2020).

Pursuant to the Climate Change Act, The Department for Energy and Climate Change (DECC) has produced a plan for reducing carbon emissions over the medium term (DECC, 2011). The amount of carbon produced within the United Kingdom is to be reduced to 57% below base year levels by 2030. The budgets which have been set for the four time periods until 2027 are given in Table 25 are below.

Budget and period	***Net UK Carbon Account $MtCO_{2e}$***
First carbon budget (2008-2012)	3018
Second carbon budget (2013-2017)	2782
Third carbon budget (2018-2022)	2544
Fourth carbon budget (2023-2027)	1950

Table 25. Carbon Dioxide reduction targets for the United Kingdom. (DECC, 2011)

More recently, the UK's Committee on Climate Change (CCC, 2018) has criticised the Clean Growth Strategy (HM Government, 2018) as not delivering the policies required to meet the targets and that more detail is needed to formulate the Fifth carbon budget.

Appendix B.10 International Panel on Climate Change

In 1988 the United Nations Environment Programme and the World Meteorological Organisation established the International Panel on Climate Change (IPCC) to provide a coherent view on climate change and its potential impacts (IPCC, 2014).

The IPCC reviews the work of hundreds of scientists, and has drawn together a series of assessment reports. The assessment reports include:

- the scientific basis for claims regarding climate change;
- the potential impact of climate change, what adaptation might be possible and who is vulnerable to its effects;
- options for the mitigation of the effects of climate change;
- a Synthesis Report which summarises the other reports and makes recommendations to policy makers.

The work published by the IPCC is extensive, however the essential conclusions are that:

- the evidence that global average temperatures are increasing are unequivocal;
- increases in average temperatures are due to human influences;

- extreme weather events are likely to increase as a result of the increase in average temperature;
- human and natural systems would be unable to adapt to the effect of unmitigated climate change;
- the effects of climate change can be mitigated.

Appendix B.11 Climate sensitivity

Hansen et al. (1981, 1984) relate the sensitivity of climate change to greenhouse gas emission. More recently, the quantified effect greenhouse gases have on climate is given the term Climate Sensitivity and has been defined as the:

> *"equilibrium global average surface warming following a doubling of CO_2 concentration"*

Estimates of climate sensitivity are uncertain; that is not to say that they are unknown, but that the predictions are quantified as a range. The "likely" (that is one with a certainty of 66%) prediction is that the mean average surface temperature of the earth will rise by between 2.0°C and 4.6°C for every doubling of the level of greenhouse gasses in the atmosphere.

Appendix B.12 Setting the target

Stern (2006) published the impacts that would be likely following a range of rises in the average surface temperature. A target of not greater than 2°C was recommended as a level at which impacts might be severe, but which would be likely to avoid the more catastrophic effects.

To achieve a better than 50% chance at stabilising the climate at less than 2°C, carbon dioxide levels need to be stabilised at below 400ppm.

As of 1 June 2019, the atmospheric carbon dioxide level was 414ppm (www.co2.earth, 2019). However, the slow reaction of the atmosphere means that the equivalent carbon dioxide levels can be allowed to climb to 475ppm before being reduced again by 2050.

Appendix B.13 Part L

The Building Act (1984) confers power on the Secretary of State to introduce regulations which control the design and construction of buildings.

The Building Regulations 2000 (Parliament, UK. 2000), most recently amended in 2010 (Parliament UK, 2010), require measures to be undertaken to demonstrate that a new building has been designed to meet a prescribed standard of energy efficiency. These requirements are documented in Part L of the amended Schedule 1 of the regulations. Before allowing construction, a Building Control Body must be satisfied that a calculated Target Emission Rate (TER) will not be exceeded. The National Calculation Method (NCM) must be used to demonstrate compliance.

Appendix B.14 Energy Performance Certificates

Under the Building Regulations (2000) amendment: The Energy Performance of Buildings (Certificates and Inspections) (England and Wales) Regulations 2007 (Parliament, UK, 2007), an Energy Performance Certificate (EPC) must be submitted to the Building Control Body within 5 days of completion. The EPC provides: an assessment of the energy performance of the building which is called the "Asset Rating" (AR); suggestions for improvement, and a reference benchmark.

Appendix B.15 Display Energy Certificates

Under the same regulations (Parliament, UK, 2007), non-domestic public building occupiers must display a Display Energy Certificate (DEC) which must display the Asset Rating and an "Operational Rating" (OR) of the building. The regulation applies to:

> *"… buildings with a total useful floor area greater than 1000m^2, that are occupied by public authorities and institutions providing public services to a large number of persons and therefore frequently visited by those persons." (Parliament, U.K., 2007, P7)*

DECs are not required for domestic buildings.

DECs have been introduced to raise awareness of the actual measured energy consumption of buildings (Department for Communities and Local Government, May 2008). DECs must be produced in accordance with the Government's Operational Rating Methodology for assessing the operational performance of buildings (Department for Communities and Local Government, October 2008).

The Operational Rating is based on the metered energy consumption of the building and its plan area, as compared to a benchmark building. Some adjustment in the energy consumption is made to account for local climatic conditions, however no adjustment is made for parameters which might enable a more direct comparison with EPCs.

Appendix B.16 Building energy modelling as part of a carbon reduction plan

This section describes the different roles that building modelling plays in the regulation, design, contracting and construction of the built environment.

Appendix B.17 Building energy models to demonstrate compliance

Modelling the energy performance of buildings has become a key element of driving forward energy efficiency policy.

Mass-produced items can be designed, prototyped and tested under laboratory conditions. This means that reliable data can be obtained and the cost can be spread across the mass, making the cost per article small.

In the non-domestic built environment, almost every building is a unique combination of complex socio-technical systems where the implications of user behaviour are difficult to isolate. In an analogy to a mass-produced product, a building would need to be tested for a year under idealised conditions before a rigorous statement about its performance could be justified. The cost of this would be prohibitive, and only allow a limited range of building designs to be constructed. Hence, some form of theoretical assessment is preferred.

Theoretical models are therefore produced to demonstrate compliance with Part L of the regulations and to produce Energy Performance Certificates that project energy use and the carbon footprint of buildings.

However, the diversity of modelling software and the flexibility in which the software can be applied (and needs to be able to be applied), means that results from building energy models are diverse and could possibly be manipulated to get a design through Building Regulations. A study compared results from a variety of software which was approved for use as a compliance tool in the UK and found large ranges in the predicted energy consumption (Raslan and Davies, 2010).

Appendix B.18 Building energy modelling as part of services engineering

The use of energy modelling software is common in building services engineering with energy models being constructed during the design stage to compare options for the selection of servicing strategies and to inform the selection of the type and size of key items of equipment.

These models are being put under increasing scrutiny. Where buildings consume more energy than predictions show, engineers can expect to be called to account for discrepancies. In some cases this process has been formalised. Subsequent sections include a summary of requirements described by the UK's Education Funding Agency's Priority Schools Building Programme and the United States Green Building Council's initiative Leadership in Energy and Environmental Design (LEED).

Appendix B.19 Private Finance Initiative

Clients for whom building energy models are produced, may ask for a prediction of energy consumption, particularly if the building is part of a Private Finance Initiative (PFI) where the bidding contractor will be responsible for the operation of the building. Public Finance Initiatives started in 1992 (Grout, 1997). In a traditional purchasing model, a public body contracts the construction of a building, which is then controlled by the public sector. In a PFI project the private sector funds, builds and owns the asset and the public sector pays for the construction under a commitment for the life of the contract.

As the public sector must allow for the cost of the operation of the building in their bid, contractors may seek an estimate of the building's energy consumption from the building designers.

Appendix B.20 Green Deal

Under the Green Deal (Parliament, UK. 2011), provisions were made by the UK government to finance energy improvements to buildings. Under this scheme, the cost of the provisions is recovered from the building owners and occupiers while keeping the total cost for energy at or below pre-modification rates.

While domestic residences are the main properties targeted by the Green Deal, there was also opportunity for businesses to apply for funds under the initiative.

The Green Deal relied on a specific rate of return from the energy conservation measures employed, often called the "Golden Rule". The actual financial benefit depended on the accuracy of the predictions of future energy consumption made in the assessments, including any building energy modelling.

The Green Deal was scrapped following a damning report from the House of Commons Committee of Public Accounts, because *"… householders were not persuaded that energy efficiency measures were worth paying for through the Green Deal…"* (HCCoPA, 2016).

Appendix B.21 Energy performance contracting

Energy Performance Contracting is a financial mechanism for the delivery of projects intended to improve the energy efficiency in buildings (Xu, Chan and Qian, 2011). Typically, a separate Energy Service Company (ESCO) will provide design and installation services for the modification of a building to improve its efficiency. The contract will also typically include a guarantee of savings so that both the ESCO and the client organisation benefit from the changes.

The American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE) and the Energy Efficiency Organisation (EVO) publish documents to provide guidance on the quantification of savings. These documents are discussed in more detail in the literature review, but it is of note that these describe the use of calibrated building energy models to establish the reference point which determine the actual savings made under the energy performance contract.

Appendix C Details of the construction used in the study of the Northampton Creative Hub

The details of the wall build-ups are contained in the eight diagrams that also reference to the clauses in the specification. The details show the construction of the wall and the anticipated thickness of the insulation. The eight types of building fabric are labelled:

- Type 01: *Reglit*;
- Type 02: *Reglit* and plasterboard back;
- Type 03: *Reglit* and stud wall base;
- Type 04: *Reglit* and stud wall back soundbloc;
- Type 05: Curtain walling;
- Type 06: Curtain wall over stud wall base;
- Type 07: Stud wall with insulated render;
- Type 08: Louvres;

Types 01 and 05 are full height glazing solutions. Types 02, 04 and 07 are opaque solutions and Types 02 and 06 are a combination of glazing and a short base wall.

Type 08: louvres are located in plant rooms, do not affect the thermal performance of the building fabric and were not considered further.

Reglit is a self-supporting glazing system from Pilkington, where glass fits into an extruded metal frame. (Reglit, 2015).

Curtain walling is a general term for a glazing system which includes the frame and which is hung from a higher supporting structure.

The roof types were contained in five drawings. The first two drawings show typical sections through the building and the other three drawings show details of the construction build-up for the roof and floor.

There were two types of roof construction: *flat roof construction*, which consisted of 300mm of concrete and a layer of insulation; and *plant room roof*, which consisted of 100mm Kingspan Topdeck insulation system.

Appendix D Northampton Creative Hub Services Zones

The division of the building into zones that could be provided with the systems detailed in Chapter 6 are given below.

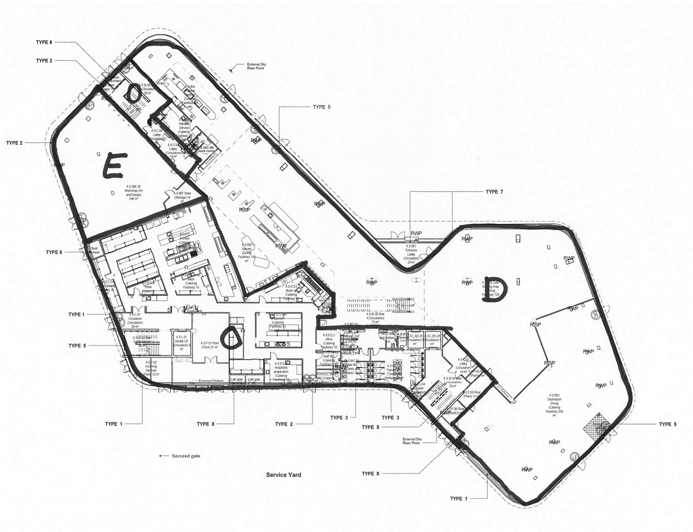

Figure 28. Ground floor plan showing the location of zones to which the combination of options were applied during optimisation.

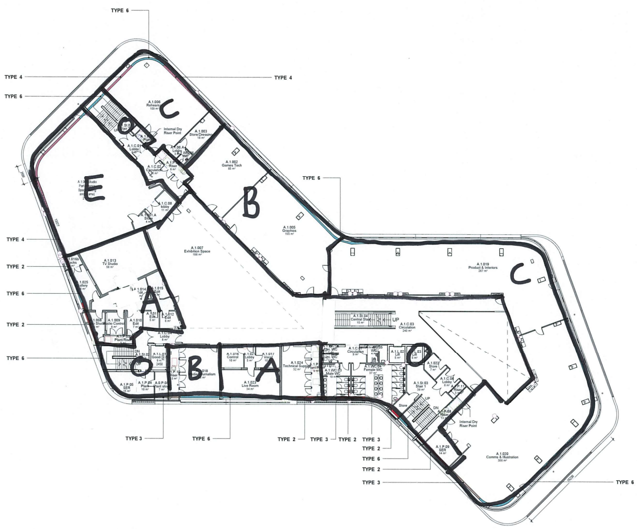

Figure 29. First floor plan showing the location of zones to which the combination of options were applied during optimisation.

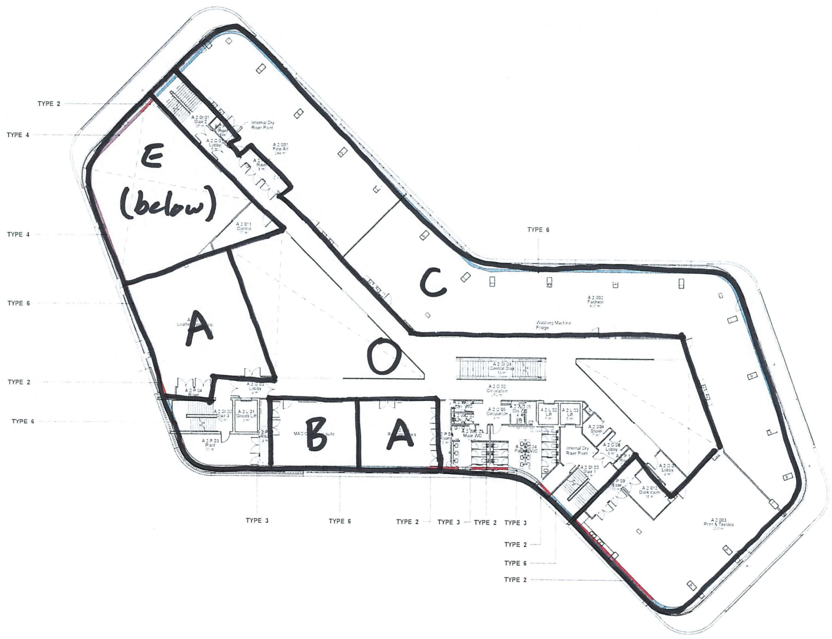

Figure 30. Second floor plan showing the location of zones to which the combination of options were applied during optimisation.

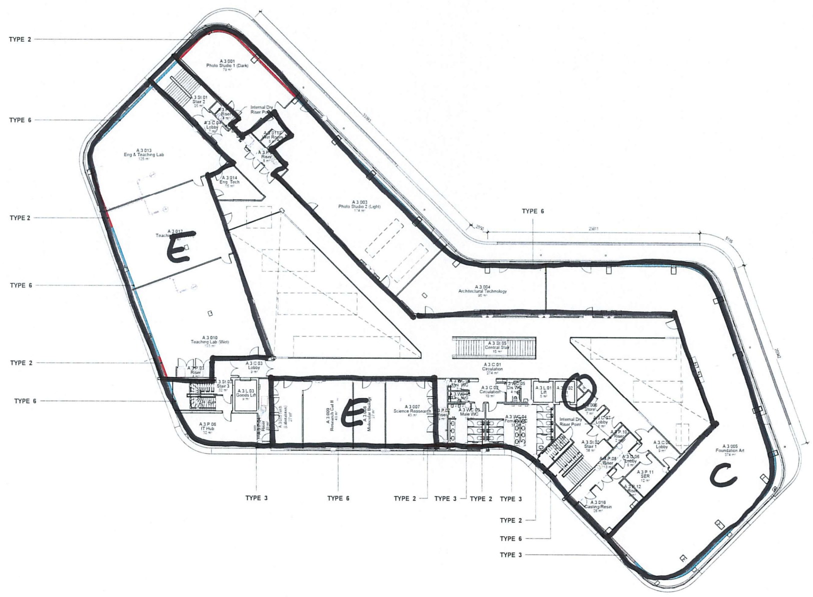

Figure 31. Third floor plan showing the location of zones to which the combination of options were applied during optimisation.

Appendix D.1 Baseline system for comparison with optimisation results

The performance and cost were simulated for the systems, which most closely reflected the original design after the rationalisation process. The locations where the systems were applied are shown in Figure 32 to 36.

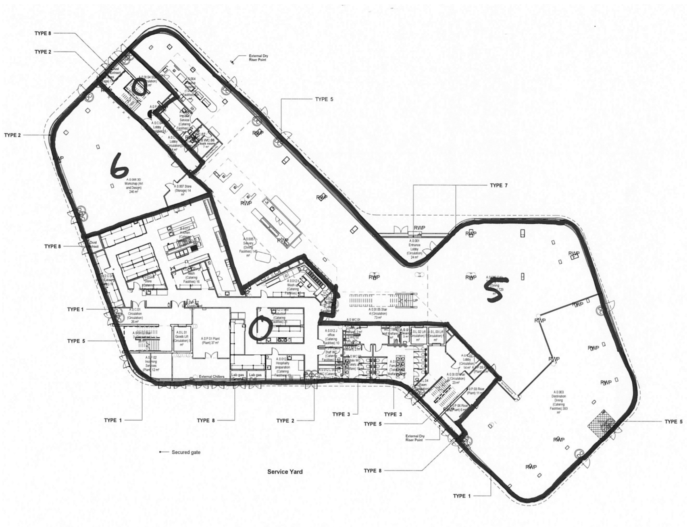

Figure 32. Ground floor plan showing the location of heating ventilation and air conditioning strategies zones before optimisation.

Figure 33. First floor plan showing the location of heating ventilation and air conditioning strategies zones before optimisation.

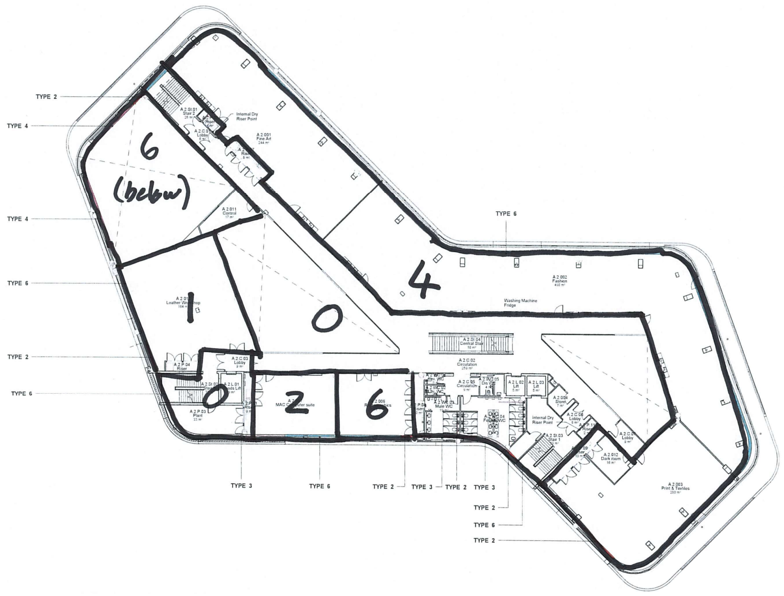

Figure 34. Second floor plan showing the location of heating ventilation and air conditioning strategies zones before optimisation.

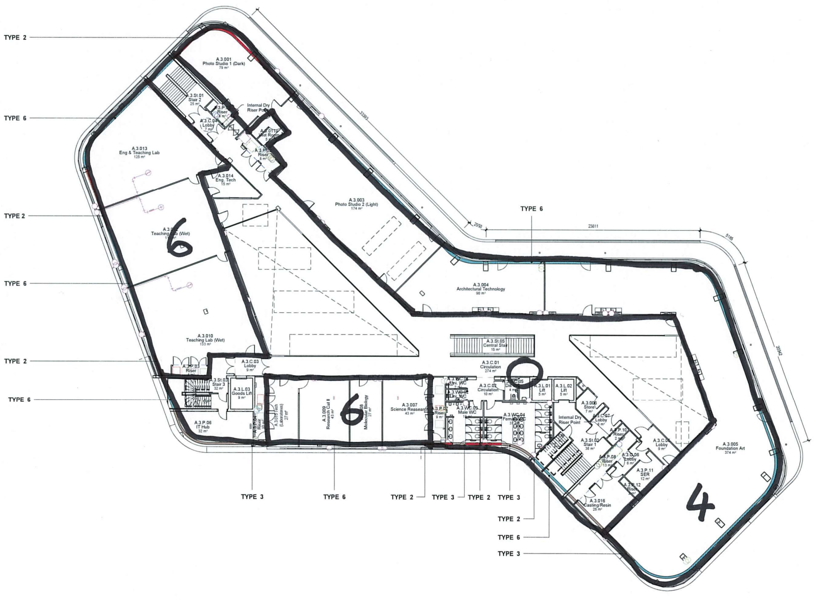

Figure 35. Second floor plan showing the location of heating ventilation and air conditioning strategies zones before optimisation.

Appendix E Analysis of data obtained from ILS1

Appendix E.1 Details of the investigation into the data available from ILS1

This Appendix contains the results of the investigation into the Institute for Life Sciences Building 1 at Swansea University.

Appendix E.2 Setting up BMS reports

At the time of the investigation, ILS1 used Tour and Anderson Controls (TAC) Vista v4.5.1 software (Schneider Electric, 2011) to access the BMS.

Hourly logs were started for 1322 data points representing a range of variables. The variables that were logged can be grouped into the following categories:

- *Fan Coil Unit* (FCU) data;
- *Air Handling Unit* (AHU) data;
- *Category 3* laboratory monitoring;
- *Combined Heat and Power* (CHP) plant;
- *Domestic Hot Water* (DHW) system;
- server room;
- fume cupboards;
- cold rooms;
- freezers;
- ground source heat pump;
- atrium louver control;
- heat meter;
- electrical sub-meters;
- outdoor temperature;
- lighting controller output.

At this stage, the intention was to use the data recorded in the logs as inputs in an *EnergyPlus™* model of the building and compare the difference in results between the original and modified models and with the actual energy consumption of the building. It was thought that the data might need substantial post-processing to get it into a format which would be useful, but at this stage the emphasis was on gathering data for analysis later.

As the logs were started, the name of the log and the BMS's name for the log point were recorded on a spreadsheet. This was also used to ensure that the logs started were an exhaustive set of the data points available via the BMS.

Appendix E.3 Storage and retrieval of data from the BMS

The method recommended for retrieval of data from the BMS was to use the *TAC Vista's* Human Machine Interface (HMI) and retrieve the data by making the appropriate selection from the screens provided (Schneider Electric, 2011). This method starts *Microsoft Excel™,* which runs a macro to access information from the database. This method was sufficient for making individual enquiries but was not going to be suitable for recovering over a thousand logs, because the time taken by an engineer to access all the data would have been unacceptably long.

The hard drive of the Personal Computer (PC) on which the HMI was installed was searched to see if the method by which data was stored could be discovered. Searching the hard drive revealed large files in a data subdirectory for the database application: *Microsoft (MS) SQL Server™ 2008 R2.* The files were called *taclogdata* and suffixed LDF and MDF. A copy of the files was taken and transferred to a local PC so that any accidental changes to the database would not affect the ILS1 BMS or MHI.

LDF and MDF files cannot simply be copied. The files are constantly being read and rewritten as the BMS records data from the building, so the Microsoft database locks the files to protect them. Instead, a copy must be made using a Microsoft database export tool. This produced two renamed files which had the same suffixes. The tool was called *DTS Services Import/Export Wizard*.

The MDF and LDF files were 670 MB and 6 MB respectively. Arup provides a *File Transfer Protocol* (FTP) facility to allow large files to be transferred. To transfer the files, the Arup FTP site was accessed from the server via *Microsoft Internet Explorer*.

Appendix E.4 Interrogating ILS1 database files

A copy of the ILS1 database was attached to *Microsoft SQL Management Studio™*.

Microsoft SQL Management Studio™ has a series of preconfigured searches which allow the contents of tables to be viewed. A preconfigured search, which lists the first 1000 lines in a table, was selected from the right-click options in the database tables. Inspection of the table *dbo.TrendLogValue* confirmed that the database contained trend log data from the BMS.

The names of the logs were found in the table *dbo.TrendLog*. The name column contained the path and log names of 1508 logs which corresponded to the path and names which had been set up for recording. This includes files that had been started by maintenance technicians in addition to those set up as part of this research. This confirmed that the BMS was logging the data points and that the data could be copied, transferred and interrogated locally once the logging had proceeded for a sufficient period. This process was expected to take at least one year.

Appendix E.5 Building Energy Model

Confident that data from ILS1 was being reliably recorded, the focus of the research was switched to creating an *EnergyPlus*™ model which could them be calibrated using the data from the BMS.

Buildings models in *EnergyPlus*™ are described in text files which are difficult to write directly. *DesignBuilder*™ provides the facility to view a representation of the model and to describe features of the building via interactive screens. Information from the original ILS1 design documents was used to describe the building, including the building geometry, fabric, glazing, electrical, heating, ventilation and air conditioning systems. Additional information was included to describe the other buildings in the vicinity of ILS1, which might provide shading, thereby affecting the solar gain, and location data including an appropriate weather file.

The model was checked during a visit to Swansea University. A walk through the building revealed that a number of changes had been made to the design during the construction phase. The changes were noted on drawings which were used to update the model.

Appendix E.6 Examination of Data from ILS1

Examination of the ILS1 BMS data revealed the following problem. Sometime in March 2015 the server, on which the BMS database resided, failed. This resulted in the loss of all data. The data logging function also stopped. All attempts to restore backups of the database failed. This meant that the only available data were in the Primary Data File (MDF) and Log Data File (LDF) which were downloaded on the 8th of August 2013 covering the period from 5 March to 7 August 2013.

These data were assessed for their potential to calibrate the building energy model, including checking for missing data.

Appendix E.7 Preliminary assessment

Using *Microsoft SQL Server 2012 Express^{TM}*, a search was run to determine the number of logs in a table called *TrendLog* which uniquely identified each log with a column called *TrendLogId*. The results of the search were copied into a spreadsheet and matched against the logs that had been started; this involved manually copying each of the logs: *Name* and *TrendLogId* to the original record. The method was laborious but thorough because it eliminated the possibility that the *TrenLogId* could be copied against two point names and that every record was associated with the original BMS tag.

There were only 1128 unique logs found from the 1322 originally recorded. Of the 168 logs associated with lighting, only 14 were represented with *TrendLogIds* and all of these logs were empty: i.e. they contained no data (rather than a list of zeros).

There were 26 logs missing from the remaining 1154 logs that were started in 2013. These logs were:

- ILS1 heat meter;
- FCU409 (5 logs);
- FCU209 (5 logs);
- FCU204 (5 logs);
- FCU122 (5 logs);
- Five alarm logs associated with the main plant;
- 14 logs containing lighting records were blank.

The ILS1 heat meter was of special interest because it would have contained data on the total heat delivered to the ILS1 which would be required to calibrate the building energy model. The fan coil unit logs had limited value and the data from the alarms would not have been useful for the calibration of the energy model.

Once the trend logs had been associated with the original data points, a time consuming but rigorous examination was made of each of the 1128 logs. Each log was individually opened by querying the database for logs with the *TrendLogId* of the log under examination.

Appendix E.8 Quantity of data available

The number of data points in each log were sorted to see the extent of data available. In the log each data recording entry is given on one row so the terms: “entry” and “row”, are used interchangeably.

The number of rows in each log were plotted on a cumulative frequency diagram which is given in **Error! Reference source not found.** Several groups of the number of rows in a log were found by inspection. These groups were identified and investigated further to see if there were any patterns.

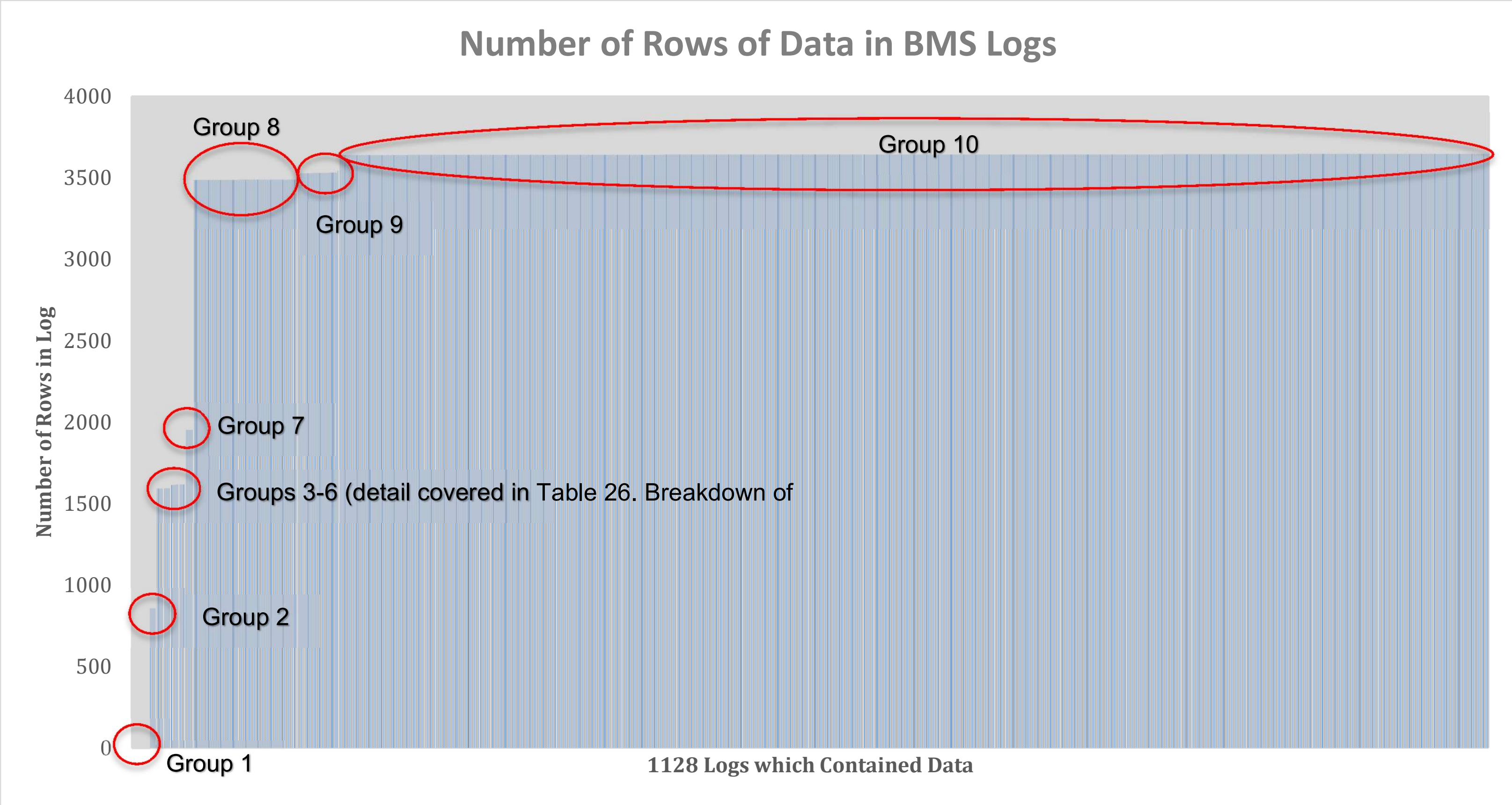

Figure 36. Diagram showing the relative number of data entries in logs and their grouping.

The start and finish times for the logs were summarized in Table 26 below, which also describes the number of data in each of the groups.

Group	Number of logs in Group	Number of Entries in Log	Data Period Start	Data Period End
Group 1	15	Nil	5 March	15 May
Group 2	5	859 entries	31 March	8 August
Group 3	5	1593entries	30 May	7 August
Group 4	5	1594 to 1596 entries	30 March	7 August
Group 5	5	1618 entries	30 May	7 August
Group 6	5	1615 to 1618 entries	30 May	7 August
Group 7	5	1952 entries	30 March	7 August
Group 8	86	3487 to 3490 entries	6 March	7 August
Group 9	34	3526 to 3544 entries	6 March	7 August
Group 10	962	3638 to 3646 entries	6 March	7 August

Table 26. Breakdown of the amount of data and the periods over which the data were collected by the BMS.

The time periods for each group are shown in Figure 37. Group 1 is the set of logs which contains no entries and is therefore omitted from the diagram.

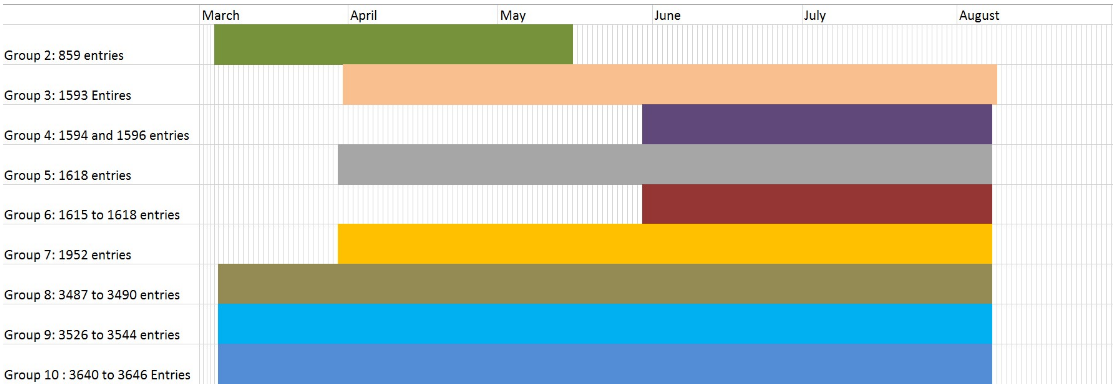

Figure 37. Visual representation of the periods over which data were collected for each of the groups in Table 26.

Given that there would have been 8760 data points in a standard year, the highest number of data points (3646) represented less than half a year's data. The logs ran from 6th of March 2013 until the 7th of August 2013 and covered a total of 3694 hours, so the maximum number of entries in the logs would be 3694 entries; this means that all of the logs were missing at least 30 entries.

The disparity of the number of results raises questions about the integrity of the data.

It is clear from the time plot that some logs with limited amounts of data contain data over a short period, while others must have gaps. Further investigation of the patterns of omission are discussed in the following sections.

Appendix E.9 Dropped points in largest data logs

As stated above, there were 962 logs with between 3638 and 3646 entries which were labelled "Group 10". The logs run from until the 6th of March 2013 until the 7th of August 2013.

To re-examine all 962 logs would have been unnecessarily time consuming, so a random sample of 30 logs was taken as a representation.

30 logs with between 3638 and 3646 entries were opened and checked for missing entries. The spreadsheet was sorted in reverse order of the number entries. Logs with 3646 entries were first followed by logs with 3645 entries and so on. The first 962 rows then represented the logs which contained between 3638 and 3646 entries (inclusive). A random number generator was used to select the row number of 30 logs and these logs were inspected to see if they contained omissions and where these omissions occurred.

Out of the 30 logs selected at random, which had between 3640 and 3646 data rows, six logs were missing data. The data were missing on four separate days between the 29th of July and the 7th of August. The difference in the number of data in the remaining logs was due to slight differences in the start and finish times of the log.

From these tests it is clear that the BMS system could not be relied upon to exhaustively record all the instrumentation readings over an extended period.

Appendix E.10 Data lost from Groups 8 and 9

A similar method was applied to the next two largest groups of data. Group 9 has 34 logs and Group 8 has 86 logs. The logs contained between 3487 and 3544 data. The logs all cover the period from the 6th of March 2013 until the 7th of August 2013, so it was evident by inspection that the logs must have gaps where data is missing.

A similar process was applied to select 30 logs from these two groups. The logs were exported from the database and examined in a spreadsheet.

The logs in Groups 8 and 9 had significant periods where data was missing. Some periods were common to all the logs in either Group 8 or Group 9 individually, but there were also periods where gaps in the data were common to both groups.

In addition, there were relatively isolated cases where 1, 2 or 3 data were lost from a number of logs at the same time.

Appendix E.11 Long periods at 100%

Having established that the larger data sets contain gaps that occur at both coincidental times and at random, attention moved to whether the data contained reliable readings. Almost all data logs which contained records of valve outputs had long periods at 100%. A properly designed building system would not typically have valves that operate at 100% for more than a few hours so in this case, long period means more than 24 hours. This was recognised as a potential indication of error or incorrect operation of the building services. The data was examined in more detail to establish the extent of the phenomenon.

Within the groups of data that were noted as having long periods at 100%, there were three subgroups:

- Data noted as simply having long periods at 100%.
- Data having exceptionally long periods at 100%.
- Data that had long periods at 100% and that either had readings only of 0% or 100%.

These notes were highly subjective so the subgroups were all examined together. There were 307 logs, which were seen and noted as having long periods at 100%. A random sample of 10 logs was taken and compared in a spread sheet.

The chart in Figure 38of the percentage opening of the cooling valve on fan coil unit 302 shows a typical profile. The profile includes long periods at 100%. The chart also shows the largest gap in data between 11:00pm on the 9th of June and 12:00pm 11th of June. Other gaps are too small so show up at this scale.

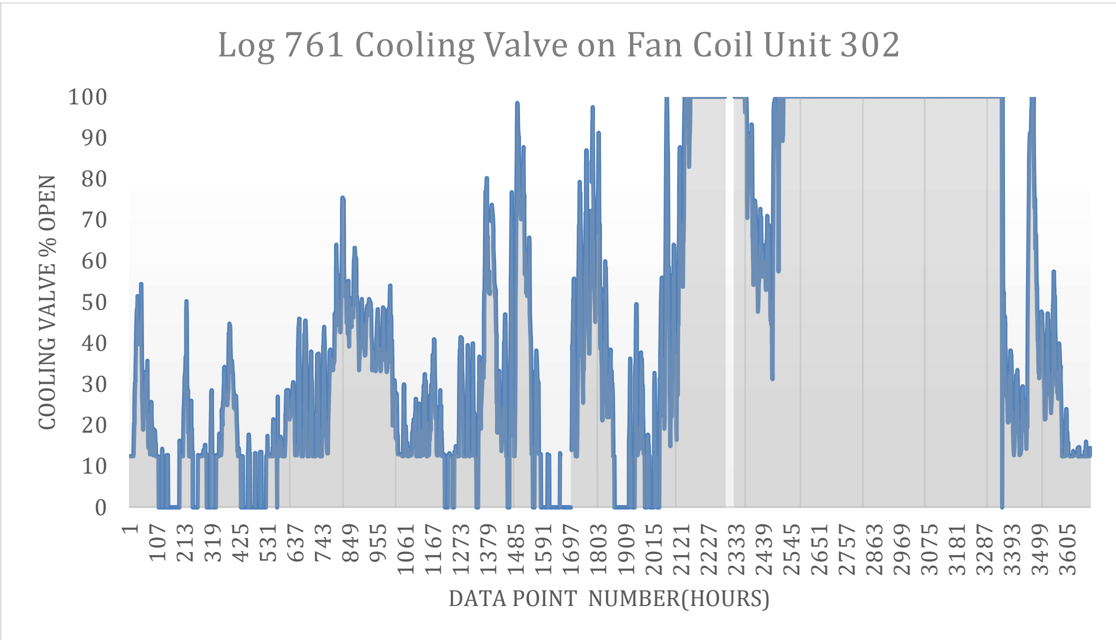

Figure 38. Cooling coil profile for Log 761 which shows significant periods open at 100%.

When all the data from the samples are superimposed on one chart as shown in Figure 39, the common periods at 100% become clearer.

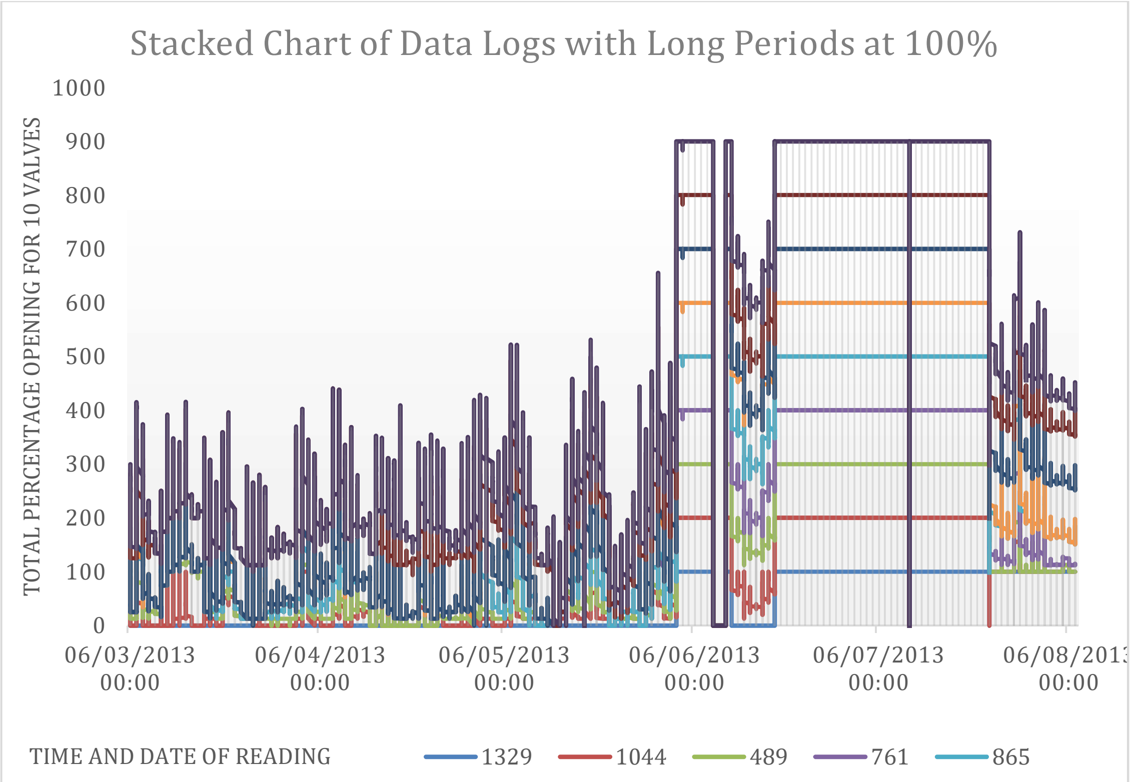

Figure 39. Stacked data showing four distinct periods when many logs show an extended common value of 100%.

The BMS could attempt to drive the control valves to 100% open for a variety of reasons:

- FCU or AHU undersized;
- AHU delivering air at an inappropriate temperature requiring the FCU to compensate for the additional load;
- Central CWS and LTHW out of service – controller calling for heating or cooling when no capacity is available;
- Heating valve trying to compensate for a cooling valve which is stuck open and vice versa.
- Doors or windows left open adding to the ventilation load;
- Additional loads such as machines or computers introduced into building in excess of design parameters;
- Coding error in controls algorithm;
- Insufficient heating or cooling capacity.

In any case, an investigation into the causes for this phenomenon was outside the scope of this study. This study is focused on investigating whether the data is suitable for use as calibration data for building energy models. It is clear from this section of the investigation into the periods where many control outputs were logged at 100% that the data associated with the period 8:00am on 3rd of June and 8:00am on 24th of July are unreliable.

Appendix E.12 Data logs suitable for building energy model calibration

The data logs for any meters available in ILS1 were extracted from the database. The data were then assessed for continuity and potential sources of error.

Data on the meters given in Table 27 were available.

Meter Name	***TrendLogID***	***Number of entries***
2nd floor emergency power	824	3641
3rd floor emergency power	1079	3642
4th floor emergency power	637	3640
5th floor emergency power	1187	3641
Active power 7	860	3642
External plant supply	897	3643
Ground source heat 1	553	3641
Ground source heat 2	1336	3643
Ground source heat 3	900	3643
ILS emergency lighting	1133	3643
ILS lighting bussbar	445	3642
ILS MCC 1	1430	3642
ILS MCC 2	393	3641
ILS Small power bus	1358	3643
ILS supply to main board	820	3641
Kitchen water meter	1033	3642
Main gas meter	404	3642
Main water meter	921	3643

Table 27. Number of data points recorded for ILS meters.

All meter records had gaps similar to data sets 8, 9 and 10 in Table 27 as well as occasional gaps which occurred at random times.

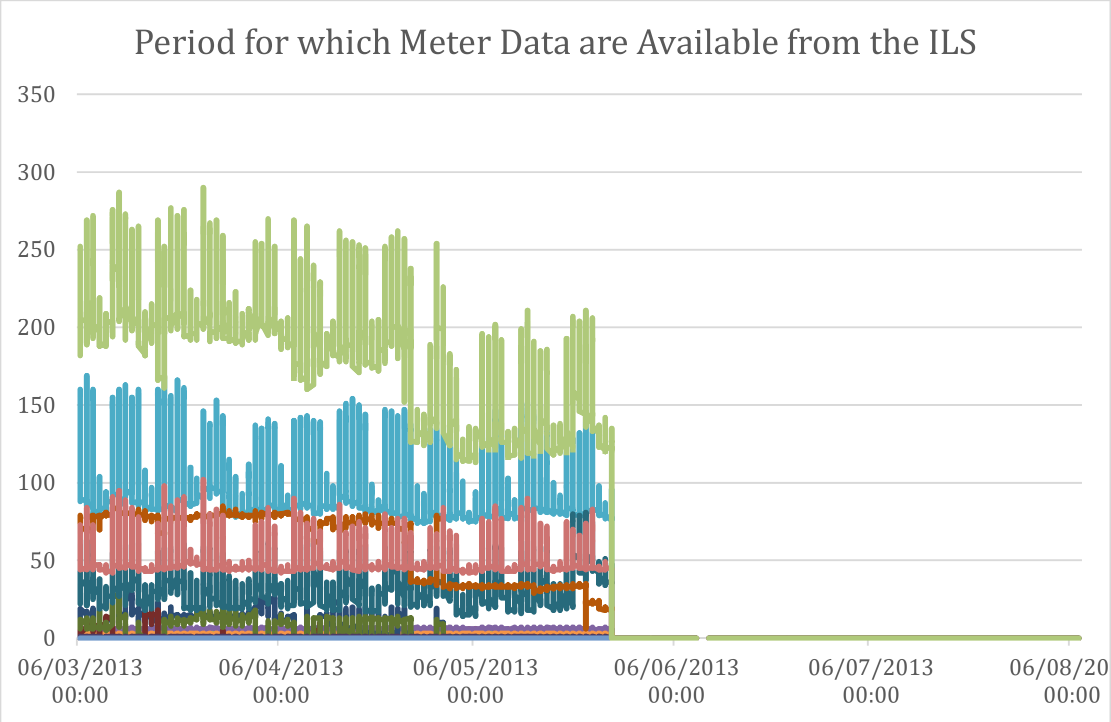

Figure 40. Periods for which meter data were available from ILS1. Colours representing various meters are intended to show the failure to record after 27 May 2013.

The meter logs for the ILS Motor Control Centre (MCC) 2 and for the main gas meter were all zero.

When the data are superimposed on a timeline as shown in Figure 40 above, it is clear that all readings stop at a common time. This was 10:00am on the 27th of May 2013 after 1967 readings. This means that calibration data are only available for just 82 days and only for electrical power.

Appendix E.13 Other questions

Looking at the data contained in the logs there were a large number of potential routes that the investigation could have taken. The data could be examined to answer an extensive list of questions, however the information gained from the investigation would not have helped answer the research questions so these avenues of investigation were not followed.