An Investigation into the Management of Energy Performance for Building Services Systems: Design to Operation

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Contents

Abstract

Non-domestic buildings account for 12% of UK greenhouse emissions (CIBSE, 2017). There is acceptance that the energy performance of buildings must improve. Presently building energy data is only available in terms of total annual fossil or electrical energy totals. These are blunt instruments for energy managers. There is a need for a method of managing the energy of individual building services components through all project phases.

This study aims to examine present methods for building energy use estimation and to develop a strategy whereby building energy use can be managed from feasibility through to building operation. The research methods centred around six case study buildings. Five of the case study buildings selected are existing, were built at different times, under different statutory energy regimes and therefore different design philosophies. The sixth case study building is under construction. Investigating the energy performance of buildings involved applying the most up to date system of energy estimating techniques and comparing results with benchmarks and actual energy use. Surveys and record data for one of the buildings was investigated in order appreciate the implications of design margins and the effectiveness of control arrangements for circulating pumps. The results of these case studies and investigations provided the basis for the development of an energy management strategy.

Although building energy models have streamlined the design process, outputs have been found to be optimistic. This study has found that it has not been possible to reconcile energy use predictions, benchmarks or utility bills with actual energy use for individual building services components. Additionally, monitored performance data is not utilised to quantify the effects of plant over-sizing. This thesis proposes an energy management strategy which enables the energy use of individual components of a building services project to be managed through all project phases. It is proposed that this methodology should also be developed into a facilities management programme for buildings.

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Abbreviations

AHU	Air Handling Unit
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning
BIM	Building Information Modelling
BMS	Building Management System
BRE	Building Research Establishment
BSRIA	Building Services Research and Information Association
CIBSE	Chartered Institute of Building Services Engineers
DEC	Display Energy Certificate
DHWS	Domestic Hot Water System
DSM	Dynamic Simulation Model
DX	Direct expansion
ECI	Early Contractor Involvement
EEI	Energy Efficiency Index
EPC	Energy performance certificate
EU	European Union
HVAC	Heating, Ventilation and Air Conditioning
O&M	Operation and maintenance
PICV	Pressure Independent Control Valve
POE	Post Occupancy Evaluation
PROBE	Post-Occupancy Review of Building Engineering
RIBA	Royal Institute of British Architects
SFP	Specific Fan Power
TM	Technical Manual
TRY	Test Reference Year

Chapter 1: Introduction

1.1 Background

Non-domestic buildings account for 12% (CIBSE, 2017) of UK greenhouse emissions. Despite the growing awareness within the construction industry of the need to control energy use in buildings, there is little reliable data on the performance of individual building services systems. Energy and carbon emission monitoring initiatives have recently been developed and, although this is a welcome development, they do not itemise energy in greater detail than annual electrical and heating totals. Utility bills also provide annual energy use in this form.

Although building energy models have streamlined the design process, outputs have been found to be optimistic. This study has found that it has not been possible to reconcile energy use predictions, benchmarks or utility bills with actual energy use for individual building services components. Additionally, monitored performance data is not utilised to quantify the effects of plant over-sizing. Part of the reason for this is the design of building management systems which do not obtain appropriate data for system efficiency analysis, and in some cases, poor metering. Building services engineering systems are interrelated with design, management, occupation and operation of buildings and therefore, prediction and analysis of their energy performance requires, not only a knowledge of building science but must also include occupant behavioural factors. Similarly, contractual and practical facilities management issues must be considered.

Priorities for facilities managers have meant that ensuring safe and satisfactory building conditions for clients takes precedence over investigation into systems performance. This can be a particular problem in existing buildings where facilities managers must deal with inherited legacy problems caused be obsolete design practices.

Although the need to improve building services design accuracy has created a considerable level of research, this strategy tends to apply to buildings at, and around handover stage. Long-term carbon reduction of building created by energy use requires resolution of the gap between actual and optimum operational performance as well as the gap between actual and design stage predictions.

There is no single cause for the sub-optimal energy performance of buildings. Consequently there is no single solution. A symptom and evidence of this phenomenon is the concept of the "performance gap". However, though useful, the performance gap can have several definitions. It is normally considered to describe the difference between the actual energy used by buildings and the levels of energy use which were predicted at design stage. De Wilde (2014) states three definitions –

- The difference between first principles predictions and measurement
- The difference between machine learning and measurement
- The difference between predictions and display certificates

All three definitions refer to a completed building where energy can be measured. They also infer new buildings where design, predictive data is available for comparison. For many existing buildings much of the information used at design stage has been discarded. Furthermore many existing buildings have changed use, have undergone refurbishments and do not have strategically located energy meters.

The type of building energy gap is dependent on the reference value to which energy use is compared. Borgstein et al (2016) have identified a range of methods for analysing, classifying, benchmarking, rating and evaluating energy performance in non-domestic buildings. Borgstien's work recognises the multiplicity of factors which can affect how a building uses energy, not least being occupant behaviour. Though this range of methods exists, they have not led to wide sources of catalogued reference data being available. The thrust of Borgstein's work tends to relate to methods of diagnosis rather than solution. Also, much of the research in this area deals with total fossil or electrical fuel use over a prescribed period, usually a year. Kampelis et al (2017) have investigated the performance gap in “Near-zero buildings” and their evaluation examines the situation in a little more detail, in that some data has been obtained from Building Management Systems (BMS). However, this is still not as specific as it could be and only considers some renewable-type equipment. Kampelis et al do, however, recognise some of the imperfections in the location of sensors reporting the BMS. BMS problems are echoed in the Innovate Uk’s Building Energy Performance Report (Palmer, Terry and Armitage 2016) which has found that—

- BMS systems are often not set up for data collection
- BMS systems typically only record a maximum of 1000 points.

1.2 Hypothesis

This study considers that sub optimal building energy performance results from incomplete methodologies for the management of building services equipment and systems.

1.3 Aim and objectives

The purpose of this thesis is summarized in the Aims and Objectives as follows:

Aim: This research sets out to consider factors which contribute to sub-optimal energy performance of building services engineering systems. From an appreciation of these factors, the study aims to develop a strategy so that poor performance of individual plant items is recognised and can therefore be improved.

Objectives:

To review how the managerial and contractual implications for building services procurement affect the accuracy of design, installation and commissioning of building services systems and consequent effect on building energy use.

To explore the characteristics of the performance gap concept in order that its role in contributing to improved energy performance for building services can be contextualised.

To examine the relationship between design-stage ratings of building services equipment and actual operational loadings.

To examine building services equipment in order to determine how energy management can be developed to monitor specific plant items.

To develop a strategy for managing the energy used by building services systems, particularly for the operational phase of a building life-cycle.

1.4 Research novelty

The imperfections involved in the processes for procuring, designing and installing building services systems require to be recognised and, therefore a realistic strategy for managing building energy use must include, not only better pre-handover techniques, but these must also co-ordinate with long-term operational management systems. This study sets out to identify causes for poor operational performance and proposes how these problems can be overcome.

1.5 Overview of this thesis

Chapter 1 introduces the topic and briefly describes why there is need for a dedicated accounting system for the energy used by individual building engineering systems.

Chapter 2 describes the context within which building services systems are designed, installed and maintained. It also underlines importance of this group of technologies in both resource and financial terms. The chapter identifies the problem of the performance gap and provide some detail on the challenges involved in delivering systems. The challenges tend to be technical in nature but part of their solution lies in improved management and co-ordination of systems. Technical problems are related to how engineering practice and theory are applied in practical, commercial situations, whereas procedural problems involve co-ordinating expertise and design responsibility within the different phases of a project. Short-term solutions such over-sizing equipment can have long term implications for efficiency and energy use.

Chapter 3 sets out the method and strategy for carrying out the study. The research methods centred around six case study buildings. Five of the case study buildings selected are existing, were built at different times, under different statutory energy regimes and therefore different design philosophies. The sixth case study building is under construction. Investigating the energy performance of buildings involved applying the most up to date system of energy estimating techniques and comparing results with benchmarks and actual energy use. Surveys and record data for one of the buildings was investigated in order appreciate the implications of design margins and the effectiveness of control arrangements for circulating pumps. The results of these case studies and investigations provided the basis for the development of an energy management strategy.

Chapter 4 describes the application, results and comparisons of the energy estimates with benchmarks and actual energy use. The estimating technique applied was based on the CIBSE TM54 process which has been developed as part of the solution to the performance gap. This technique consists of dynamic simulation modelling combined with straightforward spreadsheet calculations. The philosophy behind this approach is that dynamic simulation is effective for dynamic loads such as heating and cooling of buildings. The spreadsheet calculations are more applicable for energy use which is more related to building occupant behaviour. Results from these estimations were compared with benchmarks and actual energy use. Both of these parameters were obtained from the UK Government Display energy Certificate web site. Although, energy use and benchmark data in the form of total fossil or electrical energy is useful for comparing total energy values, it is of limited value for comparison with energy use by individual building services components.

Chapter 5 explores the relationship between design parameters and actual operating conditions, including the implications for the levels of energy improvement offered by variable speed pump control. Additionally, in this chapter the DSM estimates for the size and operational of major plant (boilers and chillers) are examined and compared with actual ratings in order to assess if load diversity plays any part in the specification process. This chapter also sets out methods for the early-stage determination of pump and fan energy, so that these values can be incorporated into a TM54 estimation process. By comparing specification parameters with commissioning and maintenance data, the ratio of design margins and their effect on pump and fan efficiency are calculated. All circulating pumps in the case study buildings have a variable speed facility and the control and performance of two sets of pumps in one of the case study buildings have been examined in detail. The result of this evaluation is that actual control of these pumps does not comply with the project specification and therefore an energy saving opportunity has not been fully exploited. More importantly, the BMS has not informed facilities managers of this situation.

Chapter 6 sets a proposed strategy for improving the energy performance of building services engineering systems. Chapters 2, 4 and 5 demonstrate the frailties in the procedures involved in transferring design ideas into practical operational schemes. These chapters also identify areas where potential improvements are available. Chapter 6 sets out a strategy for improving how the energy used by buildings managed. For greatest effect this strategy should be applied sequentially at all stages of a project. For existing buildings, this may not be possible though the strategy still applies. The design of a strategy for a particular application should take into account the resource available to facilities managers. Therefore the outputs from this energy strategy should be framed in terms which are meaningful to facilities managers from a range of backgrounds. The system should also include a capability for continuous commissioning. This will require permanently installed instrumentation, which will provide additional data so that a complete assessment of operational conditions is available. This data should be sufficiently detailed and logged so that when facilities mangers are required to replace or retro-fit equipment, legacy problems such as oversized plant can be resolved.

Chapter 7 concludes the thesis and summarises the major outcomes of this study. The chapter also identifies the limitations of this research and suggests where areas of this topic should be further investigated.

Chapter 2:

Literature Review

This chapter sets out a comprehensive literature review of the issues that influence and affect how building services engineering systems use energy. This includes a range of inter-related factors, which contribute to the effective design, management and operation of building engineering systems.

2.1. Building services: a key construction discipline

The need for improved performance within the construction industry has instigated much research into how building projects are managed. Seminal reports by Latham (1994) and Egan (1998) are widely respected for how they have transformed construction management thinking. Much of this ground-breaking research has considered an overall examination of the industry in which there has been recognition of the sometimes fragmented nature of an industry in which a single project can involve a range of disciplines, main and sub-contractors, and a range of different professional consultants.

Building services engineering is one of the key construction disciplines. The relevance and importance of building services may be viewed from a financial or an energy standpoint. Building services installations typically account for 20-30% of the total value of a project-and sometimes a great deal more (Rawlinson & Dedman, 2010) Unlike other building components buildings services are active energy users so the operational costs are frequently more important than the capital costs. Operational energy for a building refers to the energy required for heating, cooling, lifts, domestic hot water, and the other ancillary systems, which enable a building to function. Many of these system will comprise sub-systems such as pumps, fans and controls which will operate for years. Additionally, energy will be used for the maintenance, upgrading and replacement of the facilities as they become less efficient or functionally obsolete. Churcher (2013) has found that the process of extracting raw materials and construction uses around 10-20% of a project's life cycle energy, the rest being operational costs (energy). The logical inference from Churcher's work is that building services will use a considerable amount of energy during their operational lifetime.

2.2 Building services: management and energy performance

2.2.1 Building Services Coordination

Achieving an efficient, low-carbon building installation would be a more straightforward process if it was simply an engineering task. Although high quality engineering skills and equipment are vital components in a project, building services systems are not installed in laboratory conditions. The nature of the industry creates additional factors which can affect how installed systems eventually perform.

A building services installation can involve several disciplines, each of which can be the responsibility of a different sub-contractor. A successful installation will require the co-ordination and bringing together all of these dynamic systems. This is further complicated because this linking and interfacing of different systems must normally be achieved within the programming and co-ordination requirements of a complete construction project. The quote below (Clements-Croome & Johnstone, 2014) illustrates the characteristics for building services projects.

"Building services frequently comprise several technologically distinct sub-systems and their design and construction requires the involvement of numerous disciplines and trades. Designers and contractors working on the same project are frequently employed by different companies. Materials and equipment is supplied by a diverse range of manufacturers".

Clements-Croome's observations identify the project challenge of managing inter-related, but also somewhat disconnected disciplines to ensure that they interface and function to provide environments and systems that will enable building occupants to perform successfully, safely, efficiently and with an appropriate level of thermal, acoustic and visual comfort.

2.2.2 The performance gap

In an RIBA press-release for a UK Green Building Council research project (2016) , the performance gap is defined as the difference between "what building design promises and what clients actually get". In the preface to CIBSE TM54, Justin Snoxall (Head of Business Group, British Land) (2013) states that new buildings, when operational, consume between 50% and 150% more energy than original expectations. Other reports insinuate an even greater difference between how much energy buildings are designed to use and how much they actually use. In one of CIBSE's Carbon Bite electronic pamphlets, Menezes (2012) states that buildings typically consume 2-5 times more than predicted at design stage. In a report by Innovate UK (2016) non-domestic buildings were found to consume 3.5 times more energy than was expected. In this study the energy performance gap relates to the difference between the design and operational values for the electrical and fossil energy used in the case study buildings.

In order to determine a performance gap, it is necessary to quantify the energy used by a building. Graham (2015) writes "historically, it's been challenging to validate how buildings perform in real terms, and to compare that with the expectation that may exist at design stage".

Graham's comments refer to Energy Performance Certificate values for energy use which when compared to actual energy use present a considerable gap. However, though this phenomenon did create some initial concern, it is now recognised that an EPC is a compliance tool. This is explained by Lewry (2015) who describes role of an EPC as "a theoretical assessment of the asset under standard "driving conditions" typical of that type of building in that location". Actual building energy use is recorded on a Display Energy Certificate (DEC), which is similar in appearance. In a study of 163 buildings, de Wilde (2014) found that even though a comparison of EPC's and DEC's is not like for like, there could be a lot of confusion amongst clients and the general public. A DEC shows the energy performance of a building based on annually recorded energy consumption, whereas an EPC calculates a carbon emissions based on information relating to building design, energy equipment and system specifications and is therefore a certificate of compliance rather than an accurate record of building energy use. Asset Ratings appear on Energy Performance Certificates and are found by calculation, while the Operational Ratings used by Display Energy Certificates are based on metered data

One way of comparing performance with some standard is to use benchmarks. The Chartered Institute of Building Services Engineers publish benchmarks in two documents: CIBSE TM46 (Bordass, et al., 2008) and CIBSE Guide F (Cheshire, 2012). TM46 provides the benchmark data used in Display Energy Certificates (DEC's). Both of these documents can be used to assess annual electrical and fossil-thermal fuel energy use. The indices used in these documents list annual energy/carbon use in terms of either kWh/m^2 or kg $CO2/m^2$. These benchmarks can be used to quantify typical energy usage for various building types by applying an appropriate floor area.

2.2.3 Carbon Buzz

One of the responses to the problem of the performance gap has been the development of Carbon Buzz. Judit Kimpian (2014), one of the project managers for this initiative, has identified that an important factor in the challenge to resolve this gap is feedback from actual projects. Kimpian also recognises that this feedback should disclose both predicted energy use as well energy used during building use.

Carbon Buzz is a software platform which has been created as a collaborative project between CIBSE and RIBA. This platform has been set up in order to develop a database of predicted and actual energy values for building projects. The data for this database is compiled from submissions of project energy data by participating practices. Organisations who submit data electronically may do so anonymously and this is guaranteed, although submitting on a "full disclosure basis" is encouraged. There may be a reticence amongst construction professionals to submit complete details because of a fear of litigation. Robertson and Mumovic (2014) researched into the relationship between designed and actual performance and found that liability was a major reason preventing industry actors from collecting data. Robertson and Mumovic also cited costs, inability to access buildings, loss of money and reputational damage as barriers to collecting and using energy feedback.

Data submitted from a variety of sources and representing different phases of a project can be analysed so that design and actual energy-use values can be determined and compared. In this way it is planned that increased feedback and knowledge can identify and, therefore, eliminate the causes of the performance gap. Carbon Buzz is in fact, another source of energy benchmarks. Edwards (2013) comments that because Carbon Buzz crosses professional boundaries and covers most building types, the data helps build inter-professional understanding in the design and management of the building stock.

2.2.4 System Design and Installation

Building services design encompasses a wide range of technologies. These include:

- Heating
- Ventilation and air conditioning
- Controls and building management systems
- Domestic water systems (hot and cold), and drainage
- Sprinklers, drenchers
- Electrical distribution, lighting, information technology infrastructures, fire and security, smoke control, lighting protection
- Lifts and escalators
- Utility supplies – electrical power, gas, water, telephones

All of these technologies can be part of a single project which, not only demands capability in a range of disciplines, but they must also interface and co-ordinate, and must be designed, installed and commissioned within the scope set by a construction project programme. Additionally, the building services engineer is only one of a team of project stakeholders, each of which will have varying roles and priorities.

The design involvement for building services consultants will vary according to the type of commission, the nature of the project and procurement method adopted. Ideally building services designers will have input from feasibility to project handover and use. Typically these stages will include (RIBA, 2013) pre-design, briefing, concept design, concept design, develop design, technical design, construction, handover and systems operation.

The brief will vary depending on the nature of the client but should enable the designers to prepare practical, buildable and maintainable systems which will fulfil the client's needs to a level which has been agreed to be appropriate to the finances and resources available. Whatever the resources available practicality, buildability and maintainability should always be achieved, and of course, safety is non –negotiable. Portman (2014) considers that the briefing process develops from a broad statement of intent to a point prior to detailed design, when the consolidated brief should be agreed and frozen between the client and all the contributors to the project. Frozen and agreed scheme briefs are the ideal situation for managing projects but changes are often inevitable and almost guaranteed with some clients.

Sourani and Manewa (2015) recommend that the project brief should state clearly the multidimensional nature of sustainability so that it cannot be ignored at any stage of the project delivery. Clearly this is a laudable aim but in any project sustainability will compete against many other factors, not least of these being finance. The practicalities that emerge from this process may un-earth factors of which the team were previously unaware. This may require further feasibility studies or financial re-assessment and may affect the development and setting of project objectives and desired project outcomes.

The concept design stage is where building services engineers begin to translate client requirements into preliminary practical schemes. Proposals begin to be developed so that the volume, space, weight and building attendance requirements of building services systems become apparent. All of these factors have consequences for the rest of the team who can begin to be able to consider how their proposals are affected. Churcher and Sands (2014) consider at this stage building engineers will produce layouts indicating locations and routes of services, plus block diagrams which demonstrate the size and location of plant areas. The desired level of precision for this stage is plus or minus 25%. (Churcher & Sands, 2014). Although this tolerance level is stated in terms of a numerical percentage, it has been set as a guide to spatial and volumetric accuracies, which can enable designers to refine proposals as the project develops and it would be impractical for tolerances to be absolutely precise at concept stage.

If the ideas demonstrated at concept stage meet client approval and do not initiate a need for redesign, at developed design stage building services engineers firm up equipment sizes and location. They also provide details of “builder’s work” requirements. This stage is often referred to as “sketch design”. The desired level of precision for this stage is plus or minus 15% (Churcher & Sands, 2014).This work cannot be carried out in isolation and all parties should consider the physical co-ordination between building features. According to McPartland (Clash Detection in BIM, 2016) unless this is done, clashes may not be picked up until installation stage with “potentially huge costs and delays”. Mc Partland’s view is supported by Hwang and Low (2012) who consider that this type of problem can have a significant effect on “project cost performance”. Wan and Kumaraswamy (2012) further comment that poor space-conflict resolution is a critical shortcoming” in project management.

At the technical design stage building services engineers should complete detailed design calculations, provide detailed spatial co-ordination and prepare co-ordinated working drawings. The desired level of precision for this stage is plus or minus 5% (Churcher & Sands, 2014). Within the industry this stage may be described as “tender design” and is often the stage at which design responsibility can become blurred. Brewer (2005) quotes a relevant legal judgement:

> “*In conclusion, Lord Drummond Young held that the expression 'fully co-ordinated' referred to the first stage of co-ordination, not the second. The expression 'approved for construction' simply meant that the drawings in question must have attained final release status, where no further revisions would be required except in the case of minor amendment. The qualification of the subcontract therefore meant no more than that the tender drawings relied upon by Emcor in fixing its price were of a sufficient quality to comply with the first stage of the design co-ordination process. Emcor retained the obligation to develop those drawings into installation drawings to fulfil the second stage of co-ordination.*
>
> *In effect, fully co-ordinated meant only partly co-ordinated; Emcor was not entitled to assume that the tender drawings would generally have reached the stage of development where installation drawings could immediately be issued to its operatives on site”.*

This legal dispute occurred during a building services contract at the Edinburgh Royal Infirmary in 2005. The project electrical specialist contractor (Emcor Drake and Scull) considered that their bid price was based on an interpretation of the term “co-ordinated” which meant that tender drawings had been prepared to a level of completeness which meant that electrical services could be installed with no further need for design changes. In fact, further design work was required from the electrical specialist contractor in order that the electrical installation could be installed in the designated locations and link in with other inter-dependent services. Consequently Emcor Drake and Scull claimed £5m against the main contractor (Balfour Beatty Ltd.).

Some context for Lord Young's judgement is given by Rawlinson and Dedman (2010) who point out that, under typical consultant agreements, the task of detailed design is "often limited. It is common for contractors to be obliged to complete the sizing and spatial coordination of the services installation". Design responsibility often falls to contractors. A strategy statement (2017), for a large national contractor, explains that it is common practice to employ consultants up to detailed design stage. After which the contractor takes on co-ordination role in order to produce a practical scheme which reflects design intent.

Different project contributors can have varying interpretations of "design intent" and where this creates construction clashes, this can lead to re-design, re-work and delay, which can be expensive and adversely affect project progress. The BIM process has recognised these risks and consequently a specification for best practice in for the management of construction information has been developed and is known as publically available specification (PAS) 1192 (BSI , 2013). A crucial element of this specification is the recognition that construction information and design responsibility evolves and changes during project progress. Much of this will occur within a "common data environment" which is developed into a design intent model. From this model design responsibility and ownership is transferred to appropriate designers and suppliers. Of course, to apply this specification successfully all parties within a project are required to embrace these concepts.

At the construction stage, depending on the type of contract, much of design responsibility can pass to the installation contractor (Oughton & Wilson, 2015) to progress design intent. In any case contractors are responsible for the production of working drawings. This involves input from suppliers and specialist sub-contractors. The concept of "design intent" may be somewhat fluid, particularly for design and build type contracts.

Towards the end of site operations, building services designers (both consultants and contractors) become involved in commissioning the building services installation. The

Carbon Trust (2011) advise that competent commissioning can significantly reduce a building's running costs, eliminate faults and ensure the success of energy efficient designs. However, Oughton and Wison (2015) consider that, although commissioning and handover are key to the successful operation and occupation of a building, historically the importance of these stages has not been fully recognised. Potts and Wall (2002) describe commissioning as "the Cinderella activity in the construction cycle".

Commissioning should co-ordinate with handover to the client. In the past there has been a disconnection, at practical completion, between the team responsible design, installing and commissioning buildings services systems and the team responsible for their operation and maintenance. Bordass's solution (Bordass, 2011) is to regard buildings as custom products more like ships and make commissioning as "sea trials". Bordass's work has been instrumental in the development of the Soft Landings initiative. The Soft-Landings initiative is aimed at improving the operational performance and usability of the building by tackling the shortcomings involved in a cliff-edge handover approach. Building Services Research Information Association (BSRIA, 2016) defines the soft-landings process as "a cradle to operation project which enables designers and constructors to focus more on operational performance outcomes". The Soft-Landing idea has recognised that the fragmentation between construction disciplines combined with a need for greater understanding amongst clients and building users has affected post operational building performance. By maintaining a stronger relationship between designers, installers and facilities managers, Soft-Landing offers greater opportunities for fine-tuning of systems, improved resolution of defects and better operational feedback.

2.2.5. Design Margins: Over-Sized Building Services

Over-design, over-engineering or over-sizing are all terms that are used to describe building services systems or components which are larger than they need to be. Where this occurs, it can often be caused by the addition of excessive margins to plant and equipment sizes (Cheshire, 2012). Although every project must be assessed individually, the potential for this problem to occur should be recognised. CIBSE guidance on energy efficiency cites over-sizing as a risk to plant performance in chapters covering the design (2012) process, energy strategy, controls, ventilation and air conditioning, refrigeration, plant sizing, and electric motors.

Not only can over-sizing increase the capital cost of plant and equipment but this can also create energy and operating cost penalties. As regards co-ordination, plant space is often a negotiation between the various members of the design team, each of which will have priorities within their own disciplines. This type of co-ordination exercise may require some compromise. For example, an oversized ventilation duct which may run through a ceiling void may require an architect to increase ceiling void depth. This in turn may require an increase in building height, increasing the need for materials and putting additional pressure on foundations. All of these factors would be of interest to the quantity surveyor.

Apart from the problems caused by having to find room for larger plant, operation of oversized plant can increase energy use and running costs in several ways. Some if the effects of over-sized plant are (Cheshire, 2014) **-**

- Low part load efficiencies for boiler plant
- Pumps and fan using excess energy and therefore not operating at optimum efficiency
- Electric motors operating at power levels below design can negatively affect power factor
- Emitter outputs affected by different fluid heat transfer situations caused by flow regimes outside of design parameters
- Instability in control systems – for example hunting

Race (1998) defines margins as “an amount allowed beyond what is needed or an allowance for contingencies”. A more recent definition is given by Eckert et al (2017) “the extent to which a parameter value exceeds what it needs to meet its functional requirements regardless of the motivation for which the margin was included”.

In their study on over-sizing of HVAC systems, Djunaedy et al (2011) identify increased costs in terms of an immediate penalty associated with the first cost of equipment and an ongoing penalty due to maintenance and use implications. The costs associated with oversized building services are also recognized by Dvorak (2016)**,** who points out that design practices which do not account for “refined load operations and diversity” will have negative implications for both capital and operating costs. Dvorak cites the following factors which increase running costs: short-cycling, under-performance and early equipment failure. Jones et al (2018) in a study on margins for boiler plant in NHS buildings, concluded that over-sizing is apparent across the whole life-cycle of an installation and this has consequences for both capital and operating costs. In this study oversizing has been considered for pumps and fans because, although they are relatively smaller energy-using plant items, they operate for many hours during a building's operational life.

Design and procurement within a building services context is an iterative process involving several stakeholders, many of whom have an interest in ensuring that plant will always meet the imposed loads. Therefore, at each stage of design and procurement a safety-first approach may lead to generous sizing decisions. If several stakeholders take this approach, the effect will be cumulative. The motivations behind this strategy may include fear of litigation, low levels of skill and experience, lower fees leading to hurried designs, lack of feedback from previous projects, and access to simple benchmark figures.

Some studies in the USA have examined the practice of over-sizing HVAC plant. Sun et al investigated the effects of sizing HVAC plant under conditions of uncertainty. Sun et al (2014) use the term "defensive sizing" and describe a design margin as a safety factor. Sun's paper infers that safety factors are widespread in HVAC and cites reports which suggest over-sizing of air conditioning plant by 25% and more. Sun recognises that the purpose of safety factors is to ensure that the operational system will be sufficiently robust to cope with unspecified loads, but also refers to professional risk as possible motivating factor. In examining causes, Sun et al (2014) comments that although there have been great advances in dynamic simulation modelling when compared to HVAC techniques, "load calculation methods have been anchored in the ASHRAE Handbook of Fundamentals for decades". This study, though useful did not report on any feedback from actual projects.

Another USA study, however did investigate practical situations. Denchai et al (2014) investigated the relationship between energy use and system over-sizing for HVAC plant serving a range of retail outlets. The plant provided both heating and cooling as appropriate. This work reported that a definite relationship existed between oversized plant and excess energy use. In these cases, the additional energy expenditure was caused by more frequent control cycling of plant. Huang et al (2014) recognise the value of quantifying uncertainty but consider that further understanding of uncertainties "on the performance of the design" is necessary. Huang suggests that over-sizing occurs because designers apply a worst case design scenario, or add a safety-factor.

With regard to fans, various researchers have concluded that fan energy for buildings is considerable. Trane (2014) , in their corporate newsletter, state that fans consume 30%-40% of commercial HVAC energy. This figure of 40% is confirmed by Brelih (Brelih, 2012). The energy used by fans is also recognised in the UK Building Regulations (Gov.UK, 2016).

2.3 Building Service Systems

This section considers how fans and pumps use energy. Fans and pumps have in the past, been regarded as ancillary equipment which supports major plant items. However, despite their comparatively lower energy demand, fans and pumps run for long periods during building operations with a consequence that their energy use is significant.

2.3.1 Fans and Pumps

In the centralized ventilation and air conditioning systems used in non-domestic buildings, there are statutory limits on the energy that fans require. It is important that designers and facilities managers are aware of the factors that affect how a fan performs (Warren, 2016). These include:

- The types of fan used in commercial/industrial applications including their performance characteristics
- The design process for the selection of fan and ductwork systems recognising the frailties within the design, installation and commissioning process
- The implications of EU electric motor efficiency standards for the energy use of fans
- The limitations on fan energy use set by the UK Building Regulations

The energy required to drive a fan is related to the pressure required to overcome the frictional resistance of the ductwork system through which the air is delivered. Methods for fluid flow design in HVAC systems are, in most cases based on the Bernoulli theorem (Krieder, et al., 2016), which states that the total energy possessed by the particles of a moving fluid is constant. The total energy for a moving fluid is composed of its potential energy, pressure energy and the kinetic energy. If the energy is expressed in terms of a mass flow rate of 1 kg, it can be described by the formula -

$$Total\ energy\ of\ fluid\ flow = gz + \frac{P}{\rho} + \frac{V^2}{2}$$

Where

$g = acceleration\ due\ to\ gravity\ (m/s^2)$ $P = fluid\ pressure\ (Pa)$

$\rho = fluid\ density\ (kg/m^3)$ $V = velocity\ of\ fluid\ flow\ (m/s)$

$z = height\ above\ datum\ (m)$

Where this theorem is applied to air flow in ductwork, the potential energy is small and is generally ignored and the Bernoulli equation is simplified to –

$$Total\ pressure\ (P_t) = static\ pressure\ (P_s) + velocity\ pressure\ (P_v)$$

Jones (1985) explains this simplification:“Since energy is the product of an applied force and the distance over which it is acting, and since pressure is the intensity of the force, total pressure may be taken as the equivalent energy per unit volume of air flowing. The potential energy of the air stream is its static pressure. The velocity pressure may be regarded as kinetic energy per unit volume”.

There are numerous types of fans used in building services applications. CIBSE publication TM42 (2006) lists most of the types of fan used in building services applications.

2.3.1.1 Typical Fans used in commercial systems

The major types of fans specified for commercial projects are centrifugal and axial (Cowell et.al, 2006). An axial fan consists of a cylindrical casing which contains propeller type fan blades. As the name suggests, this type of fan directs air in an axial direction. The aerofoil cross section of fan blades creates forces which give motion to the air and develops pressure. Manufacturing specifications such as tip clearance and blade design will affect fan efficiency. Excess tip clearance will allow air leakage and blades should have a slight twist in their length to cope with the variation in air speed between the tip and base of the blade. The action of the blades will tend to impart a rotary component to the air flow. Some fans will have downstream guide vanes to correct this effect. The cylindrical external form of the fan means that it can conveniently co-ordinate into duct systems. There are several types of axial flow fans available, but for general HVAC applications, tube- axial and vane axial arrangements tend to be most common. According to the American Society of Heating, Refrigeration and Air-Conditioning Engineers (2015), “Vane axial fans (Figure 2.1) are essentially tube axial fans with guide vanes and reduced running blade tip clearance, which give improved pressure, efficiency and noise characteristics.

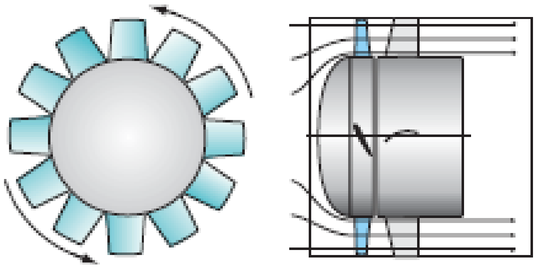

Figure 2.1 Vane Axial Fan (TM42 2006 CIBSE)

Unlike centrifugal fans, the movement of air through an axial flow fan does not involve a change of direction and therefore axial fans can be located “in-line” in ductwork. The compactness of shape and volume for axial fans means that they can be installed within tighter locations than their centrifugal equivalents. Though the air is propelled axially through the fan, it can be disturbed by the rotational effects of the fan blades. This swirl-effect can be offset by downstream guide vanes, or in some cases by the addition of contra-rotating fan blades. Axial flow fans are often specified for extract systems, which can have a lower pressure requirement that their associated supply systems, which normally include filtration and heating/cooling coils. Axial flow fans are also specified for pulse ventilation of car parks and tunnels.

A centrifugal fan operates on a different principle to the way in which axial fans work (Cowell et.al, 2006). The main moving part of a centrifugal fan is the impeller, which is a rotor on which blades are mounted. The rotation of the impeller enables the blades to throw air outwards and this creates an area of low pressure at the eye of the impeller. The process of drawing air into the eye of the impellor which is then discharged from the blades means that the air supplied to the system has completely changed direction. For most centrifugal fans the impeller spins within a volute casing which, because its shape has an expanding cross section, enables some of the high velocity pressure at the blade tips to be converted into static pressure. The speed of the flow leaving the impeller is dependent on the centrifugal and rotational components of velocity imparted to the air, which is related to the shape and angle of the blades. The major types of fan impeller used in HVAC systems are those with blades which are inclined forward and those with backward curved blades. The performance of a fan is normally analysed by means of its characteristic, which can be graphically appreciated if this shown as a curve relating supply volumes, pressure developed and efficiency. Typical characteristics for axial flow, forward curved and backward curved fans are shown in figures 2.2, 2.3 and 2.4, which have been developed from generic fan curves (Chadderton, 2014). The characteristic fan curves demonstrate that fan efficiency is not constant and therefore demonstrates how over, or under-sizing fans can negatively affect fan energy use.

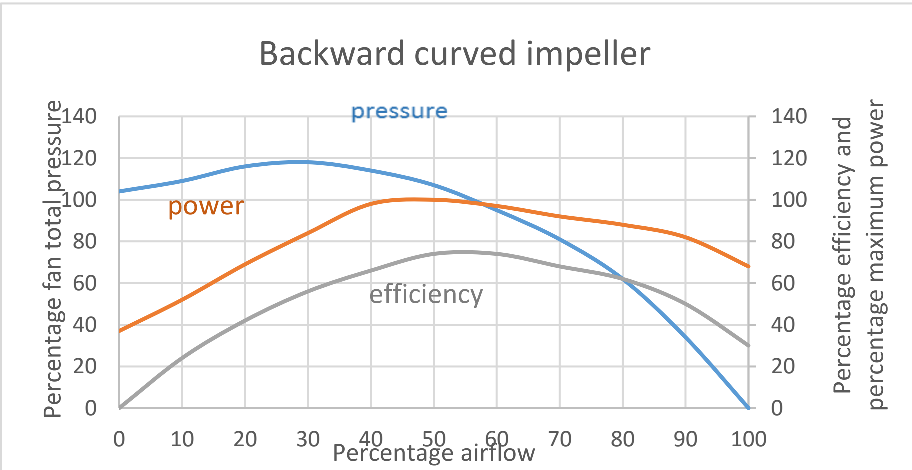

Figure 2.2 Backward curved centrifugal fan characteristic (Chadderton, 2014)

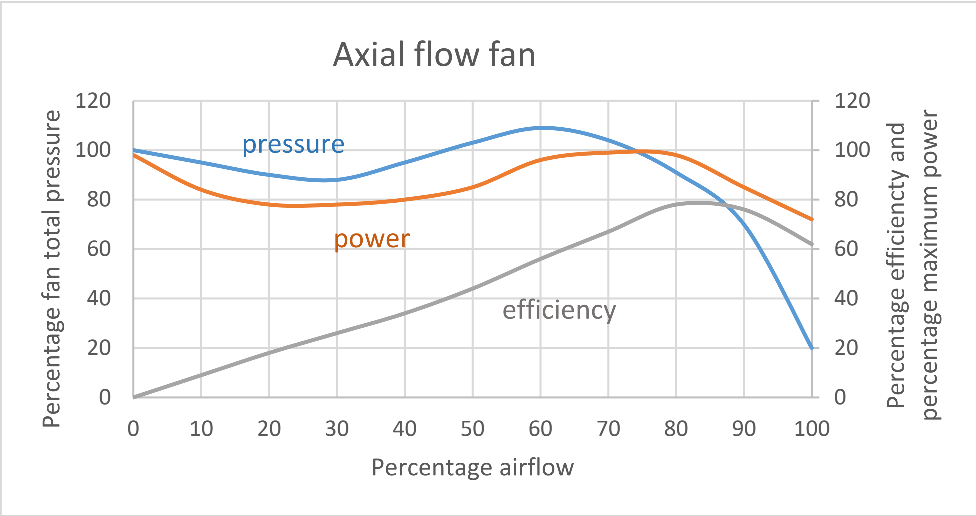

Figure 2.3 Axial flow centrifugal fan characteristic (Chadderton, 2014)

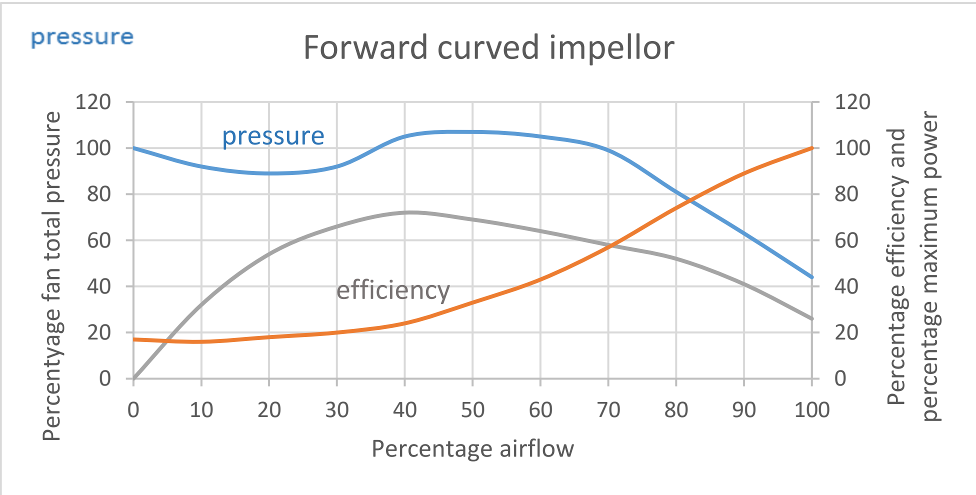

Figure 2.4 Axial flow centrifugal fan characteristic (Chadderton, 2014)

Forward curved (Figure 2.5) centrifugal fans tend to have a scooping effect on the air which results in the air having higher velocities when leaving the impeller (Cowell et.al, 2006). This provides the opportunity for lower speeds, reduced noise generation and a relatively smaller diameter impellor. The smaller impeller leads to reasonably compact air handling equipment. The smaller space requirement can make air handling units with forward curved fans attractive to specifiers for low pressure HVAC applications. However, an examination of the characteristics demonstrates a rising power curve which can create a situation in which excessive energy may be used against smaller than predicted system resistances. In a worst case condition the fan may overload. It is also important to note that the peak efficiency for a forward curved fan does not coincide with the peak pressure developed.

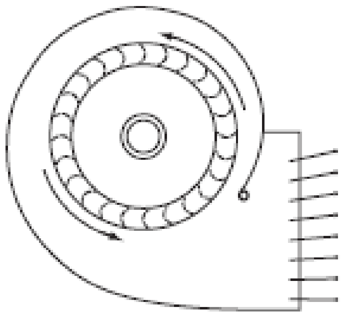

Figure 2.5 Forward Curved Centrifugal Fan (CIBSE TM42 2006)

Backward curved centrifugal fans (Figure 2.6) have impellor blades with an increased depth compared to forward curved (Cowell et.al, 2006). Backward curved fans have higher efficiencies, particularly if the blades have an aerofoil section. The angle and shape of the blades improves the air flow form by reducing eddies and shock losses. The impeller diameter is greater than that required for a forward curved fan delivering an equivalent flow rate. Reference to the performance curves show that, provided the motor is capable of meeting the peak load, backward curved fans have non-overloading characteristic. This type of fan is therefore forgiving where system resistance values may vary. Backward curved fans are specified for HVAC application where efficiency gains justify additional cost.

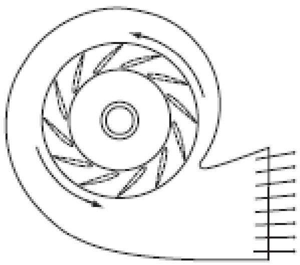

Figure 2.6 Backward Curved Centrifugal Fan (TM 42, 2006)

Plug fans (Figure 2.7) which are sometimes referred to as plenum fans, are centrifugal fans which are not located within a scroll casing (Dwyer, 2014). These types of fan are popular for use in air handling plant. In this application, they are located within the casing of an air handling unit. The fan compartment allows the fan to supply air directly into the space which becomes a pressurised plenum. The appeal of this type of air handling plant is its reduced overall size. Manufacturers claim high efficiencies but these may be related to direct drive arrangements and low-loss duct connections to the plenum. The performance curves for plug fans will be similar to the centrifugal fan characteristics (Fig.2.2 and Fig.2.4), though specific characteristics will depend on manufacturer.

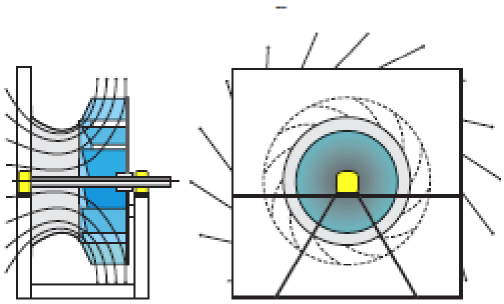

Figure 2.7 Plug Fan (CIBSE TM42, 2006)

(Note: Figures 2.1, 2.5, 2.6 & 2.7 reproduced with permission of CIBSE)

The mechanical or aerodynamic efficiency of a fan may be determined from the formula (Chadderton, 2014)

$$Fan\ efficiency = \frac{air\ power\ (vol\ flow\ \times pressure)}{shaft\ power\ (mechnical\ power\ input)} \tag{2.1}$$

All centrifugal fans experience some energy losses (Dwyer, 2014). Causes of these losses are partly because of design quality and others are caused by the nature of the air movement process. Volumetric losses occur within the volute casing due to friction, mixing of different velocities as air leaves impellers, and the orientation of the blade angles and fluid flow. There are, of course frictional losses in bearings.

Axial flow fans are also influenced by the design quality issues mentioned in the section (2.3.1.1). Efficiency can be affected by blade design. Aerofoil blades should create suitable ratios of lift and drag forces and an appropriate angle of attack.

2.3.1.2 Centrifugal Pumps in HVAC applications

Pumps have a major role in heating and air conditioning systems (Oughton & Wilson, 2015). Circulating hot or chilled water around a building is an efficient method of delivering heating or cooling energy. Similarly to fans pumps use an impellor which draws fluid into its centre. The spinning motion of the impellor thrusts the fluid in radial direction thereby creating a region of negative pressure at the impeller eye. The pump impellor spins inside a casing or volute which is shaped so that much of the velocity given to the fluid is converted into pressure energy (Figure 2.8 (Evans, n.d.))

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Figure 2.8 Centrifugal Pump Operation (Evans, n.d.)

Pump flow rate is related to the resistance of the pipe circuit, through which the fluid is delivered (Oughton & Wilson, 2015). As the resistance of the circuit increases, the flow rate will reduce. Figure 2.9 illustrates this relationship. The point at which the two curves intersect identifies the pump operating point.

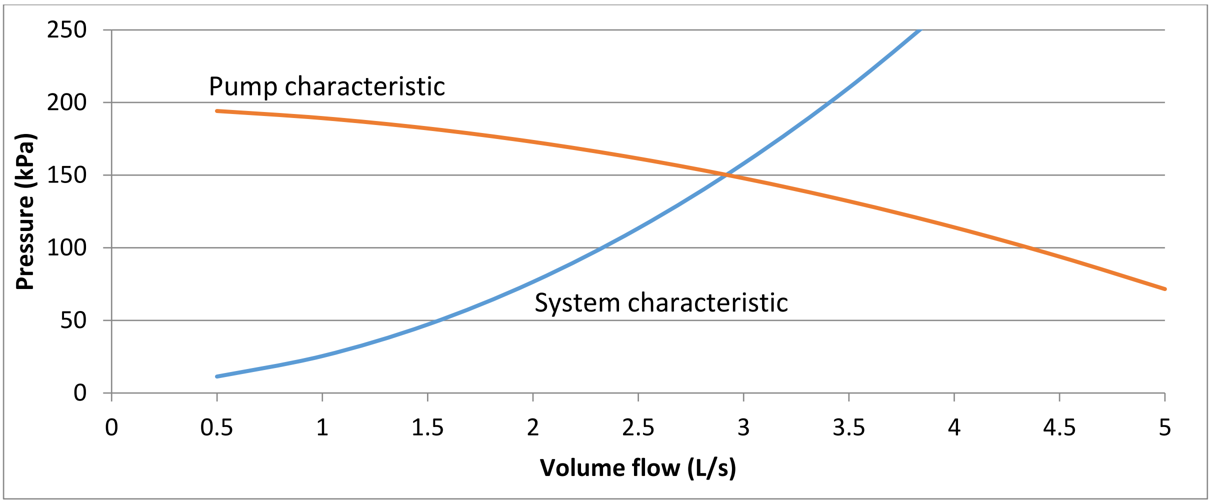

Figure 2.9 Pump and system characteristic (CIBSE, 2015)

2.3.1.3 Typical pumps used in commercial HVAC applications
There are a variety of pump types available on the market (Oughton & Wilson, 2015), but for heating and chilled water systems common applications for commercial buildings are (Figure 2.10) –

- Single stage (one impeller) close coupled end suction
- In line centrifugal pumps.

The image *originally presented here cannot be made freely available via LJMU E-Theses Collection because of copyright. The image was sourced at https://uk.grundfos.com/products/find-product/nb-nbg-nbe-nbge.html*

Figure 2.10 Close coupled end suction and in-line circulating pumps. (Source: Grundfoss Ltd.)

2.3.1.4 Duct and Pipe System Resistances
To select a fan or pump that will supply air through a ductwork or pipe work system, designers must determine the fluid volumes that must be delivered and the resistance

against which the fan or pump must operate. The pressure loss in a straight duct can be found from the D'Arcy equation (Koch & Sprenger, 2007)

$$\Delta p = \lambda * \frac{1}{d} * \frac{1}{2} * \rho * C^2$$

(2.2)

Where $\Delta p = pressure\ loss\ (Pa)$

$\lambda = friction\ coefficient$

$d = diameter\ (m)$

$\rho = air\ density\ \ (kg\ /\ m^3\ \ )$

$C = velocity\ (\ m\ /\ \ s)$

Values for fluid densities are related to temperature and can be calculated or obtained from tables. Fluid velocities can be determined from the relationship between volume flow rate and pipe/duct cross sectional area. For the determination of friction factor, CIBSE recommend the use of the Haaland equation (Koch & Sprenger, 2007).

$$\frac{1}{\sqrt{\lambda}} = -1.8 \log\left[\frac{6.9}{Re} + \left(\frac{k/d}{3.71}\right)^{1.11}\right]$$

(2.3)

Where

$R_e = Reynolds\ number$

$d = pipe/duct\ diameter\ (m)$

$k = equivalent\ roughness\ of\ \ pipe/duct\ \ material$

The total resistance which a pump/fan must overcome is not only pressure drop due to the frictional loss in straight duct, it must also account for the additional pressure losses created by pipe/duct fittings. Where the fluid flow encounters shape changes or obstacles, the effect will be to change velocity and create vortices. The technique used to determine the pressure loss dues to fittings involves applying pressure loss factors to the velocity pressure which is present at the particular fitting. The pressure loss factors (ζ) have been developed from complex data, however the fundamental equation for pressure loss in a duct fitting is (Koch & Sprenger, 2007) –

$$\Delta p = \zeta * \frac{1}{2} * \rho * C^2$$

(2.4)

Where ζ = pressure loss factor.

The mathematical formulae for determining duct size and pressure drop is suitable for use by software. CIBSE have developed excel spread sheets which incorporate the formulae (Koch & Sprenger, 2007). This offers a simpler and, provided appropriate data is submitted, a more straightforward method of determining pipe/duct sizes and pressure drops. Prior to this approach, the determination of duct/pipe sizes was more cumbersome. However, spreadsheet and software techniques still require designers to exercise judgement in the selection of parameters. Libraries of pressure loss factors are published by CIBSE and ASHRAE for various pipe/duct expansions, contraction and other configurations. Much of the pressure drop created in a pipe/duct scheme is caused by the manufactured equipment which is incorporated into the system. For example, duct systems include air handling units include coils, filters, bird mesh, dampers and other equipment. Pipe systems include boilers and heat other heat exchangers. The pressure drop for air flow through this type of equipment should be quoted by the manufacturer. Fluid pressure equations are probably more appropriate for laboratory situations. Table 2.1 (Koch & Sprenger, 2007) indicates the levels of accuracy which should be factored into duct and pipe pressure loss calculations. Designers need to be aware of the limitations of the manufacturing and installation processes, particularly since consultant designs completed to tender (technical design) stage are then effectively re-designed to become co-ordinated contractor's working drawings.

Determination of system pressure drops is an essential component of the pump/fan duty calculation (Chadderton, 2014). The product of the fluid flow rate and resistance (equation 2.5) determines the motive energy given to the water/air. The electrical power supplied to the pump/fan will be a greater value because of the efficiencies of the pump/fan and the electric motor (equation 2.6). The energy used by electric motors has been recognised in European Regulations. Table 2.2 indicates European directive 6004/2009 which sets outs four classifications for electric motors rated between 0.75

kW and 375 kW (EC Commission, 2011). The timeline for conformance is set out in Table 2.3.

Table 2.1 Guidance for pressure loss factor selection (CIBSE Guide C, 2007)

• Data from Idelchik must now be viewed with circumspection
• In the region 2000 < Re 3000 < the flow may be laminar or turbulent.....it would be prudent to base calculations on turbulent flow in this region
• Where spirally would duct is additionally swaged for stiffness, a further pressure drop can be expected but no data are available
• The concept of using hydraulic diameter (for non-circular ductwork) is fundamentally flawed. The flow in circular ductwork is symmetrical about the axis, giving identical fluid velocities close to all parts of the duct surface; this does not exist within non-circular ducts.
• CIBSE is more confident about the data for circular ductwork than for rectangular ductwork
• There is a strong possibility that the values listed may be on the low side (90^0 degree tees with enlargement taper for combined flow converging)
• Idelchik's information is derived from many other sources, so some discrepancies may be expected (Elbow 90^0 rounded inner corner)

$$Water/air\ power\ (W) = system\ resistance\ (Pa) * vol\ flow\ rate\ m^3/s$$

(2.5)

$$Motor\ power\ (W) = \frac{air\ power}{motor\ efficiency * fan\ efficiency}$$

(2.6)

Table 2.2 Electric motor efficiencies (6004/209) (Government UK, 2013)

IE1	Standard efficiency
IE2	High efficiency
IE3	Premium efficiency
IE4	Super premium efficiency

Table 2.3 Timeline for compliance with 6004/2009 (Government UK, 2013)

16th June 2011	1st January 2015	1st January 2017
Minimum efficiency IE2 0.75 kW – 375 kW	Minimum efficiency IE3 7.5 kW – 375 kW	Minimum efficiency IE3 0.75 kW – 375 kW
	OR IE2 with speed control	OR IE2 with speed control

Besides the range of motor sizes covered, the efficiency classes for this standard also include 2, 4 and 6 pole motors. The percentage efficiencies at various grades and motor sizes are included in appendix CH2-1. In order to limit the energy used by fans, the Building Regulations specify maximum specific powers that fan can use. Table 2.4 identifies the maximum specific fan power (SFP) allowable for various types of ventilation system (Government UK, 2013). The regulation allows additional losses for certain components. These allowances are listed in Table 2.5 (Government UK, 2013).

Table 2.4 Maximum specific fan power in air distribution systems for new and existing buildings (Government UK, 2013)

Maximum specific fan power in air distribution systems is new and existing buildings		
	SFP (W/(l/s)	
System Type	New buildings	Existing buildings
Central balanced mechanical ventilation systems with heating and cooling	1.6	2.2
Central balanced mechanical ventilation systems with heating only	1.5	1.8
All other central balanced mechanical ventilation systems	1.1	1.6
Zonal systems where fan is remote, such as ceiling void or roof-mounted units	1.1	1.4
Zonal extract where fan is remote from zone	0.5	0.5
Zonal supply and extract ventilation units such as ceiling void or roof units serving single room or zone with heating and heat recovery	1.9	1.9
Local balanced supply and extract systems ventilation systems such as wall/roof units serving single area with heat recovery	1.6	1.6
Local supply or extract units such as window/wall/roof unit serving single area (eg toilet extract)	0.3	0.4
Other local ventilation supply or extract units	0.5	0.5
Fan assisted terminal VAV	1.1	1.1
Fan coils unit (rating weighted average)	0.5	0.5
Kitchen extract fan remote from zone with grease filter	1	1

Table 2.5 Extending specific fan power for additional components in new and existing buildings (Government UK, 2013)

Extending specifuc fan power for additional components in new and existing buildings	
Component	SFP (W/(l/s))
Additional return filter for heat recovery	+ 0.1
HEPA filter	+ 1
Heat recovery-thermal wheel system	+ 0.3
Heat recovery – other systems	+ 0.3
Humidifier/dehumidifier (air conditioning systems)	+ 0.1

Specific fan power is defined as the “sum of the design circuit-watts of the system fans that supply air and exhaust it back outdoors, including losses through switchgear such as inverters (i.e. the total circuit-watts for the supply and extract fans) , divided by the design air flow rate through that system" (Part L, Non-domestic compliance guide, 2013)

The Building Regulations also recognise the energy used by circulating pumps and specify that, from 2013 circulating pumps should have an EEI (Energy Efficiency Index) no greater than 2.3 (H M Government, 2013). The energy efficiency index specifies how much power a pump may use when compared to a pre-defined load profile which sets a reference power for a standard circulator. Whereas the specific fan power requirement requires the building services designer to size and route ductwork so that the SFP limit is met, the onus for meeting the EEI regulation for pumps lies with the manufacturer.

2.3.2 Two Port Control Valves and Variable Speed Pumps

Two port valves control fluid flow by the process of throttling (Oughton, 2015). As they close less fluid is delivered to the load. If the pump output remains constant, then the system pressure will increase. However, if the pump has a variable speed facility, this potential increase in pressure can be offset by changing the pump impellor speed. The relationship for a two port control valve is demonstrated in figure 2.11.

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Figure 2.11 Two port valve control (Oughton, 2015)

This strategy offers an opportunity to save pumping energy if variable speed pumps are specified. Because pumps speed and fluid flow rate are proportional to pressure delivered, the pump energy requirement will vary as pump speed changes. The energy saving from speed change can be significant as indicated by the pump affinity laws which demonstrate that power changes are proportional to the ratio of the velocities cubed.

$$Power\ 2\ (related\ to\ speed\ 2, Watts) = Power\ 1\ (related\ to\ speed 1, Watts) * \left(\frac{Speed\ 2\ (rpm)}{Speed\ 1\ (rpm)}\right)^3 \qquad (2.7)$$

2.4 Defects, post occupancy evaluations (POE) and services

Atkinson (Atkinson, 1999) defines a defect as "a shortfall in performance which manifests itself once the building is operational". Atkinson's definition indicates that defects can affect building operational performance and it is a logical deduction that defective building engineering services will be less efficient than was the design intent.

Ideally, operational defects will be recognised and resolved (Lowe et.al, 2014). However, it is not always clear which is a defect and which is the result of poor maintenance. Either way defects can give facilities managers' problems for which, in some cases, the solution will be out of their hands.

The practicality of handing over defect-free complicated multi-disciplinary building projects is accepted by the construction industry (Lowe et.al, 2014). This is reflected in standard contractual procedures which set out conditions for the remedying of defects after practical completion. Chapell's (2013) definition for practical completion is "when no defects are apparent and when such minor items as are left to be completed can be completed without any inconvenience to the employer using the building as intended". Of course the definition of inconvenience to an employer may not include reduced plant efficiency, which may not be a high priority for many organisations whose business needs trump energy considerations.

Defects also have cost implications. Boothman and Higham (2013) suggest that defects add 2% to the cost of a project and that this is normally borne by the contractor. There are other less quantifiable costs which can affect contractor-client relationships. Rhodes and Smallwood (2002)consider that where defects are not managed properly "generic customer dissatisfaction may occur".

A series of case studies, known as PROBE (Post Occupancy Review of Building Engineering) was carried out between 1995 and 2002 (Bordass, 2011). The work was sponsored by the Partners in Innovation scheme. These studies tended to find that buildings were likely to use more energy than expected, and this was partly because of building services problems. Though energy performance figured largely in PROBE reports, this was also related to the building performance in terms of occupant satisfaction and productivity.

The fact that not all Post Occupancy Evaluations are completed by building services engineers has meant that that factors considered included parameters such as occupant motivations, aesthetics and logistics (Bordass, 2011). In work on POE for higher education facilities Riley et al (2002)investigated a range of POE techniques, all of which are described as having a noticeable impact on an organisation's profitability and staff morale. Whilst a case could be made that these indices are linked to the performance of the building services installations which control internal environments, these observed parameters indices tend to reflect more immediate business management priorities.
Clients, building occupants and owners do not procure buildings as a technical exercise so that building professionals can use them for obtaining data or for testing ideas (Bordass, 2011). Buildings are built and used to fulfil some business or human need. How well this need has been met may be the focus of an evaluation. However, where POE exercises are completed by a particular discipline it is possible that the priorities applied in the evaluation reflect that particular discipline. For example, a quantity surveyor may, consciously or not, apply a great weighting to costs, whereas an architect may show a greater interest in the artistic merit.

Edwards (2013) commenting on POE considers that "human performance is often poorly understood compared to building performance", and this is further complicated by "intangibles" such as "density of occupation" and "variability in climate preferences". However, Edwards does recognise the effect of technical design decisions, particularly where controls and sensors can assist in performance evaluations. Edwards does, however also criticise the design of controls and sensors in that they are sometimes over-complex and difficult for building users to understand. Post operational evaluation work by Lawrence and Keime (2016) at Sheffield University also highlight the importance of control in terms of thermal comfort where they identify a "need for a more detailed understanding of the variability of perceptions of comfort in different spaces, and the impact of environmental control". Lawrence and Kieme's paper compares passive and active environmental solutions and have identified the potential for control systems which "augment predominantly passive design solutions".

Clements-Croome and Johnstone (2014) link POE to the need for feedback to improve the planning design and operation of intelligent buildings. This work more directly links POE with the building services, the quality of which "can be determined through indoor environmental variables". In the same publication Clements-Croome and Johnstone contrast a POE exercise with an architectural review by stating that "POE is defined as the examination of the effectiveness of the design environment for human users", whereas "an architectural critique focuses on aesthetics, the evaluation of building systems or materials performance".

The theme of linking POE and building services performance is developed somewhat further in an RIBA publication: "Post Occupancy Evaluation and Building Performance Evaluation (RIBA, 2016) primer" this document recommends reviews of the project strategic brief, the client's experience and how the project meets client business needs. The document also includes examination of the technical performance of the building and how the technical performance co-ordinates with client needs. The process is not simply a comparison of design and operational technical parameters, but investigates these parameters in the context of client operational experience. Assessment methods include a mixture of questionnaires, interviews, analysis of building services systems, measurement or calculation of energy use and carbon emissions.

2.5 Barriers to optimal building performance

2.5.1 Overview

The underlying technical theories supporting building services engineering are the same mechanical and electrical principles which support other branches of engineering. Training and educational programmes for building services engineers have much in common with the training and education of other engineering disciplines. These principles of fluid mechanics, heat transfer and electrical principles provide engineers with transferable skills and form a fundamental basis for modern engineers. Therefore these skills, properly applied should deliver professionally completed building services installations. However, despite the fact the building services packages are based on sound principles, the results have not always been satisfactory. Some of this dissatisfaction is related to the performance gap.

2.5.2 Design Management and Contractor Input

The term building services covers a range of technical disciplines which are often required to interface and interact. Building services engineers must manage these links as part of the project information flow. Sosa et al (2007) discuss how this kind of problem can lead to increased costs and programme slippage on complex engineering projects. Sosa' recommends developing a communication strategy which can "catch missed interfaces before they occur". Minor interfaces, often of minimal value when they are dealt with at the appropriate time, can require expensive solutions if they are missed. Ramasesh and Browning's (2014) use the term "unknown unknowns" to describe this kind of problem, whilst Whyte (2015) defines system integration as "the process of making a system coherent by managing interactions across system elements".

In their research into causes of the performance gap Fedoruk et al (2015) concluded that the barriers to improved performance were neither technical nor economic but more related to managerial issues such as how various project phases were specified, contracted and implemented. The implications for project management effects are strengthened in a report by Zapater-Lancaster and Tweed (2016) in which they examined five project case studies. Zapater- Lancaster and Tweed observed that "in the context of design team work, design is considered a process of negotiation where defined goals are rarely fixed at the beginning of problem-solving activities".

Part of the building services design process will involve input from specialist contractors and manufacturer. McPartland (2016) also sees value in inter-mixing of consultant and contractor design input. A report by E C Harris (2013), identifies some benefits from this strategy in design management, but also sees contractual implications. EC Harris's key findings on unlocking supplier contributions are shown below:

- Under-design and variations were seen as major blockers to project performance, causing disruption to the progress of the work, reducing efficiency, increasing site management workload and causing uncertainty with respect to payment
- Incomplete design, design changes and late variations lead to significant waste
- Lead-in times available to check designs are being eroded by re-bidding of packages
- Reduced levels of professional fees have reduced available design resource, which may in turn have affected the quality and reliability of initial designs. Some aspects of design particularly building services continue to suffer from content and coordination issues
- Subcontractor engagement in detailed design supports improved project performance. However, opportunities are limited as a result of competition in supplier selection
- Wider user of highly competitive selection is reducing the incentive for subcontractors to assist main contractors in solution development
- Effective client decision-making and change management, including management of novated design consultants improves project performance
- Evidence that barriers to the implementation of change are hot high enough to discourage high levels of change orders

In a report on early contractor involvement (ECI) in the procurement of public sector facilities, Love et al (2014) describe the benefits of ECI – "A contractor's input during the pre-construction process can significantly improve project design, specification and potentially stimulate innovation". However, this report also considers barriers to this approach, not least being the requirement to remunerate contractors for their participation.

2.6 Facilities Management

Eventually the responsibility for managing the operational phase of a building services installation is transferred to the facilities managers who will then be accountable for operational energy management. Ideally, handover and soft-landings should present the building services at optimum condition, though this is not always the case. Part of the impetus behind the soft-landings philosophy has been the recognition that a sudden shift in responsibility from installer to client at project handover can create long-term problems. Whilst soft-landings has been aimed at resolving hand-over problems, the procedure recommends that it is incorporated from inception and for a limited period after handover. During this period there should be an appropriate level of client involvement with the aim that contractor involvement can diminish and, after a period of extended after care (1-3 years) end. This study identifies the need for a much longer term systems which is specifically aimed at building services systems and components.Given that facilities managers can manage building energy throughout a building's operational life, they can make the most difference to energy performance. Zaw et al (2016) consider that pro-active facilities management applied not only for regular operational purposes, but also including for ongoing commissioning and retrofits can significantly reduce building energy use. In order to successfully resolve over/under sized or poorly performing plant problems at replacement stage, facilities managers must have access to operation performance data, which obviously means that a valid energy monitoring regime must exist. Advice from Facilities.net (Facilities.Net, 2016) comments "Real-time monitoring takes things a step further, allowing facility managers and operators to begin a shift from a long reactive cycle to a much shorter reactive cycle toward being proactive. Jensen (2016) recommends facilities managers should also be directly involved at design stage.

2.7 Discussion and Research Gap

Based on the discussions above, this section identifies some research gaps. Despite the application of tried and trusted engineering technologies and theories, building services engineering systems still do not perform as well as designers and clients intend. This performance gap has been recognised within the industry. The importance of this issue underlined by the levels of finance and energy resources involved. Statutory legislation and a greater awareness of sustainability issues have improved the situation. However, although the more obvious and hence more easily resolved issues have been dealt with, there still remains a need to go further in managing the energy performance of building engineering systems. This chapter recognises that inefficiencies can be created at all stages of building services development. A realistic appreciation of the frailties and limitations involved in applying theoretical concepts is discussed, with particular relevance to fans and pumps. Also, despite strides in project management techniques, it must be also recognised that building services engineering systems are the only construction discipline that is dynamic and actively uses energy throughout a building operational lifecycle. Furthermore, building services engineering is the only construction discipline where design responsibility effectively shifts between consultants, contractors, specialist sub-contractors and suppliers. The linking theme between each of these participants being design-intent. Depending on the nature of the procurement method, the priorities and recompense of and for each participant, design intent can be interpreted differently by different parties. This difference in in interpretation can also be compounded by the inevitable ambiguities, which creep into specifications and contract documentation. Perfecting procurement techniques is an on-going challenge, but, in the meantime, the group who can have the greatest influence on the energy used by building services systems are the facilities managers who will manage these systems throughout the operational life of the project. For effective and successful lifecycle energy management, facilities managers need to be able to measure and monitor building energy use. By this means, discrepancies and short-coming between design and operation of building engineering systems can be resolved. This can involve, not only managing systems, but retro-fitting accurately rated plant where necessary. Presently, the systems for achieving this do not provide facilities managers with an energy accounting system which is sufficiently detailed to achieve these aims.

Chapter 3:

Research Methodology

3.1. Research Concepts

How data and phenomena are gathered and analysed in research is important because the strategy employed should be devised to obtain conclusions, or solutions which are valid and reliable. Though engineering research naturally involves practical and applied techniques, they are in many cases underpinned by classical research philosophies (Fellows & Liu, 2015). To achieve worthwhile outputs, the research methods should appropriate to the needs of the study. This chapter considers various research styles, the research strategies adopted for this study and the practical interpretation of those strategies.

3.1.1 Epistemology

Construction professionals tend to be familiar with techniques based on previously derived data which is often tabulated or otherwise prepared to facilitate simplicity of use (Fellows & Liu, 2015). In professional and commercial circumstances there is generally little time available to investigate the concepts and theorems from which data is derived. It could be argued that for professionals, the basis for much of their applied knowledge is faith. Faith in these circumstances is supported by trust in the respected organisations which have compiled this data. However, for technical researchers it is important to consider the basis from which knowledge has been developed. This is important because it creates an awareness of the fragility of knowledge as well as its validity and appropriateness for the particular research which is being undertaken.

Epistemology is the term which describes the philosophical context of knowledge. In philosophical terms knowledge may be described as "justified true belief" (Knight & Turnbull, 2007). How knowledge is justified can lead to some profound assessments. Thermodynamics may be considered to be the theoretical basis for engineering, however, any in depth study of thermodynamics will lead rational thinkers to be aware of the limits of practicality. For example, the concept of entropy, though useful in day-to-day engineering mathematical formulae, concerns intangible factors relating to the finite nature of the universe. Practising engineers may use the concept of entropy for heat engine calculations but probably avoid its implications regarding energy disorder.

The model of knowledge may observed differently by engineers, sociologists, historians or theologians (Knight & Turnbull, 2007). There are various classifications within epistemology which help to justify how knowledge can be applied in research.

Classical epistemology tends to relate to concepts which have been developed since, and from early Greek philosophers (Plato, Aristotle, Socrates) and concern matters such as the legitimisation of ethics, politics and the true nature of humanity (Knight & Turnbull, 2007). Perhaps this could be described as a search for truth unhindered by factors which limit clear thinking. Alternatively, modern epistemology can relate to natural sciences such as physics, chemistry and biology, etc. A rationalist or positivist approach considers that knowledge derives from logic. That positivism aims to obtain objective facts would indicate that this style of research appeals to researchers with technical, quantitative aims.

Empiricism has a similarity in that knowledge must be verifiable through sensing or measuring (Wennings, 2009). "The empirical approach to knowledge consists of reason constrained by physical evidence. For example, reason in conjunction with observation helps scientists know that the earth is spheroidal", (Wennings, 2009). Despite Wenning's modern view of the shape of the earth, it is important to remember that there has been a time in history when the available evidence indicated that the earth was flat.

The research methodology selected is influenced by epistemological considerations. The choices between a positivist and an interpretive approach are discussed by

Amaratunga and Baldry (2001). In their work on performance measurement in facilities management, they concluded that a combination of positivism and an interpretive approach was appropriate. The reasoning behind this style was that “the researcher should not gather facts or simply measure how often certain patterns occur, but rather appreciate the different constructions and meanings people place upon their own experiences and the reasons for these differences”.

Epistemological considerations for this study indicate that the work is largely positivist in character (Amaratunga and Baldry, 2001). However, it must be recognised that knowledge is not static but changes as access to knowledge increases. This is demonstrated by the famous quote by Isaac Newton which illustrates effectively how knowledge develops: “If I have seen farther, it is by standing on the shoulders of giants”.

The justification of knowledge for this particular research can be defined by stating that it is Newtonian (Rayner, 1997). In other words, it is based on the thermodynamic principles and rules developed by Isaac Newton. Although further developments in science, such as quantum mechanics are superseding these principles, much of the modern world still operates on Newton’s laws and this includes most practicing engineers within the construction industry. It is necessary to be aware that, although these principles are a step in the development of physics they remain legitimate. However, their potential limitations contextualize the data and theorems applied.

3.1.2 Case Studies

Dul and Hak (2008) define a case study as “a study in which (a) one case (single case study) or a small number of cases (comparative case study) in their real life context are selected, and (b) scores obtained from these cases are analysed in a qualitative manner”. Yin (2003) defines a case study as “an empirical enquiry that investigates a contemporary phenomenon within its real life context, especially when the boundaries between phenomenon and context are not clearly evident”.

It is noted that Dul and Hakk’s definition (2008) refers to a qualitative approach to case studies. However, for engineering and technical questions, some quantitative elements are necessary. Korzilius (2018) recognises that qualitative methods are commonly used in case study research and but for studies involving an “empirical-analytical scientific approach” a quantitative analysis may be appropriate. Korzilius supports this strategy by stating that, for some areas of research only a quantitative approach can explain certain phenomena. Korzilius's reasoning behind this statement is demonstrated in Table 3.1.

*Table 3.1 Qualitative and quantitative methods (*Korzilius, 2018).

Research: Social science	Researchers aim to understand and interpret behaviour in the context organizational change and feelings of stress	Qualitative
Research: Technical topics	Researchers gain knowledge through sensory perception and systematic observation resulting in scientific theories	Quantitative

Selecting case study research as a suitable strategy infers that a real-life context for the study is necessary (Yin, 2009). Unlike surveys, this may mean that the number of cases will be small (in some situations a single case). However, if the implications for the effects of real life situations create conditions which vary from the theoretical or laboratory situation, then this must be part of the investigation. The situations considered in this study are affected by contractual, managerial and technical factors which only occur in actual conditions. In fact, the performance gap could be defined as the difference between a "laboratory" performance and actual performance. In both cases the same engineering theory is applied but, for too many cases, the practical situation results do not comply with expected theoretical outputs.

The smaller number of cases involved requires that care is necessary if general conclusions are to be drawn from the study. Mark (2011) describes generalization as "the process of drawing general conclusions from specific observations". However, Korzilius (2018) points out that for case studies "the ideal is to realize, not statistical generalization but analytical generalization, to be able to generalize results to a broader theory". On the matter of case studies and generalization, Flyberg (2006) considers that "formal generalization is overvalued as a source of scientific development, whereas the force of example is underestimated". For this study, the cases considered are projects with long time-scales. Though the work identifies where solutions exist, the application of those solutions is an iterative process and will require patient monitoring.

Dooley (2002), who comments that case studies methodologies are essential for applied disciplines, provides a further perspective on the appropriateness of case study research for a technical investigation. Case studies, in this document involve the analysis of real-life factors and situations. This means that the effects created by the variables involved must be accepted and observed rather than controlled. In this context, Teegavarapu et al (2008) liken case studies to experimental research in which replicated experiments may support generalized theories.

Meredith (1998), writing on the subject of building operations management, is an advocate of the case study approach. Meredith's report sets out to explain where case research is more appropriate than the more traditional rationalist theories. Whilst pointing out that valid empirical generalizations depend on rigorous sampling procedures, Meredith cites work by Aldag and Stearns (1988) who examined research methodology issues and concluded that "87% of the research studies considered included samples based on the investigator's convenience or opportunity". Important elements, which affect the selection of a particular research method, are validity and reliability. Achieving these aims must be related to the techniques which are described in research theory. These techniques or systems must be applied practically in order to enable some analysis and understanding to be obtained. The term "understanding" requires a context. It should be noted that Hudson and Ozanne (1988) consider understanding to be a never-ending process. The context for case study research lies in the need to carry out an in-depth study rather that a wide statistical survey. Unlike statistical analysis, a case study is characterized as an application of analytical analysis. Statistical analysis leads to generalization based on a population sample. Moriceau (2011)considers that a pre-condition for this approach is that the sample is large. Yin (2013) comments that "increasing the number of case considered would mean sacrificing the in-depth and contextual nature of the insights inherent in using the case study method in the first place".

Yin (2009) sets out three criteria by which a case may be an appropriate research strategy –

- Type of research questions posed
- The extent of the control the researcher has over actual behaviour
- The degree of focus on contemporary issues

In this study, it has been necessary to determine how and why the problems exists. Soy's guidance for case study research comments: "Case study research generally answers one or more questions which begin with "how" or "why." The questions are targeted to a limited number of events or conditions and their inter-relationships" (Soy, 2006).

The extent of researcher control in this study is nil. This also indicates the appropriateness of a case study approach and, according to Rowley (2002), "the ability to undertake investigation into the phenomenon in its context is a strength of case studies". In fact, for the researcher to be involved in these cases could contribute to a situation which could become a controlled replication which could nullify some of the relevant influences.

As regards the focus on contemporary issues, this study involves technical data, which is influenced by innovation as well as statutory and non-statutory issues.

3.1.3 Action Research

The purpose and methods applied in research are varied and changing. Some of this change can be related to the different types and aspirations of students; for example, industry professionals who wish to carry out research which is not classically academic. This change is illustrated in a paper by Wildey et al. (2015) "In the past a doctorate was a higher research degree sought by those wishing to pursue an academic career. Candidates pursued a largely solitary journey as full time students, often with scholarships guided by a supervisor in the field of research. The successful doctoral thesis was a passport to the academy. However, in the past two years the ground has been shifting. For a range of reasons universities are offering doctoral degrees that relate more closely to the field of practice and candidates in full time employment are seeking to expand their knowledge and skill as of professional practice".

The impetus for change outlined by Wildey et al (2015) was also recognised by Pearson (1999) who comments "Many of the changes affecting doctoral education and its massification are part of longer-term shifts in the role of higher education world-wide: the drive to pursue economic growth through investment in technology and innovation and the demand for a highly skilled and flexible workforce".

In the context of applied practical study, action researchers are considered to adopt a problem-solving approach. This strategy has a natural appeal to professionals whose working life often revolves around finding solutions to problems. As a bona fide research strategy, Azhar et al (2010) consider that action research "combines both applied and basic research by contributing toward solution of practical problems and creation of new theoretical knowledge at the same time. Action research reviews the existing situation (problem domain), identifies the problems, gets involved in introducing some changes to improve the situation, and evaluates the effect of those changes".

There are similarities between case study research and action research. In both cases researchers "gain an in-depth understanding of particular phenomena in real-world settings and many action researchers adopt the specific guidelines for doing research which the proponents of case study offer"(Blichfeldt,2006). This strategy is demonstrated in work by McManners (2015) who adopted an action research-case study approach in investigating sustainability in aviation. In this work McManners argues that a combination of the prescriptive discipline of case study methods and a "flexible action oriented approach" of action research provided the appropriate structure for achieving the desired objectives".

Although action research is often associated with social science type research, McManners' work illustrates an application in a technological area (McManners, 2015). Another technical example of the application of action research is demonstrated by Farooq and O'Brien (2015) in their study of manufacturing supply chains. Farooq and O'Brien (2015) offer a link between action research and case study research in stating "sometimes action research can take the form of a traditional case study written in retrospect, where the written case is used as an intervention agent".

For this study the major difference between a case study approach and action research is that there is no participation by the researcher. Another way of describing this difference can be to state that the focus of a case study is to investigate “how” and “why”, whereas action research is considered to investigate “how to”. Although a case study approach is applied in this study, an element of solution is included. However, the results from this solution are long-term and therefore feedback is effectively outside of the scope of this work. The application of action research methods in this study are demonstrated in Table 3.2.

*Table 3.2 Action research method (*Wildey et al., 2015)*.*

Action Research Methodology		Relevance to study
Diagnosing	Gathering of data from a range of available sources. Organising data to identify discrepancies	√
Action Planning	Evaluation of data in order to determine particular solutions	√
	Determination of practical methods for the application of solutions	√
Action Taking	Application of solutions to actual situations	Limited relevance
	Feedback from applied strategies	

The applications of the research concept for this thesis are demonstrated in figure 3.1. The major strategies applied include case studies, which have been selected in order to simulate a real-life situation because this is an important factor in actual building operations.

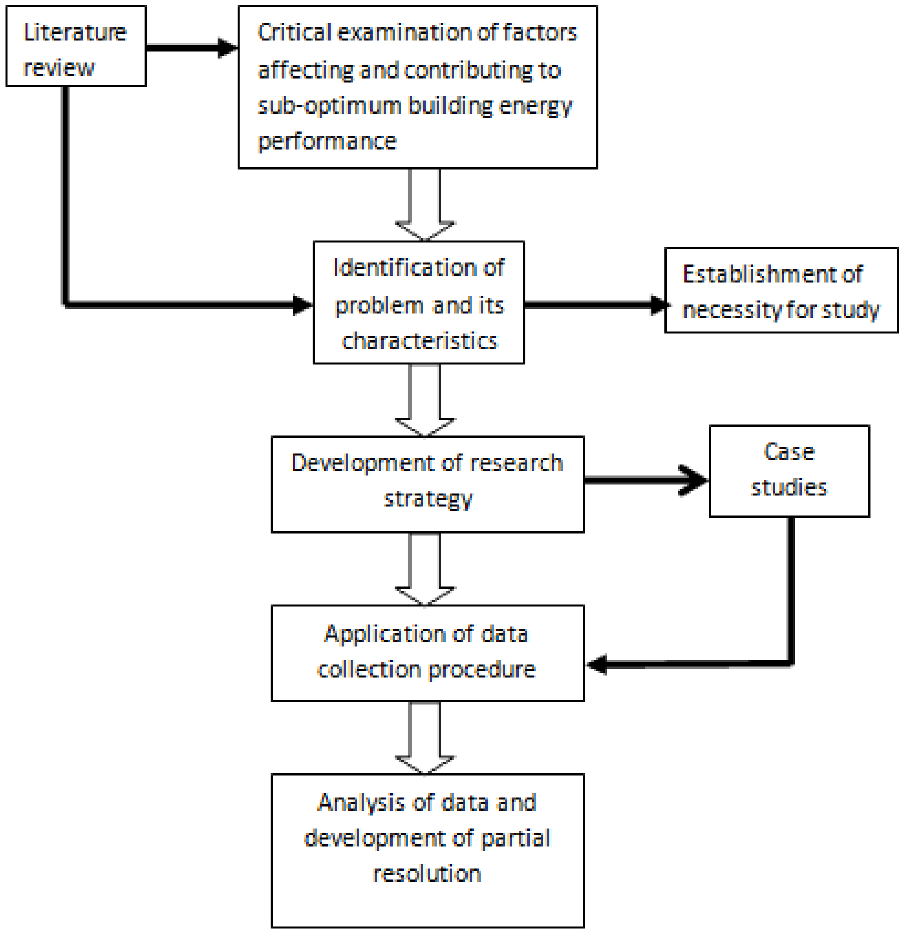


Figure 3.1 Research concept flowchart

3.2. Research Methodology

The methods applied in this thesis have been structured to gain a greater awareness of the current levels of effectiveness for building energy accounting. The methods have been applied in a logical order. Firstly, design stage estimates have been determined for five existing university buildings, enabling comparisons with recognised benchmarks and actual building energy use. The design stage estimates have been prepared using an approach based on the latest system recommended by CIBSE, involving a combination of computer simulation modelling and non-dynamic calculations. The second section of the study considers the five case study buildings from an operational perspective. This examination includes record drawings, maintenance information and monitoring of specific plant items using the LJMU building management system (BMS). For two areas of plant performance which are not measured by the BMS, portable instruments have been used. The third part of the study involves an examination of consultant ventilation equipment design data and its equivalent contractor interpretation for a large hospital project.

The buildings examined in this study are existing as operational buildings or as a building under construction. The case study approach is therefore appropriate and may be described as “quasi-experimental” (Fellows & Liu, 2015). This approach offers the opportunity to develop a concept which is “verifiable and empirically robust” (Sato,2016). Figure 3.2 sets out the logic and structure behind this investigation.

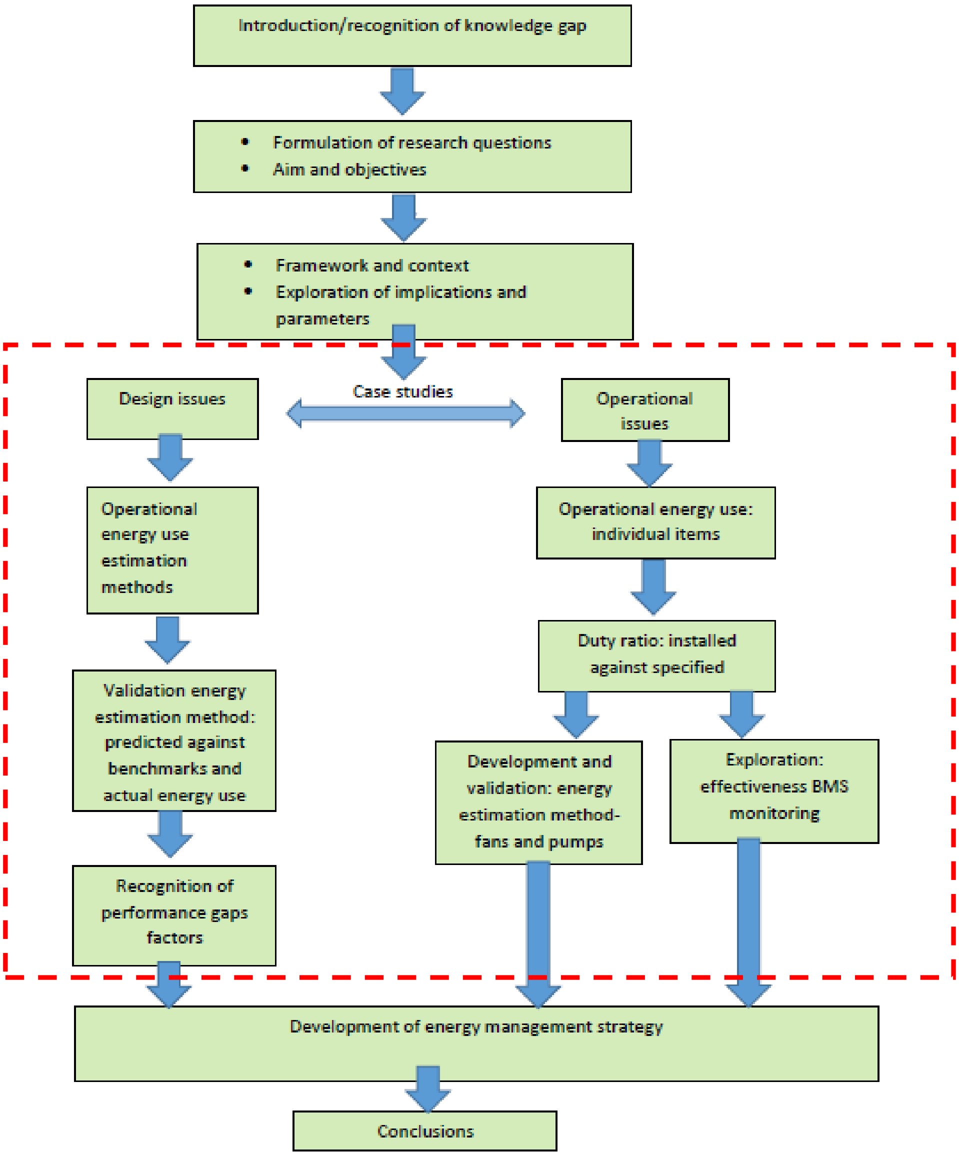


Figure 3.2 Research strategies (red broken line)

3.3. Case study buildings in Liverpool

The six buildings selected as case studies are all public buildings located within the Liverpool city centre, each of which has been built under different regulations. Five of the six buildings selected as case studies are LJMU university buildings located within the campus at LJMU. The sixth building is a large general hospital located in Liverpool. The LJMU building case studies involve energy estimates and HVAC equipment performance assessments. The hospital project has been confined to a study of ventilation fan performance, construction and architectural features have not been considered.

3.3.1 Architectural features and construction characteristics (LJMU buildings)

The energy used by building services reflects the loads imposed because of architectural design characteristics. Table 3.3 outlines the architectural features of each building.

Table 3.3 Architectural Features of five case study buildings

Building	Architectural Features
Peter Jost	The building is four-storey steel-framed structure with a stainless steel external façade. Windows are double-glazed. Metallic insulated roof extends beyond exterior walls. The building is set on a sloping site with the ground floor plant room effectively occupying a basement location. Services routes are in structural risers and within demountable ceilings
Tom Reilly	Four storey concrete frame construction. The external façade is a curtain wall system comprising solid and glazed components. The glazed sections allow natural light into the interior. The exterior facade has openable double glazed colour treated windows. Concrete insulated roof. Interior finishes include exposed concrete structure. Services routes are in structural risers and within demountable ceilings
Cherie Booth	The Cherie Booth Building is a three storey steel frame building with an aluminium cladding external facade and a concrete insulated roof. Clear glazing on East –facing facade except for third floor which also has treated windows on West face. Services routes are in structural risers and within demountable ceilings.
Henry Cotton	The Henry Cotton Building is a concrete framed three storey structure with blockwork facades. The pitched roof is finished in slate. Double glazing is used throughout. Internal spaces divided by demountable partitions and lightweight block walls Services routes are in structural risers and within demountable ceilings
Engineering Workshops	The engineering workshops are an industrial style building and with large open spaces within the workshops. Single storey apart from new two storey extension. Recent over-cladding of workshop zones. Services within false ceilings but exposed in some areas

Apart from the engineering workshop, all of the buildings are multi-storey. These buildings include steel and concrete frames, curtain wall cladding and block-work facades. Overall building dimensions reflect the area of site available and are factors which will affect building thermal performance. The Peter Jost, Tom Reilly and Cherie Booth buildings are all effectively narrow plan. The Henry Cotton building is a deep plan building. The Engineering Workshops are mainly a single storey portal frame construction apart from the newly constructed two-storey office/research area.

Table 3.4 Statutory (Part L) U values for case study buildings

Building and construction year	**Engineering workshops 1966**	**Henry Cotton 1989**	**Peter Jost 1994**	**Cherie Booth 2005**	**Tom Reilly 2009**
Fabric	**U-value (W/m K)**				
Walls	1.7	0.6/0.7[1]	0.45	0.35	0.35
Floors		0.6/0.7[1]	0.45	0.25	0.25
Pitched roof	1.4	0.6/0.7[1]	0.45	0.25	0.25
Flat roof		0.6/0.7[1]	0.45	0.16	0.16
Windows metal		5.7	5.7	2.2	2.2
Windows all other		5.7	5.7	2	2.2
Window area		35%/15%[2]	35%/15%[2]	25%	
Pedestrian doors				2.2/2	2.2
Vehicle doors				0.7	1.5
Entrance doors					6
Air permeability					10 ($m^3/(h.m^2)$ @50Pa)

1. First value for shops, offices and places of assembly. Second value for industrial and other buildings
2. Window area allowance 35% for places of assembly, offices and shops. 15% for industrial and storage buildings
3. Air permeability values ($m^3/(h.m^2)$ @50Pa)
4. Blank cells indicate no requirement under Part L of Building Regulations

(Molloy, 2018)

Table 3.5 U values for case study buildings simulation

Building and construction year	Engineering workshops 1966	Henry Cotton 1989	Peter Jost 1994	Cherie Booth 2005	Tom Reilly 2009
Fabric	**U-value (W/m K)**				
Walls	1.7	0.7	0.45	0.35	0.35
Floors	0.91[1]	0.7	0.45	0.25	0.25
Pitched roof	1.4	0.7	0.45	0.25	0.25
Windows	3.27[2]	3.27[2]	3.27[2]	2	2.2
Pedestrian doors	1.8	1.8	1.8	2.2	2.2
Vehicle doors	0.7				
Air permeability	1[3]	1[3]	1[3]	1[3]	10 ($m^3/(h.m^2)$ @50Pa)

1. Table 3.21 CIBSE Guide A
2. Table 3.27 CIBSE Guide A
3. Air permeability values ($m^3/(h.m^2)$ @50Pa) . Air change rate for pre-2009 (CIBSE Guide A Table 4.10)

Blank cells indicate that the construction element does not apply for that building

Table 3.4 lists the statutory requirements (Building Regulations: Part L) for fabric insulation values which were appropriate at the time of construction. It can be seen that the building regulations have become progressively more rigorous. For example, the 1966 regulations only specified insulation limits for floors and walls. The values are relevant for energy estimations. Where no Part L values are specified they have been determined from building surveys. Table 3.5 lists the U values that have been used in the energy simulations for case study buildings.

3.3.2 Building Service Systems (LJMU buildings)

As well as offsetting the energy loads imposed by the dynamic characteristics of the interaction between the structure and the climate, the nature of energy used by building services is also related to the types of mechanical and electrical equipment which is specified for a building.

Table 3.6 Mechanical and electrical services for the case study buildings

	Peter Jost	Tom Reilly	Cherie Booth	Henry Cotton	Engineering Workshops
Fossil (Gas)					
Radiators	√	√	√	√	√
Warm Air					√
DHWS		√		√	
Electricity					
All air cooling	√		√	√	
Fan coils		√			
Chilled Beams		√			
Split Systems					√
Lifts	√	√	√	√	√
Lighting	√	√	√	√	√
Small Power	√	√	√	√	√
Server	√	√	√	√	√
Laboratory equipment		√		√	√
DHWS			√		√

Table 3.6 outlines the mechanical and electrical services which have been installed in the case study buildings. The terms mechanical and electrical services are sometimes considered to be synonymous with fossil and electrical energy use. In fact, there can be a considerable electrical energy requirement for mechanical services. Although gas is the fuel used for heating the case study buildings, pumps and fans which move hot water or warm air use significant amounts of electrical energy. Refrigeration

equipment, which is the basis for the air conditioning systems used in the case study buildings, is powered by electricity.

The energy use characteristics of the heating, ventilating or air conditioning systems (HVAC) vary considerably depending on the systems which are specified. Table 3.7 lists the HVAC systems, which have been installed in the case study buildings. The major role of HVAC equipment is to transfer heating or cooling energy from where it is generated to where it is required. The media used to effect this movement of thermal energy is either water or air. Delivering heating or cooling energy by pumping hot or chilled water is much less energy intensive than by delivering an equal amount of energy using ducted air systems (Dwyer, 2014).

Although only partially air-conditioned, the Peter Jost, Cherie Booth and Henry Cotton buildings use constant volume all-air systems and therefore are more energy intensive than the fan coil and chilled beam systems used in the Tom Reilly building. Fan coil and chilled beams transfer heat energy using both smaller air- flow volumes and much of the heating/cooling energy is delivered by piped water systems. However, the all-air systems are simpler to design and easier to maintain and control. Although design factors are important, the ability to maintain plant at optimum conditions can have a significant effect on energy use (CIBSE, 2014).

Table 3.7 HVAC systems in five case study LJMU buildings

Building	Peter Jost	Tom Reilly	Cherie Booth	Henry Cotton	Engineering Workshops
Location	L3 3AF	L3 5AF	L3 3AF	L3 2ET	L3 3AF
University Department	Technology and Environment	Sport and Exercise Sciences, Natural Sciences, Psychology	Technology and Environment	Health and Applied Social Science	Technology and Environment
Floor Area (m^2)	2554	6626	1039	7743	1700
Year Built	1994	2009	2005	1989	1966
Operational hours (M-F)	12	12	12	12	12
HVAC	Gas-fired LPHW heating-radiators. Modular boilers. Constant volume air-conditioning. Toilet extract. DHEWS supplied from central plant	Gas-fired LPHW heating-radiators. Dual boilers (66% load/boiler). Chilled beam air-conditioning. Fan coil air-conditioning. Gas-fired DHWS. Toilet extract	Gas-fired LPHW heating-radiators. Dual boilers (66% load/boiler). Constant volume air-conditioning. Split system air-conditioning. Toilet extract.	Gas-fired LPHW heating-radiators. Modular boilers. Constant volume air conditioning. Split system air-conditioning. Gas-fired DHWS. Toilet extract	LPHW heating-unit heaters and radiators. No on-site heat generators. Split system air-conditioning. Toilet extract
Notes	DHWS heating energy is not metered at point of supply		Gas supply is not metered at point of use		Both primary heating and electrical supplies are derived from central system. Neither service is metered at point of use.

3.3.3 Building Use and Occupancy (LJMU buildings)

Other variables which affect building energy use are building use and occupancy. Table 3.8 identifies the functions which occur in each of the case study buildings. Whilst some of these activities are regulated by time-tabling, others are less predictable and are rarely monitored.

Table 3.8 Functions of five case study buildings

	Peter Jost	Tom Reilly	Cherie Booth	Henry Cotton	Engineering Workshops
Lectures	√	√	√	√	√
Administration	√				
Enterprise	√				√
Academic offices	√	√	√	√	√
Laboratories		√		√	√

Occupant behaviour relates to energy use for lighting and equipment, which can be considerable. At design stage occupancy patterns are often set as a standard pattern, which is convenient but unrealistic. Also, function descriptions are somewhat fluid. For example, all staff are involved in administration to some level, but the term administration in Table 3.7 refers to full time administrative staff. Unless the client's brief sets out clearly how and when buildings will be occupied and used, designers may have difficulty in selecting appropriate load diversity factors.

3.4. CIBSE TM54: Evaluating Operational Energy

3.4.1. Introduction: CIBSE TM54

In response to the recognition that a gap between design and actual energy often exists for new buildings, CIBSE have developed an improved technique for design stage estimations of building operational energy. This system is TM54 ((Cheshire & Menezes, 2013) and is one of CIBSE's technical manuals

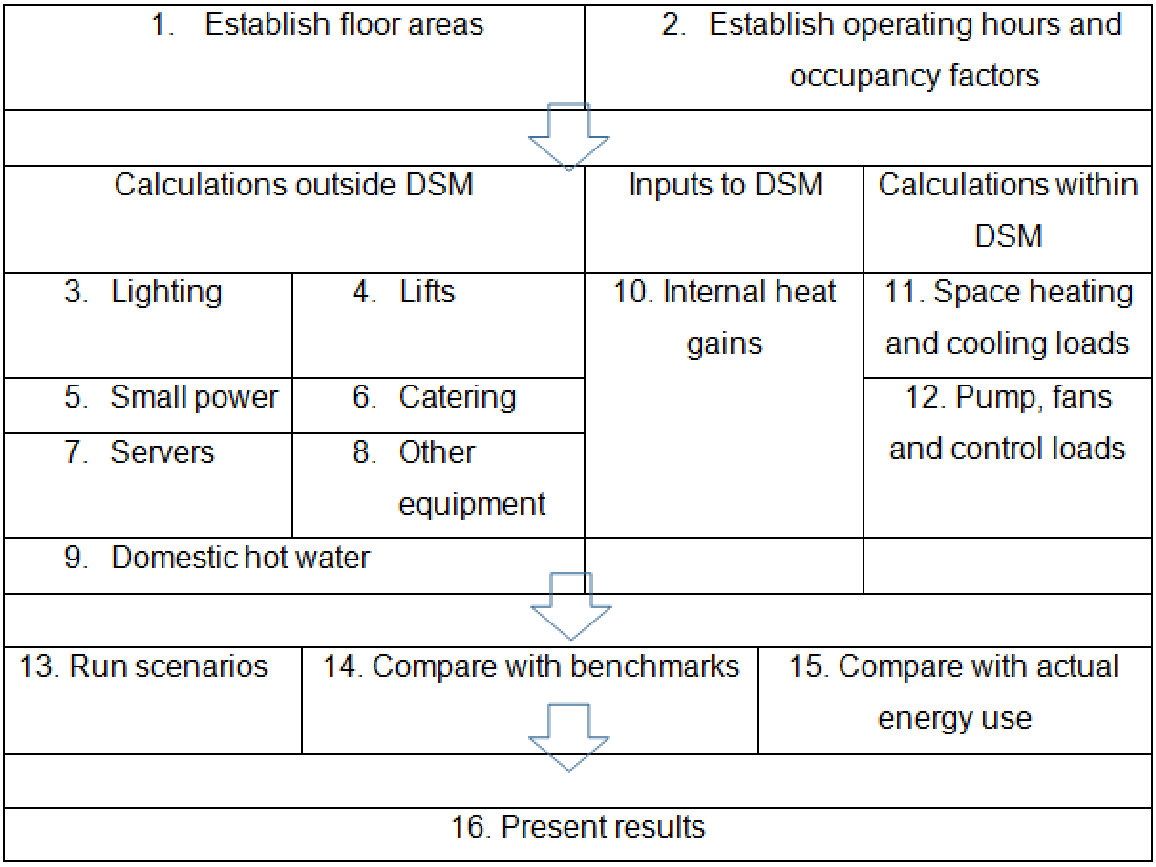


Figure 3.3 Energy estimation method TM54 (Cheshire & Menezes, 2013)

Figure 3.3 sets out the steps involved in the TM54 process, which have been applied to the case study buildings. The logic behind this procedure is to apply the most appropriate (dynamic or non-dynamic) calculation method for each area of building energy use.

3.4.2. Operational scenarios for LJMU case study buildings

CIBSE TM54 method ((Cheshire & Menezes, 2013)has been applied to each of the case study buildings. Although this technique has been prepared for use during design stage, its application to existing buildings has enabled estimates to be compared with actual energy use.

In both new and existing buildings, precise operational details are rarely available. Therefore, several likely operational scenarios for the case study buildings have been created on the basis of surveys (walk-around) and interviews with occupants and facilities managers (see Table 3.9). Selecting appropriate parameters for the various scenarios involved an examination of the LJMU academic calendar and a review of staff operational hours. Additionally, discussions with facilities managers assisted in obtaining plant operational hours. Information from building occupants, in some cases tended to rely on memory rather than recorded data.

Table 3.9 Design and operational scenarios for energy estimates

Peter Jost Building						
Scenarios	Occupancy (hours)	Lift use (starts/day)	Small power (hours)	DHWS (L/person/day)	RH	Lighting
1	14	300	7	7	70%	Manual
2	12	200	6	15	50%	Auto
3	14	300	7	7	50%	Manual
4	12	200	6	15	70%	Auto
Tom Riley Building						
1	14	500	7	15	50%	manual
2	12	500	7	15	70%	Manual
3	14	350	6	7	50%	Auto
4	12	350	6	7	70%	Auto
Cherie Booth Building						
1	12	500	7	15	50%	manual
2	12	350	6	7	70%	manual
3	12	350	4	7	70%	manual

Henry Cotton Building							
Scenarios	Occupancy (hours)	Lift use (starts/day)	Small power (hours)	DHWS (L/person/day)	RH	Equip (hours)	Lighting
1	12	300	7	15	70%	300	manual
2	12	300	6	7	70%	150	auto
3	14	300	7	15	50%	300	manual
4	14	300	6	7	50%	150	auto
Engineering Workshop							
1	12	30	6	15	70%	10	manual
2	12	60	7	7	70%	8	manual
3	12	30	5	15	70%	6	manual

There is a range of causes for building energy use. Weather is a major factor which influences the energy used for heating and cooling buildings. However, energy used in (and by) buildings is also related to occupancy effects. Occupant behaviour can affect energy use, not only directly from use of equipment but also, indirectly where occupants create system loads related to the need to provide internal conditions, which are comfortable, safe and appropriate. The category and number of people within a space will affect the selection of design conditions. Occupants also contribute to cooling loads, ventilation needs and heating requirements. Most buildings cannot rely on daylight as their only means of illumination. Persons within buildings become involved in processes and activities, which invariably use energy. Additionally, the times spent by staff or residents of building is the basis of plant operational schedules. Anticipating and predicting building energy use requires that accurate as possible building use scenarios are considered. For this study, weather effects were largely reliant on the weather data contained within the dynamic simulation software. Weather-related building energy use is also affected by decisions on internal conditions, hours of operation, building orientation and construction. Some of this information is comparatively straightforward to compile but envisaging scenarios for occupant behaviour and equipment use can be more challenging. The TM54 process, used in this study, recommends that estimates of energy used for heating, cooling, humidification and ventilation should be determined by dynamic simulation methods, and that occupancy-related energy use should be investigated through appropriate scenarios. For the case –study buildings, there is no recorded data for use of lifts, domestic hot water, lighting or small power. Cooling coil dew-points stated in maintenance manuals indicate that tight room humidity’s may be achieved, though this depends on actual control settings. Room percentage saturation is not monitored by the building management system. Because occupancy and associated equipment use in the case study buildings is not monitored it has been necessary, in some cases to apply statistical/benchmark techniques. Although this is industry practice, it does impose limitations and it also requires estimator judgement in selecting factors. Table 3.10 demonstrates the factors upon which scenarios have been developed.

Table 3.10 Scenario development logic

<table>
<tr><td>Parameter</td><td></td></tr>
<tr><td>Occupancy (hours)</td><td>Academic calendar
Estate manager advice
Interviews with building occupants.
Student attendance is monitored for some time-tabled sessions but not for self-study hours</td></tr>
<tr><td>Lift use</td><td>Interviews with building occupants.
The disposition of lifts / staircases
Lift speed
CIBSE Guide D
<table>
<tr><td>Lift Duty</td><td>Starts/day</td><td>BS IDO/DIS 25745-1</td></tr>
<tr><td>Low

Medium

High

Intensive</td><td>≤ 100

300

750

1000</td><td>Residential care, goods, library, entertainment centre, stadia (intermittent).
Office car parks, general car parks, residential, university, hotel, low-rise hospital, shopping centre.

Office, airport, high-rise hospital

Headquarters office</td></tr>
</table></td></tr>
<tr><td>Small power</td><td>Site survey
Interviews with building occupants.
Occupancy hours</td></tr>
<tr><td>Domestic hot water</td><td>Site survey
Interviews with building occupants.
CIBSE Guide G</td></tr>
<tr><td>Lighting</td><td>Site survey
Interviews with building occupants.
BS EN 15193:2007 section 4</td></tr>
<tr><td>Relative humidity (sensible and latent cooling)</td><td>Site survey
Maintenance manuals/record drawings
estate manager advice</td></tr>
</table>

3.5. Building Energy Modelling and Calculation (LJMU Buildings)

3.5.1. Dynamic simulations: IES VE

Energy modelling for buildings involves the application of complex equations which can only be realistically resolved by numerical simulation methods. The value and convenience of using software for these applications has led to the development of a range of commercial dynamic simulation packages. The package used in this study is IES VE (IES VE, 2016). Although all models are "a simplified view of the real world" (Williams, et al., 2015), a reliable level of accuracy is required. IES is validated for space heating, cooling and building envelope and fabric loads by the American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE, 2016). The ASHRAE tests include comparisons of IES software with other leading commercial packages. The test reveals that, although outputs are similar, there are differences between systems. IES is also approved for UK compliance calculations (UK Government, 2008).

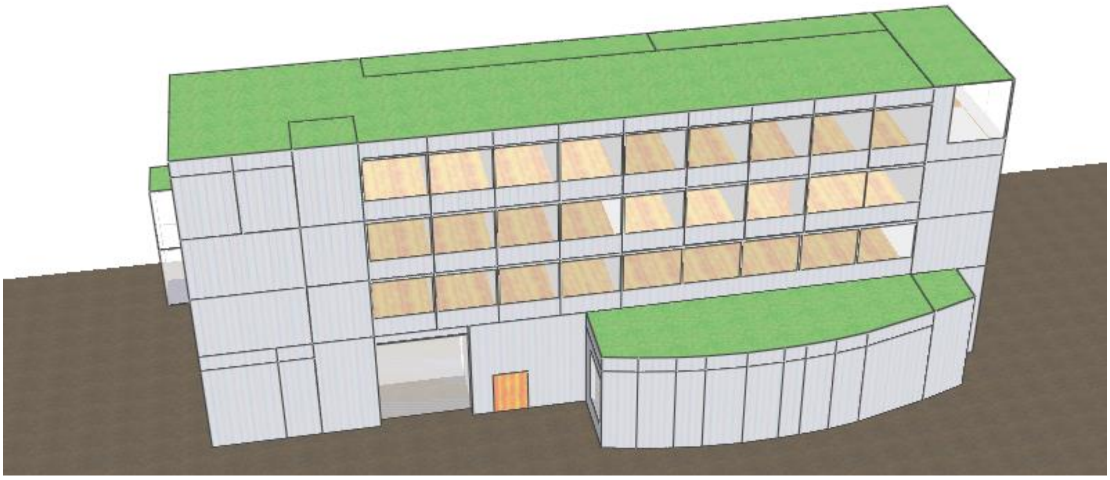


Figure 3.4 IES model (Cherie Booth Building)

There are various analysis modules within the IES package. The modules used for the case study buildings in this study are:

- Modelit
- Suncast
- Apache thermal
- Vista.

Although the climate and location for each building is the same, they each have a different geometry. This is entered into the software by the process of building the 3D model. An example of a model of one of the case study buildings (Cherie Booth) is shown in Figure 3.4. Inputting the internal environmental design data into the model is completed by means of templates. The inputting parameters included for the five case study buildings are identified in table 3.11. None of the LJMU case study buildings has a humidifying facility. All of the LJMU case study buildings have some form of air conditioning, which have a de-humidification function. The energy used for de-humidification is incorporated within the cooling loads which account for both sensible and latent cooling.

Table 3.11 tabulates the design data which has been inputted into the dynamic simulation packages. For the IES thermal simulation model one of the methods in which engineers can interface with the software is to create templates. IES incorporates several templates by which data for floor areas, construction, window performance, lighting and internal conditions can be entered into the package. The information in Table 3.9 has been entered into a "thermal" template. Where a service has not been installed in one the study buildings, this is indicated by "N/A" (not applicable). This is an engineer-friendly method of interfacing practical design parameters into the simulation package. However, accurate data input to templates relies on access to a complete and comprehensive client brief. This is not always available. Also, by designing "user-friendly" template input systems, software designers may limit the level of detail for submitted data. The software package has the capability of determining loads in terms of kW and annual heating and cooling loads in terms of kWh. The annual energy values used in this study have been determined in (kWh).

Table 3.11 Parameter settings for applied in IES simulation for LJMU case study buildings.

		Peter Jost		Tom Reilly		Cherie Booth		Henry Cotton		Eng workshops	
		W	S	W	S	W	S	W	S	W	S
Room conditions	Offices	19^{0}C	23^{0}C	19^{0}C	23^{0}C	19^{0}C	23^{0}C	19^{0}C	23^{0}C	19^{0}C	23^{0}C
	Class rooms	19^{0}C	23^{0}C	19^{0}C	23^{0}C	19^{0}C	23^{0}C	19^{0}C	23^{0}C	N/A	
	Lecture theatres	19^{0}C	23^{0}C	19^{0}C	23^{0}C	19^{0}C	23^{0}C	19^{0}C	23^{0}C	N/A	
	Laboratories	19^{0}C	23^{0}C	19^{0}C	23^{0}C	19^{0}C	23^{0}C	19^{0}C	23^{0}C	19^{0}C	
	Toilets	16^{0}C		16^{0}C		16^{0}C		16^{0}C		16^{0}C	
	Circulation	18^{0}C		18^{0}C		18^{0}C		18^{0}C		18^{0}C	
System	Offices	Heating		Air Con 70%		Heating		Heating		Air Con 70%	
	Class rooms	Heating				N/A		Heating		N/A	
	Lecture theatres	Air Con 70%				Air Con 70%		Air Con 70%		N/A	
	Laboratories	N/A				N/A		Air Con 70%		Heat	
	Toilets	Heat/Vent		Heat/Vent		Heat/Vent		Heat/Vent		Heat/Vent	
	Circulation	Heating		Heating		Heating		Heating		Heating	
	IT Suite	N/A		N/A		Air Con 70%		N/A		N/A	
Internal gains	Offices	Lighting, pc's, printers, people		Lighting, pc's, printers, people		Lighting, pc's, printers, people		Lighting, pc's, printers, people		N/A	
	Class rooms									N/A	
	Lecture theatres	Lighting, people		N/A		Lighting, people		Lighting, people		N/A	
	Laboratories	N/A		Lighting, pc's, printers, people, equipment		N/A		Lighting, pc's, printers, people, equipment		Lighting, pc's, printers, people, equipment	
	Toilets	N/A		N/A		N/A		N/A		N/A	
	Circulation	N/A		N/A		N/A		N/A		N/A	
Air Exchanges		ACR	L/s	ACR	L/s	ACR	L/s		L/s	ACR	L/s
	Offices	1	N/A	0.25	8L/person	0.25	N/A	1	N/A	1	N/A
	Class rooms	2	N/A	0.25	8L/person	0.25	N.A	2	N/A	N/A	N/A
	Lecture theatres	1	8L/person	0.25	8L/person	0.25	8L/person	1	8L/person	N/A	N/A
	Laboratories	N/A	N/A	0.25	8L/person	0.25	N/A	1	N/A	1	N/A
	Toilets*	1 & 6		0.25 & 6		0.25 & 6		1 & 6		1 & 6	
	Circulation	1	N/A	0.25	N/A	0.25	N/A	1	N/A	1	N/A

*Note : toilets air exchange include infiltration and mechanical extract

3.5.2 Non-Dynamic Energy Calculation (LJMU Buildings)

Except for the dynamic simulation above, this study also includes non-dynamic methods to calculate building equipment energy use. The TM54 process (Figure 3.3) recommends that energy use from items listed under “calculations outside of the DSM” are determined from methods other than dynamic simulation. These energy using items are more closely related to occupant behaviour than the dynamic performance of a building. In fact Menezes et al (Menezes, et al., 2012) consider that “occupant behaviour is “significantly more complex than is allowed for in current energy modelling techniques.

A total of eight steps of non-dynamic energy calculation were implemented for each case study building as follows:

<u>Step 1. Establish Floor areas</u>

The treated floor area for each building describes those area of the building which are serviced by the building engineering plant. For the case study buildings, the treated floor areas are taken from the relevant Display Energy Certificates (Department for Communities and Local Government, n.d.).

<u>Step 2. Operating hours and occupancy factors</u>

The plant operational times have been obtained from facilities managers for LJMU. Occupancies within that period have been determined from surveys and interviews.

<u>Step 3. Lighting</u>

Electrical energy used for illumination has been determined from (Raynham, et al., 2012). The equation of annual energy use for lighting is:

$$W_p = (W_1 + W_P) \tag{3.1}$$

$$W_1 = \Sigma \{(P_n * F_c) * [(t_d * F_o * F_d) + (t_n * F_0]\}/1000 \tag{3.2}$$

$$\Sigma (W_{pc} + W_{em}) \tag{3.3}$$

Where

$W_p = parasitic\ energy\ consumption\ (kWh)$

$P_n = total\ installed\ lighting\ power\ in\ room\ or\ zone$

$F_c = Constant\ illumimainance\ factor$

$t_d = daylight\ time\ usage\ measured\ in\ hours$

$F_o = Occupancy\ dependency\ factor$

$F_d = Daylight\ dependency\ factor$

$t_n = Non - daylight\ time\ usage\ measured\ in\ hours$

<u>Step 4. Lifts</u>

Annual energy use by lifts has been determined from (Barney, et al., 2010)

$$E_L = \left(\frac{S\ P\ t_h}{4}\right) + E_{standby}$$

(3.4)

Where

$E_L = Energy\ used\ by\ a\ single\ lift\ in\ one\ year\ (kWh)$

$S = number\ of\ starts\ made\ per\ year$

$P = rating\ of\ main\ drive\ motor\ (kW)$

$t_h = time\ taken\ to\ complete\ one\ half\ of\ reference\ cycle\ trip\ (hours)$

$E_{standby} = standby\ energy\ used\ by\ a\ single\ lift\ in\ one\ year$

<u>Step 5. Small power</u>

For the case study buildings the major energy using item for small power is office machinery. Determining energy use is effectively a case of multiplying equipment Wattage by hours of operation small power.

$W_{sp} = [(Pav *\ H_{op}) + (Psleep * (8760 - H_{op})] * number\ of\ workstations$ (Menezes, et al., 2014)

(3.5)

Where

$W_{sp} = annual\ energy\ consumption\ work\ station\ small\ power$ (kWh)

$P_{av} = average\ power\ demand\ during\ operation$ (kW)

$P_{sleep} = sleep\ mode\ power\ demand\ (kW)$

$h_{op} = hours\ of\ operation$

Note: small power for the case study buildings also includes vending machines, microwaves, toasters and tea points.

Step 6. Catering

This part has been included in Step 5.

Step 7. Domestic Hot water

The calculation of domestic hot water is based on the formula (Cheshire & A.C., 2013)

$$Annual\ energy\ consumption\ (kWh) = \left(m * \ \Delta t * \ C_p\right)/3600 \tag{3.6}$$

Where

$m = mass\ of\ water\ consumed\ per\ year\ (kg)$

$\Delta t = temperature\ difference\ between\ cold\ feed\ and\ outflow\ (typically\ 55^0 C)$

$C_p = specific\ heat\ capacity\ of\ water\ (4.187\ \ kJ/kg^0\ C).$

Step 8. Other equipment

Other equipment in the case study buildings comprises kit used for supporting experimentation and workshop practices. Annual energy use is determined from the product of equipment Wattage and hours of operation. Equipment ratings were found by survey. Hours of usage is not recorded and therefore has been estimated from occupant interviews.

3.6. Building and System Monitoring for LJMU Buildings

This study has examined operational performances of installed building services by obtaining data from LJMU BMS system.

3.6.1 Introduction: BMS

Building Management Systems (BMS) (Figure 3.5) can now communicate control intelligence and system data electronically. This combination of improved communication and distributed intelligence has developed alongside control and data innovations for building equipment and services. This enables energy to be controlled, monitored and logged continuously.

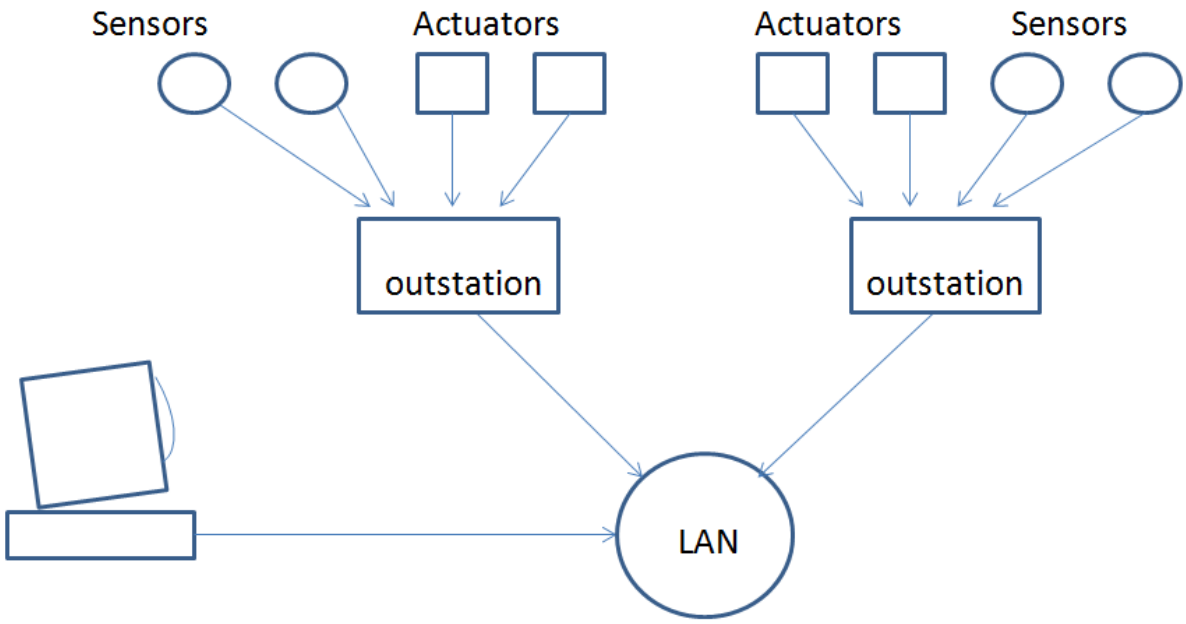


Figure 3.5 Building management systems (source: Spirax Sarco Ltd.)

3.6.2 Building Management System

The building management system used in monitoring equipment in this study is manufactured by Trend Ltd. and is deployed throughout the LJMU university campus. The BMS was used to monitor the performance of air to air heat recovery equipment and cooling coils. This section of the study examines the effectiveness of BMS monitoring and control for building services equipment in the Tom Reilly Building.

3.6.2.1 Air to air heat recovery (Tom Reilly Building)

Figure 3.6 is an example of parameters of air to air heat recovery which are monitored by the LJMU BMS in graphical form. It illustrates the parameters which are measured and reported by the BMS. The heat recovery section bypass (“recoup”) is designed to modulate between 0% and 100% open so that supply air can be pre-heated by energy recovered from extract air, thereby reducing the load on the re-heater. In addition, Figure 3.7 illustrates how the BMS logs the position of the air to air bypass control. This information should be designed to enable the effectiveness of the heat recovery equipment to be assessed. However, it is noted that the supply and extract volume flow rates identified in Figure 3.6 are clearly incorrect. The supply volume is indicated to be 18260 m3/s and extract volume is 520 m^3/s. For an air velocity of 6m/s (CIBSE Guide C, 2007) this would require duct cross sectional areas of 3043m^2 and 86.6m^2.

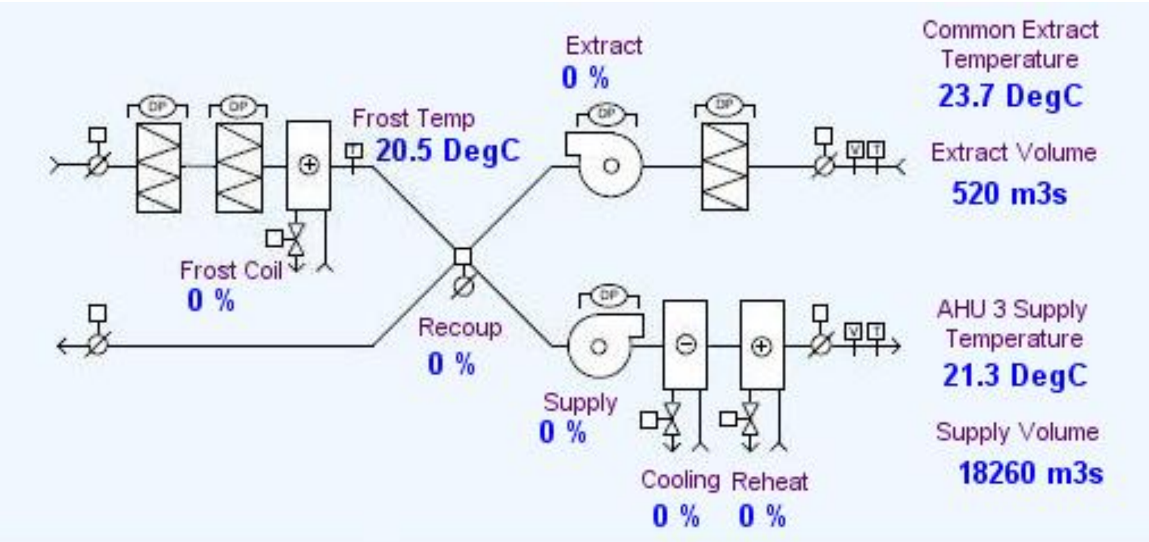


Figure 3.6 BMS monitoring of air to air heat recovery bypass control (Source: LJMU Trend BMS)

Heat recovery effectiveness is found from the formula (3.7).

$$Heat\ recovery\ effectiveness = \frac{t_2 - t_1}{t_3 - t_1}$$

(3.7)

Where

$t_1 = outside\ air\ temperature\ (^0C)$

$t_2 = heat\ recovery\ off\ coil\ supply\ temperature\ (^0C)$

$t_3 = extract\ temperature\ (^0C).$

Graph | List

Selected trace: AHU 3 Face-Bypass Output (15 minute) IP192.168.26.53L1O13P35 (%)

Time	Value
22-Sep-2013 11:00:00	0.00
22-Sep-2013 11:15:00	0.00
22-Sep-2013 11:30:00	0.00
22-Sep-2013 11:45:00	0.00
22-Sep-2013 12:00:00	0.00
22-Sep-2013 12:15:00	0.00
22-Sep-2013 12:30:00	0.00
22-Sep-2013 12:45:00	0.00
22-Sep-2013 13:00:00	0.00
22-Sep-2013 13:15:00	0.00
22-Sep-2013 13:30:00	0.00
22-Sep-2013 13:45:00	0.00
22-Sep-2013 14:00:00	0.00
22-Sep-2013 14:15:00	0.00
22-Sep-2013 14:30:00	0.00
22-Sep-2013 14:45:00	0.00
22-Sep-2013 15:00:00	0.00
22-Sep-2013 15:15:00	0.00
22-Sep-2013 15:30:00	0.00
22-Sep-2013 15:45:00	0.00
22-Sep-2013 16:00:00	0.00
22-Sep-2013 16:15:00	0.00
22-Sep-2013 16:30:00	0.00
22-Sep-2013 16:45:00	0.00
22-Sep-2013 17:00:00	0.00
22-Sep-2013 17:15:00	0.00
22-Sep-2013 17:30:00	0.00
22-Sep-2013 17:45:00	0.00
22-Sep-2013 18:00:00	0.00
22-Sep-2013 18:15:00	0.00
22-Sep-2013 18:30:00	0.00
22-Sep-2013 18:45:00	0.00
22-Sep-2013 19:00:00	0.00
22-Sep-2013 19:15:00	0.00
22-Sep-2013 19:30:00	0.00
22-Sep-2013 19:45:00	0.00
22-Sep-2013 20:00:00	0.00
22-Sep-2013 20:15:00	0.00
22-Sep-2013 20:30:00	0.00
22-Sep-2013 20:45:00	0.00
22-Sep-2013 21:00:00	0.00
22-Sep-2013 21:15:00	0.00

Figure 3.7 Air to air heat recovery bypass control (source: LJMU Trend BMS)

3.6.2.2. Cooling coil (Tom Reilly Building)

Monitored data from the BMS was used to assess capacity control of a cooling coil. Figure 3.8 demonstrates how the output from the cooling coils in the air handling equipment at the Tom Reilly Building are controlled by two port valves. The diagram (Figure 3.8) is a schematic representation which demonstrates the chilled water supply to the cooling coils in AHU's 3 and 4. For both coils the two-port control valves are located downstream of a strainer (symbol ST). The flow rate of chilled water is measured by the orifice plate (symbol OP) mounted on the return pipe work. The orifice plate flow measuring equipment has been installed for commissioning purposes and the output signals are not monitored by the BMS.

Figure 3.9 is an example of the BMS logging record of the control signal percentage for the two port valve serving the cooling coil in AHU 3. Although the BMS does not monitor fluid flow rates to the coil via the orifice plate, the percentage of electrical power to the control valve is monitored and this is analogous, though indirectly.

Relating the valve signal strength to the fluid flow rate requires that the control valve characteristic is factored into the calculation.

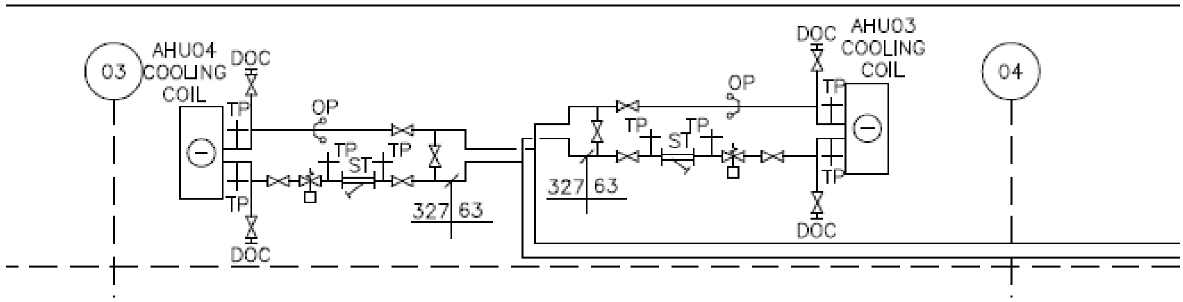


Figure 3.8 Two-port control valves for AHU cooling coils.

28-Jul-2014 09:00:00	24.02
28-Jul-2014 09:15:00	29.56
28-Jul-2014 09:30:00	36.33
28-Jul-2014 09:45:00	40.03
28-Jul-2014 10:00:00	42.49
28-Jul-2014 10:15:00	46.19
28-Jul-2014 10:30:00	49.88
28-Jul-2014 10:45:00	49.27
28-Jul-2014 11:00:00	49.88
28-Jul-2014 11:15:00	53.58
28-Jul-2014 11:30:00	54.81
28-Jul-2014 11:45:00	56.04
28-Jul-2014 12:00:00	57.27
28-Jul-2014 12:15:00	59.12
28-Jul-2014 12:30:00	60.97
28-Jul-2014 12:45:00	54.19
28-Jul-2014 13:00:00	49.27
28-Jul-2014 13:15:00	47.42
28-Jul-2014 13:30:00	43.72
28-Jul-2014 13:45:00	41.26
28-Jul-2014 14:00:00	48.65
28-Jul-2014 14:15:00	56.66
28-Jul-2014 14:30:00	57.27
28-Jul-2014 14:45:00	56.04
28-Jul-2014 15:00:00	52.96
28-Jul-2014 15:15:00	52.34

Figure 3.9 Percentage control signal for AHU 3 cooling coil control valve. (Source: LJMU Trend BMS)

3.6.3 Portable sensing / monitoring

In this study, there were situations where the data available from BMS is incomplete for the case study buildings. For two locations (Tom Reilly and Cherie Booth buildings), therefore, portable temperature measuring sensors (Figure 3.10) have been temporarily installed to obtain information which would not be available. The sensors were used in the indoor and outdoor units of active chilled beam secondary air grilles

(Tom Reilly Building) and split system air conditioning units (Cherie Booth Building). The specification parameters for the portable sensors are identified in Table 3.12.

The image originally presented here cannot be made freely available via LJMU E-Theses Collection because of copyright. The image was sourced at https://www.lascarelectronics.com/data-loggers/temperature-humidity/

Figure 3.10 Stand-alone temperature and humidity sensor/logger (source: Lascar Electronics Ltd.)

Table 3.12 Specification for temperature and humidity sensor/logger

EL-USB-2-LCD Temperature, Humidity and Dew Point Data Logger – Specification		
Temperature	Measurement range	$-35\ to + 80^0C$
	Internal resolution	$0.5\ ^0\ C$
	Accuracy (overall error)	$\pm 0.3^0\ C$
	Repeatability	$\pm 0.1^0C$
	Long term stability	$< \pm 0.02C^0$
Relative humidity	Measurement range	$0 - 100\%\ RH$
	Internal resolution	$0.5\%\ RH$
	Accuracy (overall error)	$\pm 2\% RH$
	Repeatability	$\pm\ 0.1\%\ RH$
	Long term stability	$< 0.25\%$
Dew point		$\pm\ 0.1\%\ RH$
Logging rate	User selectable between 10 seconds and 12 hours	
Operating range	$-35\ to + 80^0C$	
Battery life	2 years (at 25^0C and 1 minute logging rate, LCD on)	

3.6.3.1. Chilled Beam Air Conditioning (Tom Reilly Building)

The active chilled beams which are used to control room conditions at the Tom Reilly building are supplied with dehumidified primary air which meets ventilation requirements and offsets space latent gains. The room sensible gains which are not met by the primary air should be offset by a secondary air supply. Figure 3.11 demonstrates how the secondary coil is designed cool the secondary (induced room air) supply. Figure 3.12 demonstrates this method on a psychrometric chart where the secondary coil sensible cooling is illustrated by process line T1 to T2, and primary cooling is illustrated by the process line linking outside condition to primary air ADP (apparatus dew-point). The level of secondary cooling energy is related to the difference in temperature between T1 and T2. These temperatures have been measured and logged hourly over an extended period (21-09-2018 to 31-10-2018). Analysis of measured temperatures is demonstrated in Table 3.13 which indicates that the amount of secondary cooling during that period is negligible. This infers that all space cooling loads are met by primary cooling alone, which indicates that the chilled beams are over-sized.

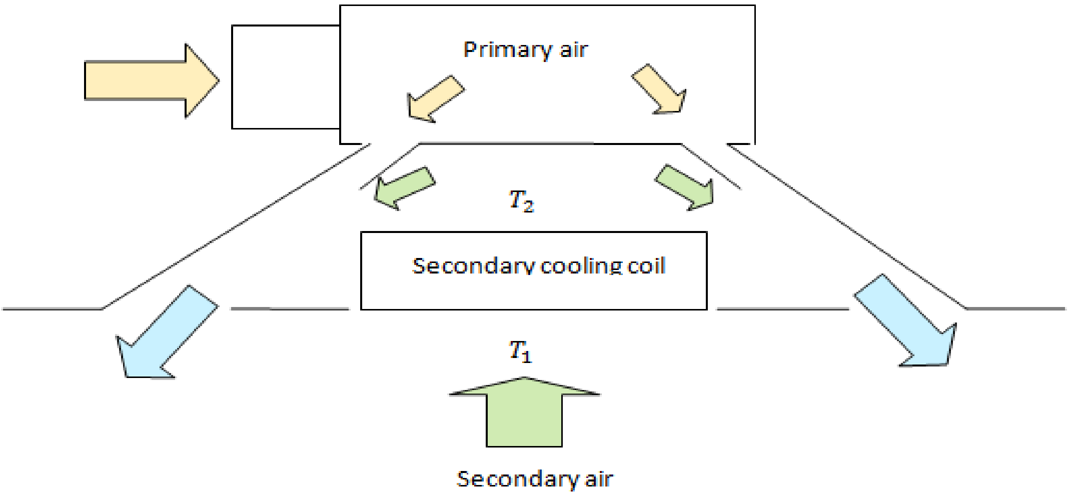


Figure 3.11 Primary and secondary air supplies from an active chilled beam (Source: Dadanco Ltd.).

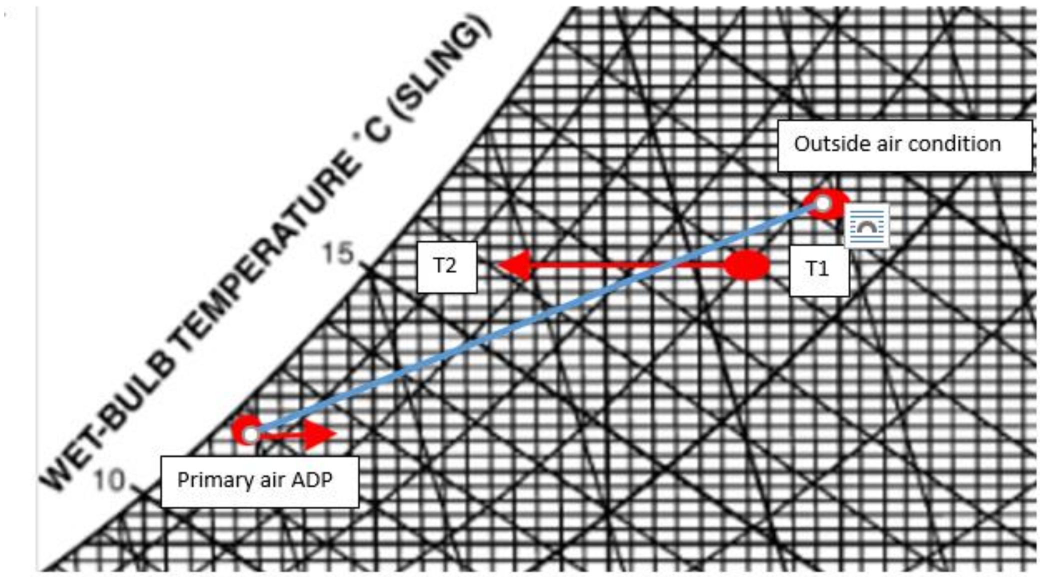


Figure 3.12 Sensible and latent cooling for chilled beams

t Test									
		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	Interval of the				
					Lower	Upper			
Pair 1	T1 - T2	0.25157	0.47790	0.01026	0.23145	0.27169	24.521	2169	0.000
		Mean difference between two temperatures is 0.25 (T1 > T2)							p<0.05 me

Figure 3.13 Statistical analysis of secondary cooling effect on temperature T1 and T2

3.6.3.2. Split System Air Conditioning (Cherie Booth Building)

Figure 3.14 demonstrates the location of portable temperature sensors which were mounted on the split system air conditioning unit serving the IT suite room at the Cherie Booth building. Sensor T1 was located within the indoor ceiling mounted cassette unit in order to measure the off-coil supply temperature. Sensor T2 was mounted on the outdoor unit which is installed on the rear exterior wall of this building. Neither of these temperatures is recorded, or logged by the BMS.

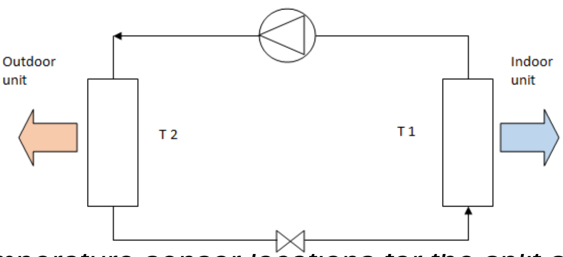


Figure 3.14 Temperature sensor locations for the split system air conditioning at Cherie Booth Building.

If these temperatures are measured/recorded, the coefficient performance for the air conditioning systems can be assessed by the formula (3.8) (Beggs,2009):

$$Coefficient\ of\ performance\ (ref) = \frac{T_1}{T_2 - T_1}$$

Where $T_1 = absolute\ temperature\ at\ evaporator\ (K)$

$T_2 = absolute\ temperature\ at\ condenser\ (K)$ (3.8)

(COP calculation included at appendix Ch3-2)

3.6.4 Other sources

To complement the data determined through prediction and monitoring, other sources which indicate energy consumption and building services equipment performance have also been adopted in this study. These sources include energy benchmarks, actual energy use, record drawing and maintenance information for the five case study buildings.

3.6.4.1 Energy Benchmarks and Actual Energy Use

In order to assess the accuracy of the design stage energy evaluations for the case study buildings (described in section 3.4), the estimates were compared with both benchmarks and actual energy use. Energy benchmarks and actual energy use were obtained from the display energy certificates (DEC) for each of the case study buildings. All of the case study buildings have a floor area greater than 1000 m^2 and therefore DEC's have a one year validity. An example is illustrated in Figure 3.15: Year 2014-2015 DEC for the Cherie Booth Building. The red marked section states the value for benchmarks and actual heating and electrical energy use in kWh/m^2. The document also states the "useful" floor area. The product of area and benchmark or actual energy use gives the total annual energy figure.

Display Energy Certificate

How efficiently is this building being used?

HM Government

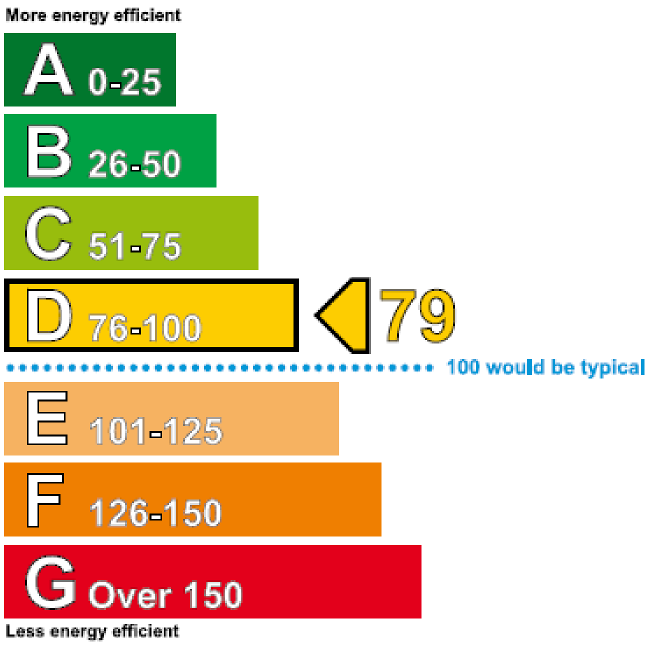
Liverpool John Moores University
CHERIE BOOTH BUILDING
Liverpool John Moores University
Byrom Street
LIVERPOOL
L3 3AF

Certificate Reference Number:
0746-0114-1349-9698-4006

This certificate indicates how much energy is being used to operate this building. The operational rating is based on meter readings of all the energy actually used in the building. It is compared to a benchmark that represents performance indicative of all buildings of this type. There is more advice on how to interpret this information on the Government's website www.communities.gov.uk/epbd.

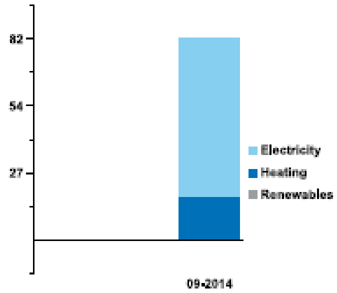
Energy Performance Operational Rating

This tells you how efficiently energy has been used in the building. The numbers do not represent actual units of energy consumed; they represent comparative energy efficiency. 100 would be typical for this kind of building.



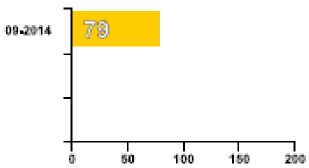
Total CO_2 Emissions

This tells you how much carbon dioxide the building emits. It shows tonnes per year of CO_2.



Previous Operational Ratings

This tells you how efficiently energy has been used in this building over the last three accounting periods.



Technical Information

This tells you technical information about how energy is used in this building. Consumption data based on actual meter readings.

Main heating fuel: Natural Gas
Building environment: Heating and Natural Ventilation
Total useful floor area (m²): 1039.0
Asset Rating: Not available

	Heating	Electricity
Annual Energy Use (kWh/m²/year)	86	114
Typical Energy Use (kWh/m²/year)	254	94
Energy from renewables	0%	0%

Administrative Information

This is a Display Energy Certificate as defined in SI 2007/991 as amended.

Assessment Software:	DCLG, ORCalc, v3.6.2
Property Reference:	494341610006
Assessor Name:	Darren Fyles
Assessor Number:	STER000412
Accreditation Scheme:	Sterling Accreditation Limited
Employer/Trading Name:	Clouds Environmental Consultancy
Employer/Trading Address:	Unit 2.1 Central Point, Kirpal Road, Portsmouth, Hants, PO3 6FH
Issue Date:	03-10-2014
Nominated Date:	08-09-2014
Valid Until:	07-09-2015
Related Party Disclosure:	Contractor to the occupier for EPBD services only.

Recommendations for improving the energy efficiency of the building are contained in the accompanying Advisory Report.

Figure 3.15 Display Energy Certificate for Cherie Booth Building 2015-2015.

3.6.4.2 Record Drawings and Maintenance Information

Record drawings and maintenance information also enable a comparison between actual and designed performances of building services and equipment. For this study, maintenance documentation has been considered in order to assess the performance and applied design margins for circulating Pumps at the Tom Reilly Building.

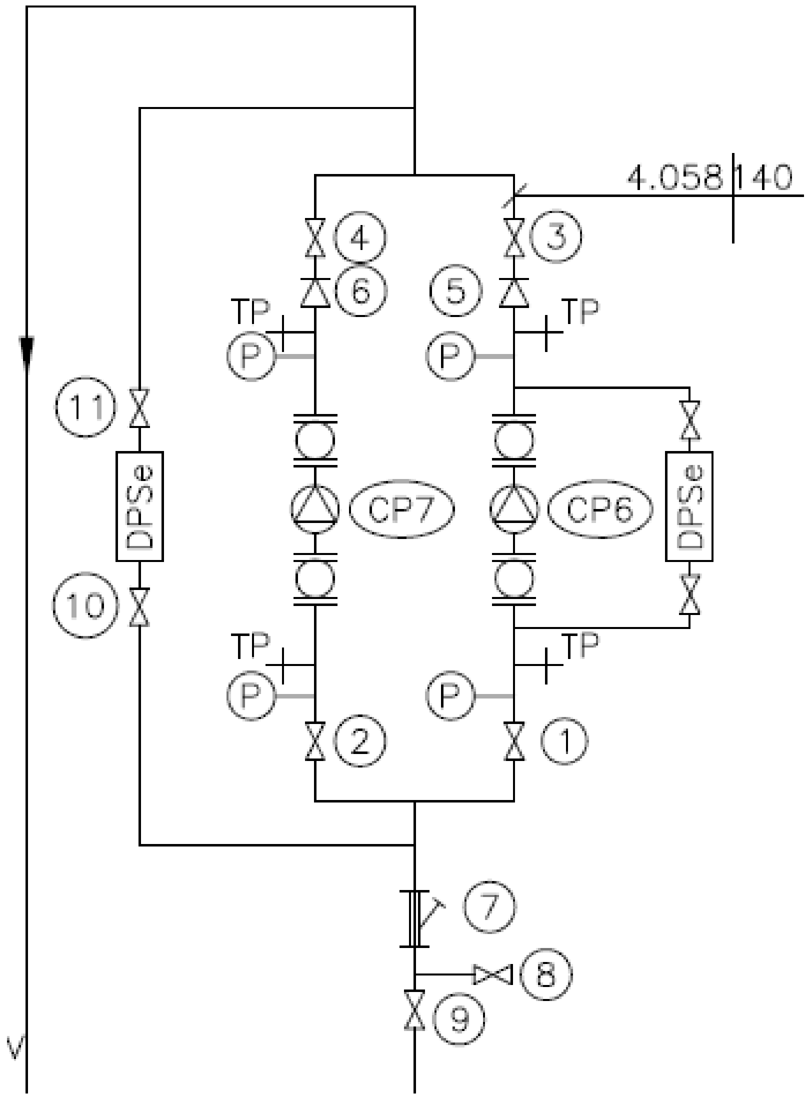


Figure 3.16 Design data for chilled water pump CP6 and CP7 (Tom Reilly Building)

Figures 3.16 and 3.17 are extracted from the maintenance information for circulating pumps at Tom Reilly. Figure 3.16 is a part copy of the schematic record drawing for chilled water pumps at Tom Reilly which indicates the commissioned values for chilled water pump C7. Figure 3.17 indicates the design consultant’s specification for the heating and chilled water pumps. The designed and commissioned data enable a “before and after installation” comparison.

Ref	Function Location	Type	Model No	Pump		Motor	
				Des Flow L/S	Speed Rpm	Rating Kw	Speed Rpm
				Head Kpa		F.L.C. Amps	Elec. Supply
CP03	CHW Second Floor Plantroom	Close Coupled End Suction	NB40-125/127	11.600 150	As Motor	3.00 6.30	2900 400V/3Ph/50hz
CP04	CHW Second Floor Plantroom	Close Coupled End Suction	NB40-125/127	11.600 150	As Motor	3.00 6.30	2900 400V/3Ph/50hz
CP06	CHW Second Floor Plantroom	Close Coupled End Suction	NB40-125/127	11.600 150	As Motor	3.00 6.30	2900 400V/3Ph/50hz
CP07	CHW Second Floor Plantroom	Close Coupled End Suction	NB40-125/127	11.600 150	As Motor	3.00 6.30	2900 400V/3Ph/50hz
HP01	LTHW Second Floor Plantroom	Close Coupled End Suction	NB40-160/177	7.900 75	As Motor	11.00 19.40	2950 400V/3Ph/50hz

Figure 3.17 Design consultant's specification for circulating pumps at the Tom Reilly Building.

3.7 Building Service System: Fans (Liverpool General Hospital)

3.7.1 Brief review of current practical methods

Fans deliver power to the air supply in order to provide it with the energy it needs to overcome the frictional resistance of a duct system. The energy input to the system to provide this power is greater than that given to the air because of the inefficiencies in the fan and pump.

The process of selecting the appropriate fan is interrelated with the fluid mechanical principle involved in duct design. Technical and managerial aspects are discussed in chapter 2, however, like most services design techniques, the design of fan and duct systems is an iterative procedure which must be carried out in tandem and co-operation with all the project design disciplines and in compliance with client and statutory requirements.

Clearly this is not an exact technique. Earlier comment in the literature review discussed the imperfections and tolerances that are part of practical fan and duct design. Although designers should aim to achieve optimum operational performance, it is necessary, when predicting energy use by fans to factor the fan and motor inefficiencies into the calculation. It is also necessary to appreciate the level of accuracy that should be expected.

Ideally the specified fan for a project will operate at its highest efficiency. However, the actual operating point for a fan is dependent on the system pressure drop or characteristic. The previously discussed limitations and tolerances often mean that the operating point is moved along the efficiency curve. This shift from optimum can be compounded because designers, in response to contractual risks can be tempted to add unnecessary margins. A strategy of defensive sizing can lead to over-sized systems, wasted capital costs and systems which operate far away from optimum efficiency. This effect is shown in Figure 3.18.The best efficiency point (BEP) is point 1 but if the fan is over-sized the actual operating efficiency will be at point 2.

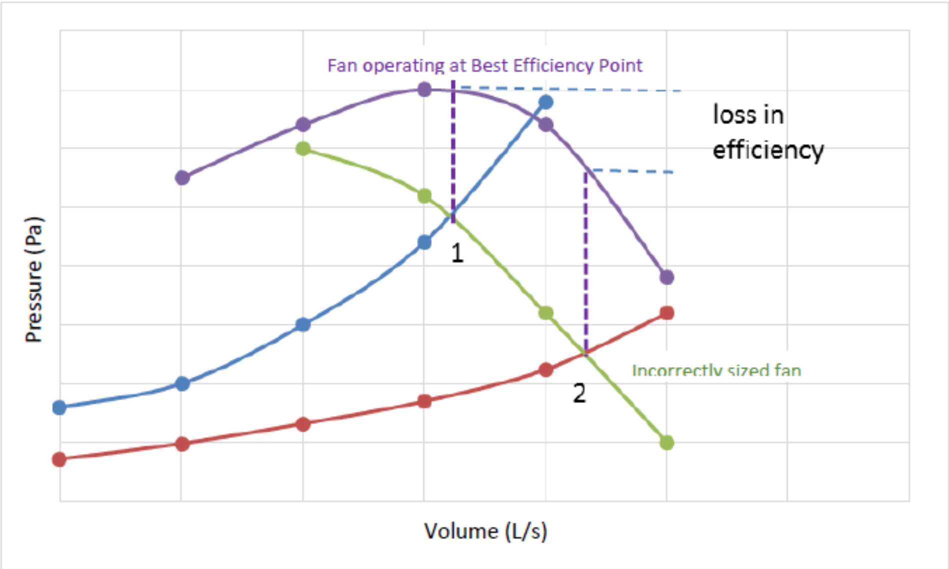


Figure 3.18 The relationship between operating point and fan efficiency

3.7.2 Case Study: Hospital Project

Technology has an important role in the operation of modern hospitals. Parts of that technology are the building services engineering systems which control environments and ensure safe and hygienic conditions. The air –handling requirement for a large project, currently under construction include, comprises more than 85 air – handling units. Each of these unit contains one or more fans.

3.7.2.1 Annual Fan Energy Use

It is comparatively recently that it has been recognised that the energy used to power fans represents a significant fraction building total energy. The concept of specific power is explained in chapter 2. For the equipment specified for the hospital, specific power, compliance will mean units must comply with specific power values ranging from2.2 W/L to 3 W/L. If these parameters are applied to the design consultant's schedule of air handling equipment, the annual energy use by fans will be between 16.5 and 22.5 MWh (Table 3.13). These are significant levels of energy use.

The total annual energy used by the fans in the hospital project will depend on the accuracy of the designers. Fan and motor efficiencies are not fixed and vary as the fan operating point varies. Theoretically precise operating points are rarely specified and would be unlikely to be achieved in installation. Chapter 2 discusses the frailties and tolerances between design and installation.

Table 3.13. Hospital Project: Annual Energy Use Fans.

Fan Energy		
Total fan energy power at design SFP	860	kW
Total fan energy power at maximum SFP	1163	
Annual fan energy use at design SFP	16470	kWh
Annual fan energy use at maximum SFP	22537	

3.7.2.2 Fan Energy Prediction at Early Design Stage

A system of energy accounting or monitoring should begin at the preliminary design stage of a project. However, this is the phase when detail design has not begun and precise project details have not been finalized. Nevertheless, in a similar way to the CIBSE TM54 method of estimation for other equipment, it is necessary to be able to approximate the energy that fan systems will use. Not only will this contribute to an overall building energy estimate, but also it will initiate an energy management plan for fan energy use.

The definition of "early design stage" for this estimation method is the point at which three parameters will be available to designers –

- Allowable specific fan power
- Approximate route/length of duct run
- Approximate air flow rates
- Sketch designs for building layout, orientation and plant space locations.

Where the designation of zone activities is decided, appropriate specific powers can be determined based on fan efficiencies (Table 3.14). Similarly, preliminary duct routes between plant space and conditioned (or ventilated) zones can be identified and, hence duct lengths measured.

Table 3.14 Typical practical fan efficiencies (EC Commission, 2011)

Fan Efficiencies			
B C Centrifugal	0.7	0.65	0.6
F C Centrifugal	0.7	0.65	0.6
Axial	0.8	0.7	0.65

The proportion of fan duty necessary to overcome the internal components within air handling units is significant. Typical values for these pressure drops are included in appendix CH3-1. These typical values have been compared with internal pressure losses for the hospital case study project. Table 3.15 lists internal component pressure loss ratios. Good practice refers to an air speed of 1.5 m/s. Standard practice refers to air speeds above 1.5 m/s.

Table 3.15 Internal Component Pressure Loss Ratios. (Schild & Mysen, 2009)

Internal component pressure loss ratio	
Typical	0.5
Good practice	0.45

3.8. Summary

This chapter has set out the methods by which the effectiveness of building energy management is examined. Because building energy management is a process that should occur at all stages of a project, this study considers case studies at design, specification, installation and operational phases. Six buildings have been applied as case studies (Table 3.16). Five of these buildings are within a university campus. The sixth building project has provided data on fan systems in ventilation systems.

The design phase has been considered by applying a CIBSE recommended energy estimation technique to five existing buildings within the LJMU campus. The accuracy of the technique is assessed by comparing a range of estimates, based on varying scenarios, with benchmarks and actual energy consumption data. The case study buildings are existing, and were constructed in different eras of statutory regulation for energy use. Additionally, the energy performance characteristics of the case study buildings are affected by their occupancy, function and servicing strategy, and these were factored into the estimation. The estimation technique recommended by CIBSE recognises both the frailties and value of dynamic simulation modelling (DSM). Therefore the estimation technique applied DSM methods to dynamic building energy loads and included non-dynamic calculation methods where building services and equipment energy use correlates more closely with occupant behaviour.

Operational building energy use is considered through the use of the LJMU university building management system. This part of the study also assessed the comprehensiveness of building management system inputs and outputs. This can highlight shortcomings where monitored data can be incomplete. For some systems it was necessary to install temporary portable temperature measuring sensors to enable energy performance assessment. Analysis of the effects of lacking BMS data points indicated that the major operational penalty would be plant efficiency.

A comparison of design for air conditioning plant was obtained from an examination of consultant design parameters, record drawings, maintenance handbooks, manufacturer's parameters revealed how margins are applied to calculated values. (The margins specified in the consultant's tender schedule are +7.5% for supply and extract systems, +10% for supply volumes and +16% for extract volumes) The fan systems for the hospital project were assessed in order to study the implications on design margins and to provide data for the development of an early stage fan energy prediction technique.

Table 3.16 Research methods applied to case study buildings

Peter Jost	Dynamic simulation (thermal modelling)	Non-dynamic calculations (energy associated with occupant behaviour	Comparison of estimates and historical energy use	Estimation of major plant sizes and comparison with existing		
Tom Reilly	Dynamic simulation (thermal modelling)	Non-dynamic calculations (energy associated with occupant behaviour	Comparison of estimates and historical energy use	Estimation of major plant sizes : comparison with existing	Examination of maintenance data to determine energy implications of discrepancies between design and commissioned performance	Supplementary (outside of BMS) and examination of chilled beam air conditioning

Table 3.16 Research methods applied to case study buildings (continued)

Cherie Booth	Dynamic simulation (thermal modelling)	Non-dynamic calculations (energy associated with occupant behaviour	Comparison of estimates and historical energy use	Estimation of major plant sizes and comparison with existing	Supplementary (outside of BMS) and examination of split system air conditioning	
Henry Cotton	Dynamic simulation (thermal modelling)	Non-dynamic calculations (energy associated with occupant behaviour	Comparison of estimates and historical energy use	Estimation of major plant sizes and comparison with existing		
Engineering workshops	Dynamic simulation (thermal modelling)	Non-dynamic calculations (energy associated with occupant behaviour	Comparison of estimates and historical energy use	Estimation of major plant sizes and comparison with existing		
Liverpool General hospital	Comparison and analysis of ventilation fan equipment to determine actual practical system fan energy use					

Chapter 4:

Building Energy Performance Appraisal: CIBSE Method

4.1 Introduction

This section investigates the energy performance of five case study buildings by applying the recently developed CIBSE method for design-stage estimation of building energy use. This technique combines dynamic simulation modelling (DSM) with arithmetic spread sheet calculations. The logic of this approach is that, although DSM's are suitable for evaluating the results of the dynamic heat transfers which occur as heat is absorbed, reflected, convected and radiated within a building's structural features, energy use related to operational and occupant behavioural matters is more accurately determined by spreadsheet calculation (Cheshire, D. 2013). An example of how non-dynamic annual energy has been determined is shown in Table 4.1 and appendix CH4-1.

Table 4.1 Manual calculations method for annual small power energy use

	Number	Watts	Sleep Watts	Hours op	Hours sleep	Op kWh	Sleep kWh	kWh
Work stations (PC's)	60	150	80	1866	6894	16794	33091.2	49885.2
Screens	60	45	1	1866	6894	5038.2	413.64	5451.84
photocopiers	2	1100	300	1244	7516	2736.8	4509.6	7246.4
printers	2	320	70	1244	7516	796.16	1052.24	1848.4
Microwave	1	800	100	622	8138	497.6	813.8	1311.4
Refrigerator	1	350		8760				3066
Kettle	4	1000		311				311
Projectors lecture theatre	2	1050		2488				2612.4
Projectors conference	2	1050		1244				1306.2
							Annual kWh	73038.84

Instead of estimating annual totals for heating and fossil fuel use, this appraisal will determine annual energy totals for the various engineering service systems operating within these buildings. The accuracy of the estimates will be assessed by comparing them with benchmarks and actual energy use data.

These buildings exist and are operational. Surveys have been carried out and information has been made available from facilities managers and occupants. However, this is limited and much energy use is unrecorded. Despite having access to the buildings, not all operational and design factors are available. Therefore, each building will be assessed under varying likely scenarios. The weather data used in simulations is from the ASHRAE design weather database (Version 5, 2013)

4.2 CIBSE TM54 Method (2013): Calculation & Simulation

4.2.1 Scenarios for Building Conditions and Operations

The validity of building energy estimates is related to the level of data available. In most situations not all operational factors are known and therefore several realistic scenarios have been considered for each building. Details of the various scenarios are available in section 3.4.2.

4.2.2 The Peter Jost Building

The results of the energy estimates for the four scenarios considered for the Peter Jost Building are graphically illustrated in figures 4.1 to 4.4.

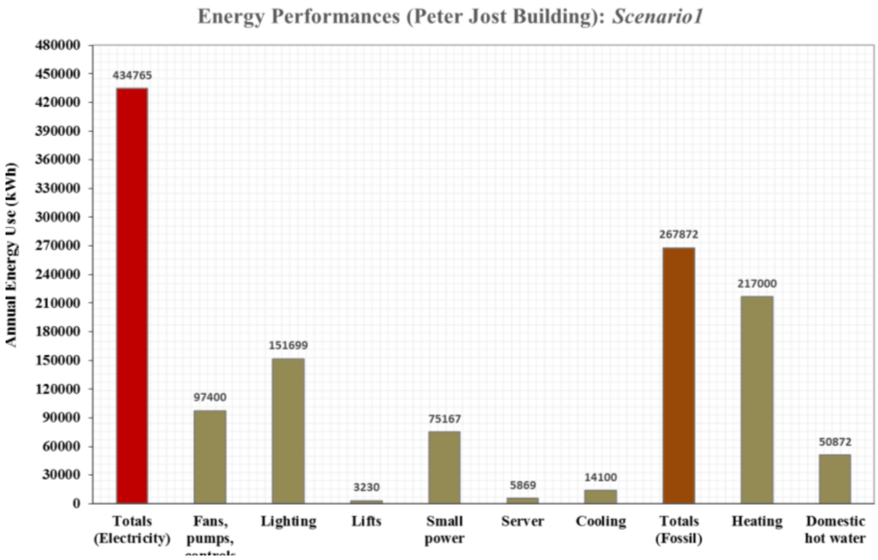


Figure4.1 Building services energy use: scenario 1: Peter Jost

Figure 4.1 identifies the energy used by individual building services systems. Some of these energy-using systems may be described as “controlled” in that they operate between set limits of time, temperature, humidity and rate of energy transfer. Other systems, such as small power are not similarly controlled but operate in response to occupant activities and requirements.

In this document the two types of building services system will be referred to as “controlled” and “non-controlled”. For energy managers, non-controlled can present challenges. The percentage of non-controlled energy use in scenario 1 is around 40%.

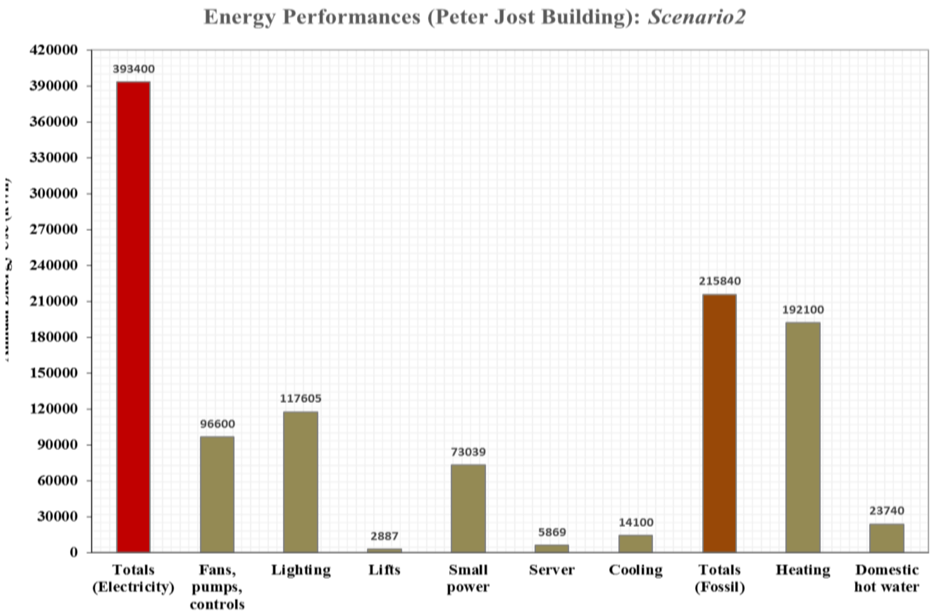


Figure4.2 Building services energy use: scenario 2: Peter Jost

In scenario 2 (figure 4.2), the non-controlled loads for lighting and small power continue to be significant. Domestic hot water energy changes considerably, however this can also be considered a “non-controlled” load because, despite being an engineering service operating to set temperatures, the load is mainly governed by occupant use. Non-controlled energy use is around 36% of total load.

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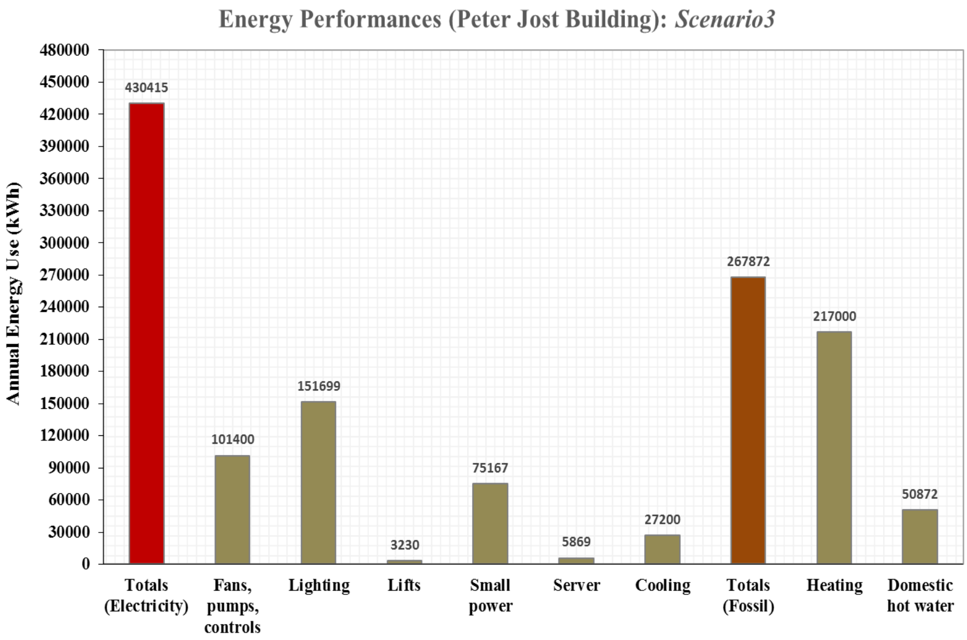

Figure4.3 Building service energy use: scenario 3: Peter Jost Building

In scenario 3 (Figure 4.3), electrical energy remains the highest source of power. In fact almost all of the services except heating and domestic hot water are electrically powered. Air conditioning is mainly driven by electricity but fossil fuel provides the energy for heating coils in the air conditioning plant. The non-controlled energy use in scenario 3 is 40%.

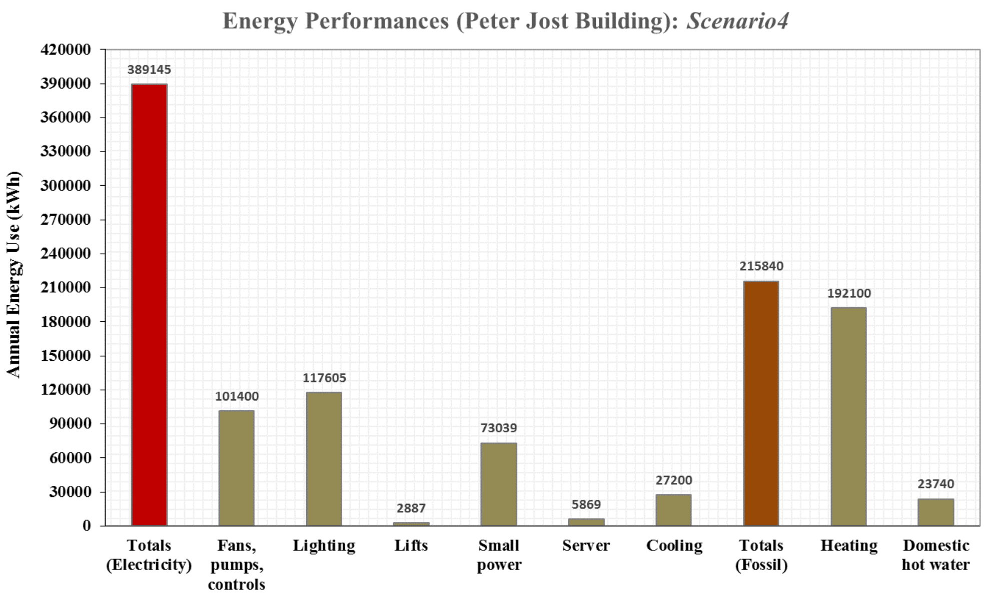

Figure4.4. Building services energy use: scenario 4: Peter Jost.

Scenario 4 (Figure 4.4) again identifies electricity as the largest energy source. Although some building services equipment such as boiler plant and air conditioning is shut down in non-occupied periods, energy users such as lifts and servers do not switch off. Despite this, their estimated energy use is a small fraction of the total energy demand. The non-controlled energy use in scenario is 36%.

The Peter Jost Building is now more than 20 years old. Like many other UK buildings, Peter Jost has been built to standards and practices that have changed considerably. Not only have statutory regulations become much tighter, but working practices and attitudes are also quite different in terms of energy and sustainability. Also, there have been several sets of “tenants” since the building was opened.

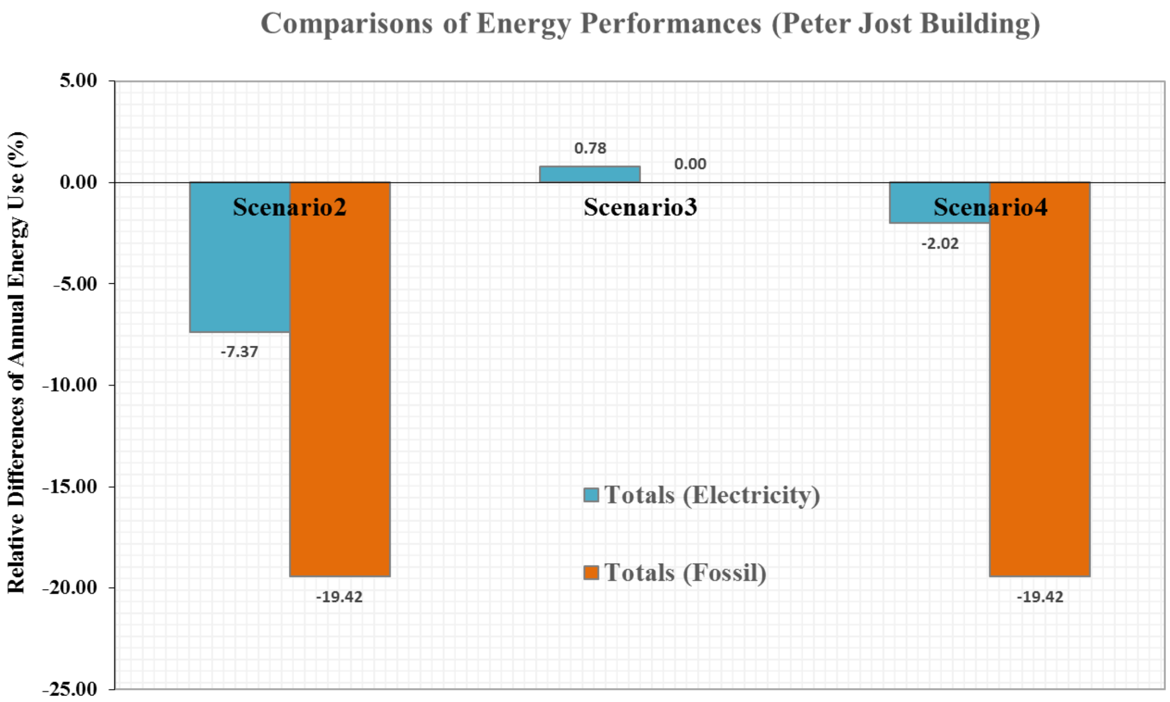

Figure4.5. Relative differences for energy use at different scenarios: Peter Jost

The scenarios indicate that electricity is the major fuel for this building. The changing scenarios have the greatest effect fossil fuels in terms of relative difference (Figure 4.5). However, the largest absolute change in energy use occurs in lighting load. Though energy used for cooling doubles where dew points are altered, this is only a small part of the total load. Fans and pumps contribute a significant fraction of the building energy load.

Table4.2 Percentage share of electrical or fossil energy at different scenarios: Peter Jost

Percentage of building load (PJ)							
Scenario 1		Scenario 2		Scenario 3		Scenario 4	
Elec	Fossil	Elec	Fossil	Elec	Fossil	Elec	Fossil
56	44	59	41	58	42	60	40

The major change factor for this building is related to lighting and small power (see Table 4.2). Both of these parameters are linked with occupancy and behaviour; neither of which is monitored. This building has a narrower plan for storeys above ground floor. The wider ground-floor footprint is mainly composed of a lecture theatre, entrance corridor and plant space. This effect increases the ratio of heat losing external surfaces for the upper floors. The building is mainly heated by radiators but the lecture theatres on the ground floor are air conditioned. The lift is small (6 persons) and slow. The building is located on a sloping site and there is access from outside to first (upper ground) floor. Student attendance is normally on ground and first floor. Consequently lift use is infrequent.

Table 4.2 demonstrates that, for the Peter Jost Building the various operational scenarios do not greatly affect the ratio of fossil and electrical energy use. This is logical with regard to equipment energy for which operational hours feature in estimation calculations. Electrical factors such as lift energy and dew-point settings are less significant for this ratio. However, only a relatively small part of the building is air conditioned and the lift is small, slow and its entrance at ground floor is not clearly visible to building visitors.

4.2.3 Tom Reilly Building

Four scenarios were considered for the Tom Reilly Building. The results are demonstrated in figures 4.6 to 4.9.

Scenario 1 (figure 4.6) for the Tom Reilly Building, demonstrates that electricity is the major fuel. Although the building is largely air conditioned, the electrical cooling load is less than either lighting or small power. The Tom Reilly Building has been designed so that structural thermal mass is exposed and this would indicate that is a successful strategy in terms of absorbing heat gains and consequently reducing the need for mechanical cooling. Nevertheless, fossil fuel energy is the second largest energy user. The share of non-controllable energy use is around 54%. This is the most modern building evaluated. The ratio of controllable and non-controllable energy use is an indicator of the success of statutory regulations regarding building insulation and the efficiency of controllable building engineering services.

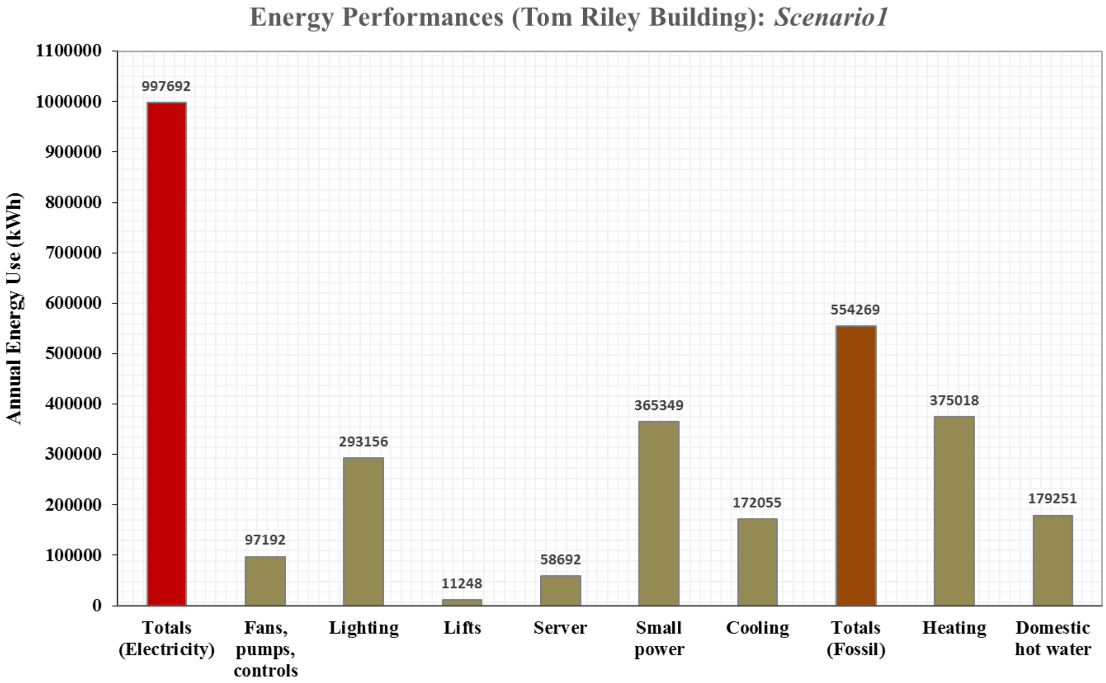

Figure4.6: Building services energy use: scenario 1: Tom Reilly Building

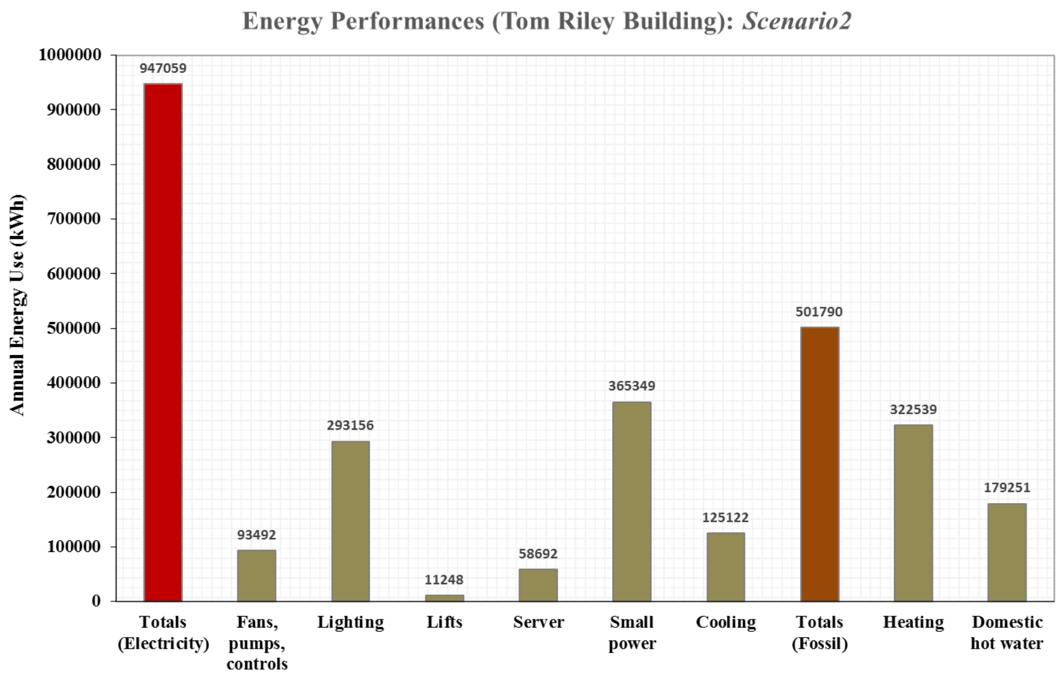

Figure4.7: Building services energy use: scenario 2: Tom Reilly

Figure 4.7 again demonstrates that electricity is the major fuel for the Tom Reilly Building. Setting a tighter relative humidity target has significantly increased electrical cooling energy, though this still remains small in comparison with lighting and small power loads. Fossil fuels are the second largest user, despite the building being largely air conditioned. Non controllable energy use for this scenario is 59%.

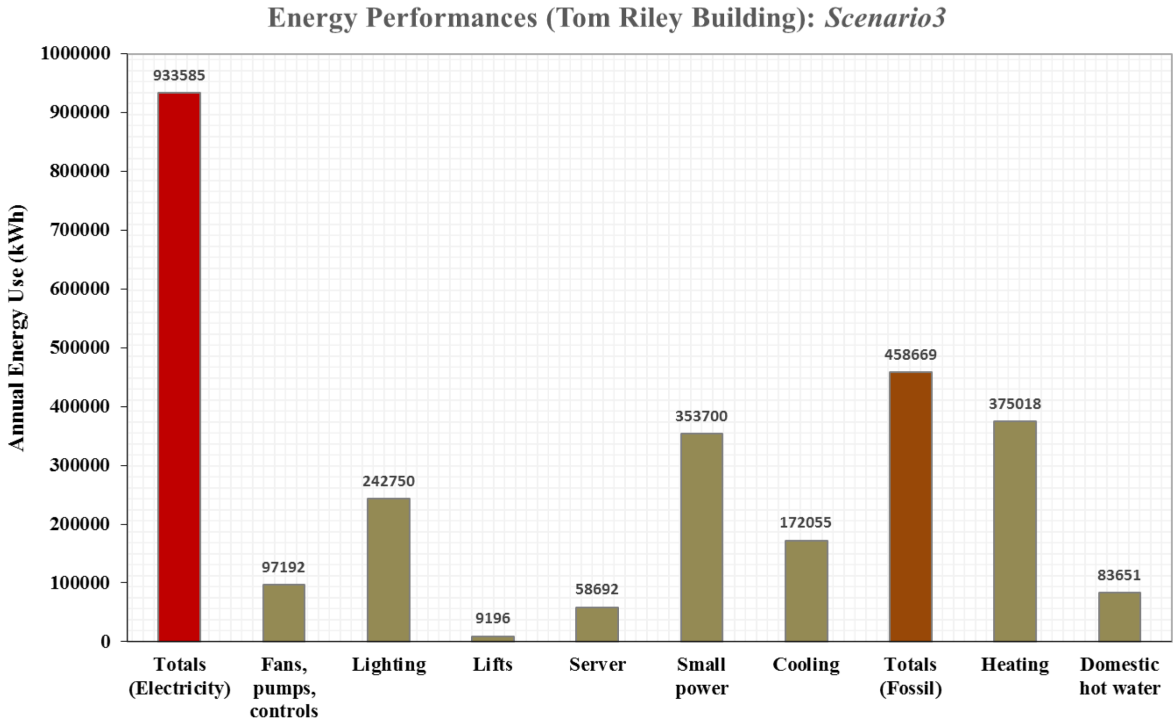

Figure4.8 Building services energy use: scenario 3: Tom Reilly

Figure 4.8 indicates a scenario in which there is less predicted lift use, less predicted domestic hot water demand and automatic control reduces lighting where daylight is available. However there is tighter control of room humidity. The overall effect of this mix of services energy use results in lower building total energy use. Electricity remains the largest fuel. Non-controllable energy ratio is 54%.

Figure 4.9 (Scenario 4) represents the conditions for lowest building energy use. There are no dramatic shifts in the range of energy use, and electricity remains the largest fuel used for the Tom Reilly Building. Clearly shorter occupational periods are significant for major energy using plant. However, smaller equipment energy use accumulates and improved energy performance for these services is key. The ratio of non-controllable energy is 54%.

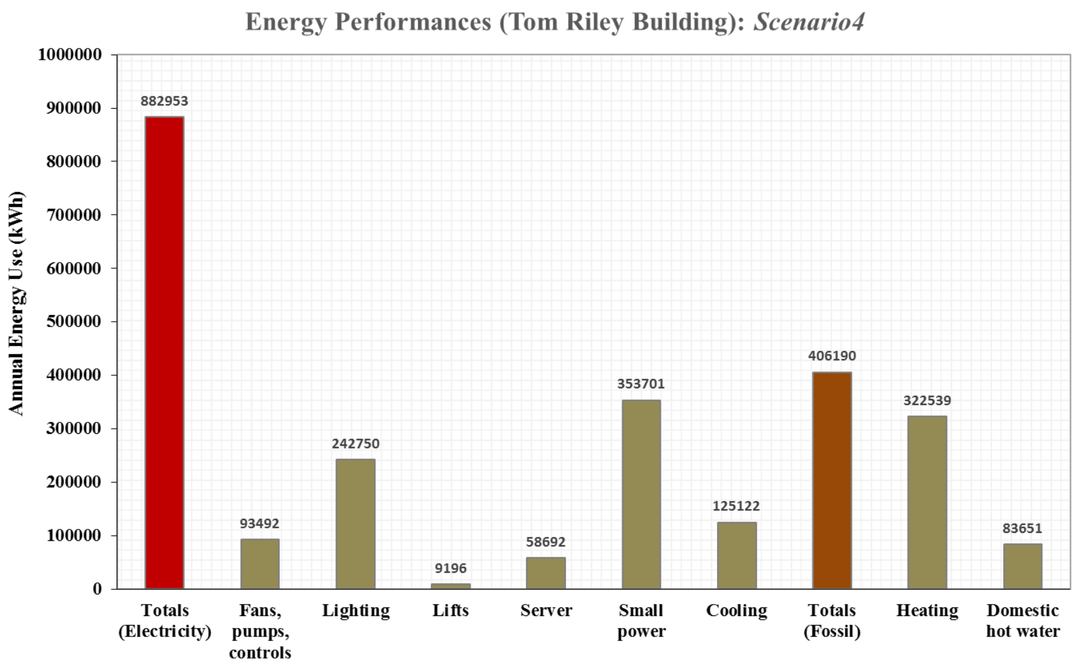

Figure4.9 Building services energy use: scenario 4: Tom Reilly

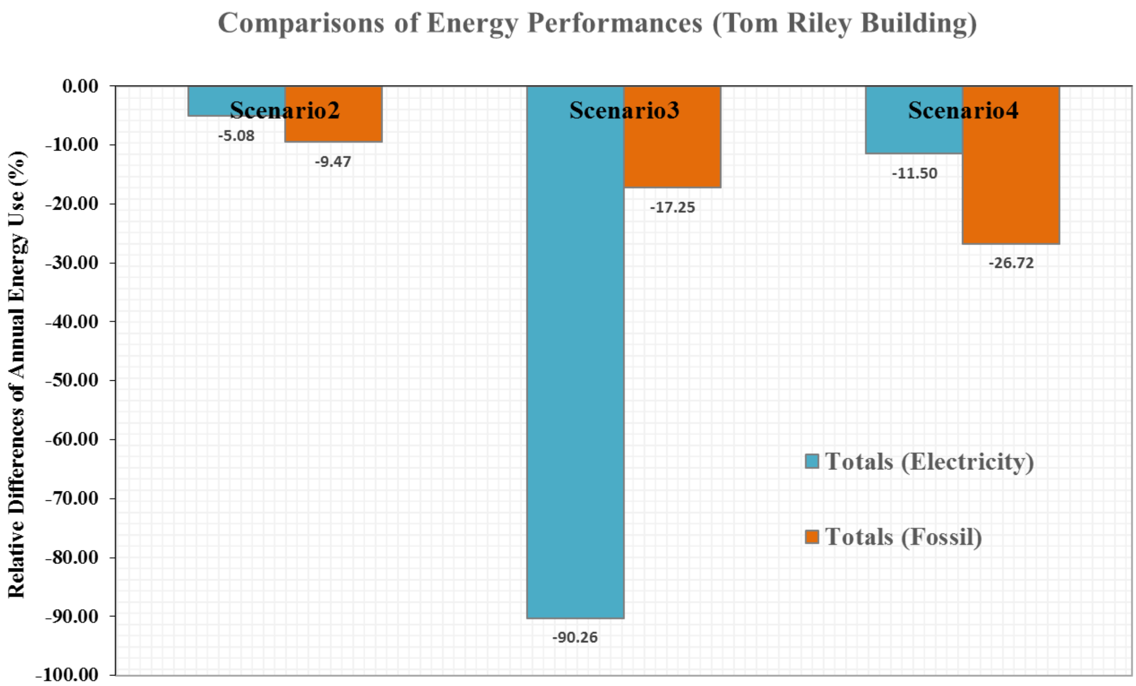

Figure 4.10 Relative differences for energy use at different scenarios: Tom Reilly

The Tom Reilly Building is the newest of the case study buildings and therefore sustainability and energy issues will have had greater influence on design decisions. Electricity is the largest power source for this building and is relatively most affected by changes in operational scenarios (Figure 4.10). This building is largely air conditioned and cooling energy is more significant. However, the architecture reveals much of the internal concrete structure, but for which, the proportion of energy for cooling may have been higher. Table 4.3 indicates that the ratios of electrical and fossil fuel are not excessively sensitive to the varying operational conditions. The scenarios have been developed to reflect typical situations. The greatest loads for each of these fuel sources comprise heating, lighting and small power and a significant change in the energy balance should be unlikely. Shifts in this ratio would require a major change in building operational procedures.

Table4.3 Percentage share of electrical or fossil energy at different scenarios: Tom Reilly

Percentage of building load (T R)							
Scenario 1		Scenario 2		Scenario 3		Scenario 4	
Elec	Fossil	Elec	Fossil	Elec	Fossil	Elec	Fossil
64	36	65	35	67	33	68	32

4.2.4 Cherie Booth Building

Because occupancies for the Cherie Booth Building are clearer, three scenarios were deemed appropriate. The results are demonstrated in Figures 4.11 to 4.13.

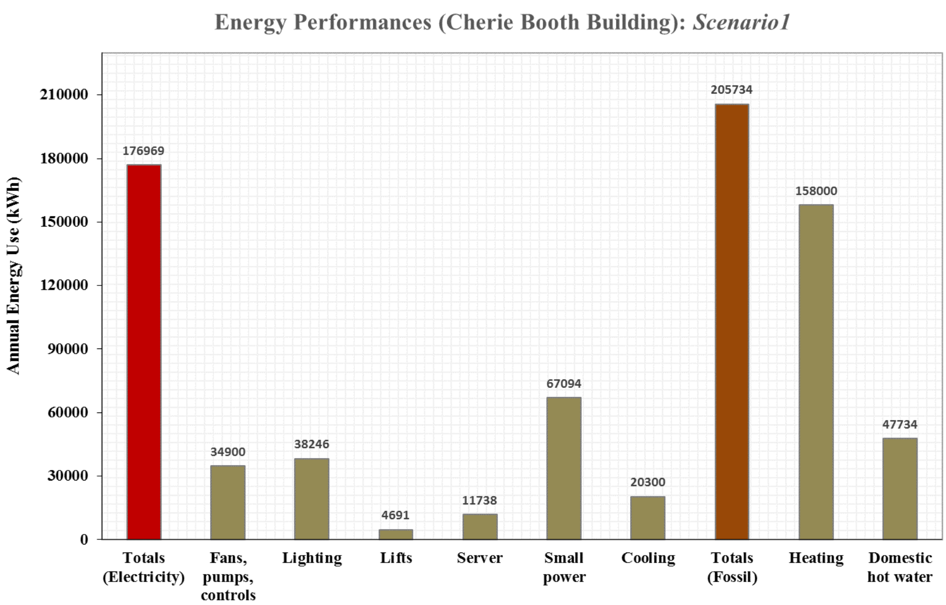

Figure4.11 Building services energy use: scenario 1: Cherie Booth.

Figure 4.11 indicates that fossil (heating) is the major energy user. This is consistent with the servicing strategy for this building which is largely served by a gas-fired radiator system. Operational data for the Cherie Booth Building sets out a fixed period of occupation and therefore all three scenarios are based on 12 hour occupancy. The activities within this building include some lecturing and student IT access but the major use is for academic administration. The occupants mainly comprise teaching staff who alternate between offices and teaching duties elsewhere on campus. The ratio of non-controllable energy is 41%.

Figure 4.12 sets out predicted energy use at Cherie Booth for scenario 2. The largest influence on energy use is by occupant behaviour. This is reflected in the small power changes from scenario 1 and relates to the fact that academic offices are often unoccupied during teaching periods. This has a knock-on effect to domestic hot water use. The lift at Cherie Booth is conveniently located at building entrance and tends to be used in preference to stairs. The ratio of non-controllable energy is 37%.

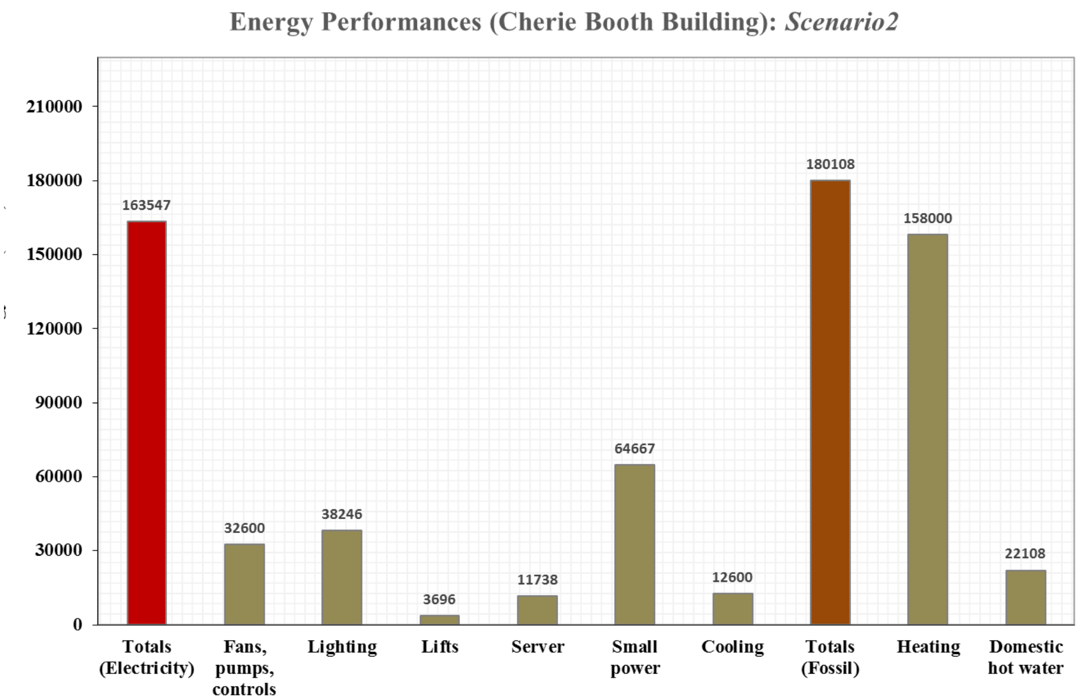

Figure4.12 Building services energy use: scenario 2: Cherie Booth

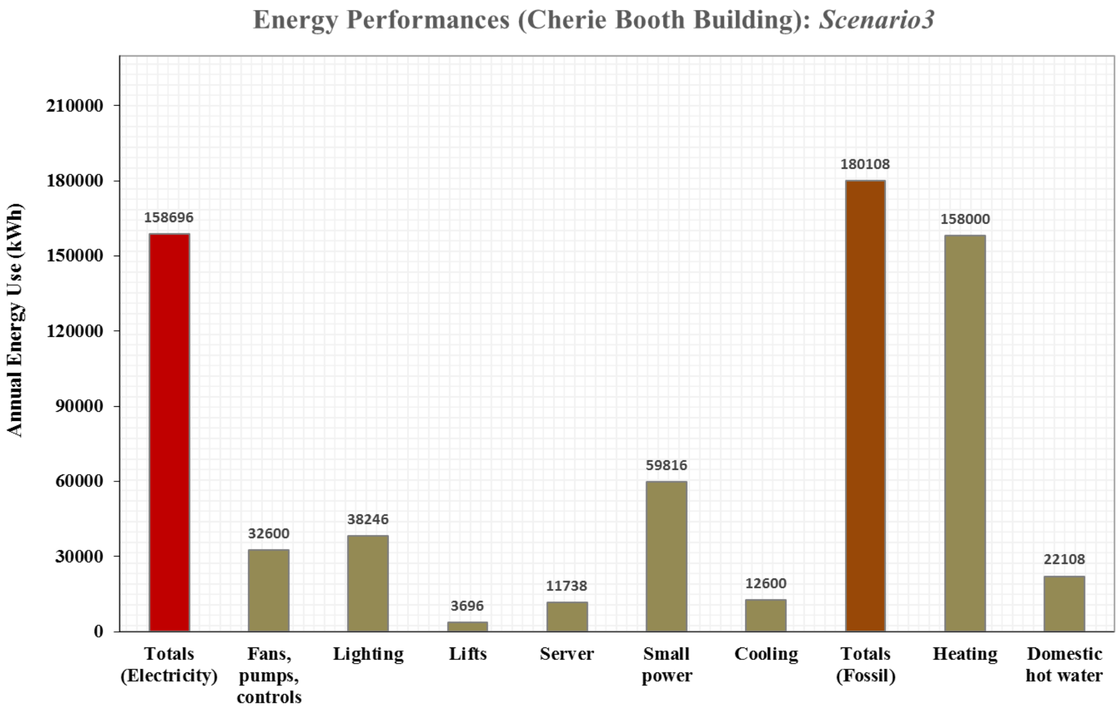

Figure4.13 Building services energy use: scenario 3: Cherie Booth.

Figure 4.13 (Scenario 3) again indicates that heating is the largest energy user. This scenario considers the situation in which teaching staff are present in the building for the minimum time and this affects small power and domestic hot water use. Although only the lecture theatre and IT suite are cooled, the scenarios have also considered the energy implications of internal humidity design targets. The Cherie Booth Building is also relatively new but will have been designed to less rigorous Building Regulations than the Tom Reilly building. Lower insulation values will affect heating loads. The Cherie Booth building has the narrowest floor plan of the case study buildings and consequently has the largest ratio of external wall: this is reflected in a proportionally higher heat load. The ratio of non-controllable energy is 36%.

Table 4.4 demonstrates a stable ratio between electrical and fossil energy use. The prediction scenarios for this building have included practical and likely variations in building activities and occupational periods. Though small power is sensitive to these changes, so also is the demand for domestic hot water. The combination of these two changes offset each other sufficiently to maintain the balance between fossil and electricity demand.

Table4.4 Percentage share of electrical or fossil energy at different scenarios: Cherie Booth

Percentage of building load (CB)					
Scenario 1		Scenario 2		Scenario 3	
Elec	Fossil	Elec	Fossil	Elec	Fossil
46	54	48	52	47	53

Changes in scenarios affect relative changes heating energy slightly more than for electricity (Figure 4.14). These are not major changes in the energy use characteristic for the building. The largest relative change is for fossil fuel and that is related to domestic hot water use. Where estimates of domestic hot water demand is based on statistical data larger shifts in prediction values can occur.

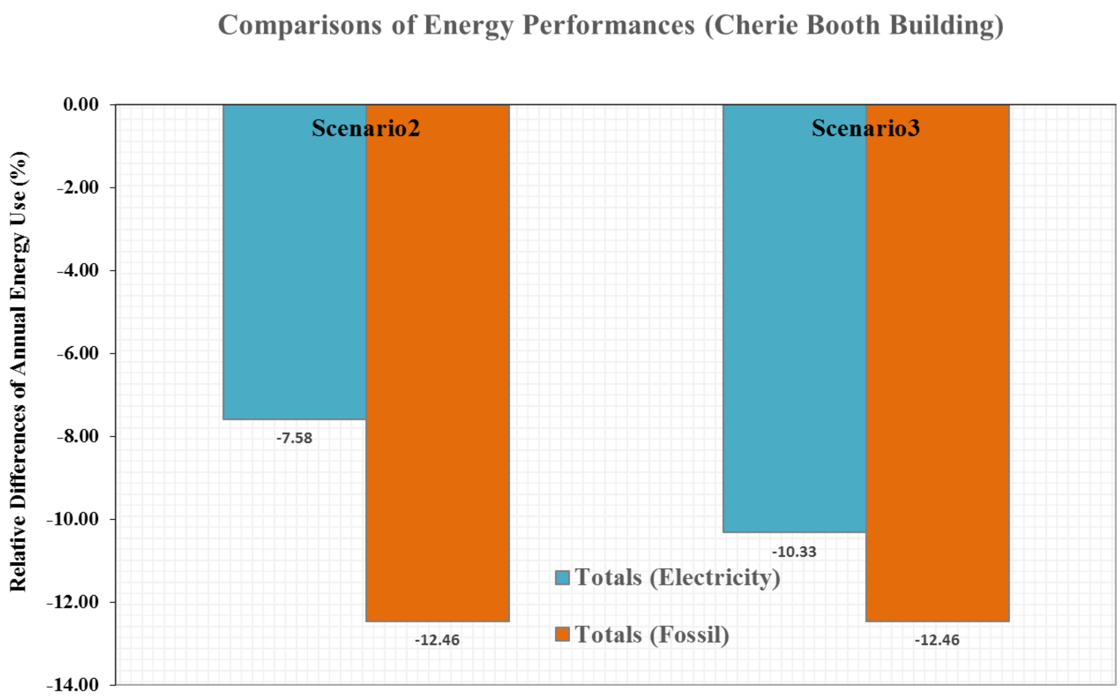

Figure4.14 Differences for energy use at different scenarios: Cherie Booth.

4.2.5 Henry Cotton

Four scenarios were applied to the Henry Cotton Building. The results are demonstrated in Figures 4.15 to 4.18.

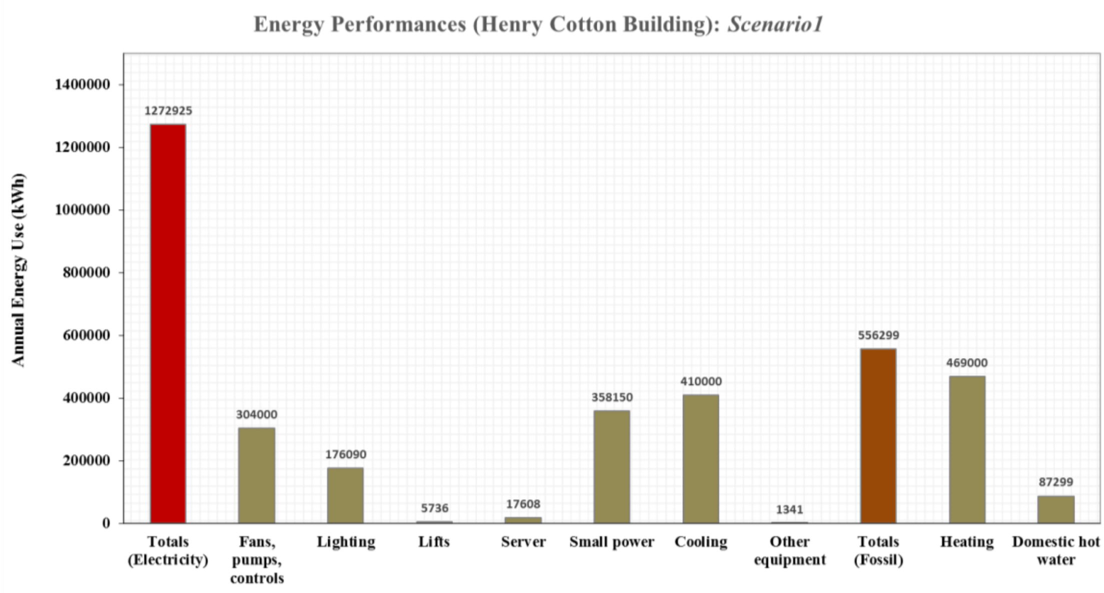

Figure4.15 Building services energy use: scenario 1: Henry Cotton

Figure 4.15 (Scenario 1) indicates that electricity is the largest energy requirement at the Henry Cotton Building. Though heating energy is the next largest energy source it is low in comparison to the electrical demand. This is consistent with the building size and shape. The Henry Cotton Building is deep plan with a consequent lower ratio of heat losing surfaces. This style of architecture also means that Henry Cotton has a number of internal spaces with no access to daylight or natural ventilation from windows. Though not all the building is cooled, in this scenario, the cooling load is almost as high as the heating load.

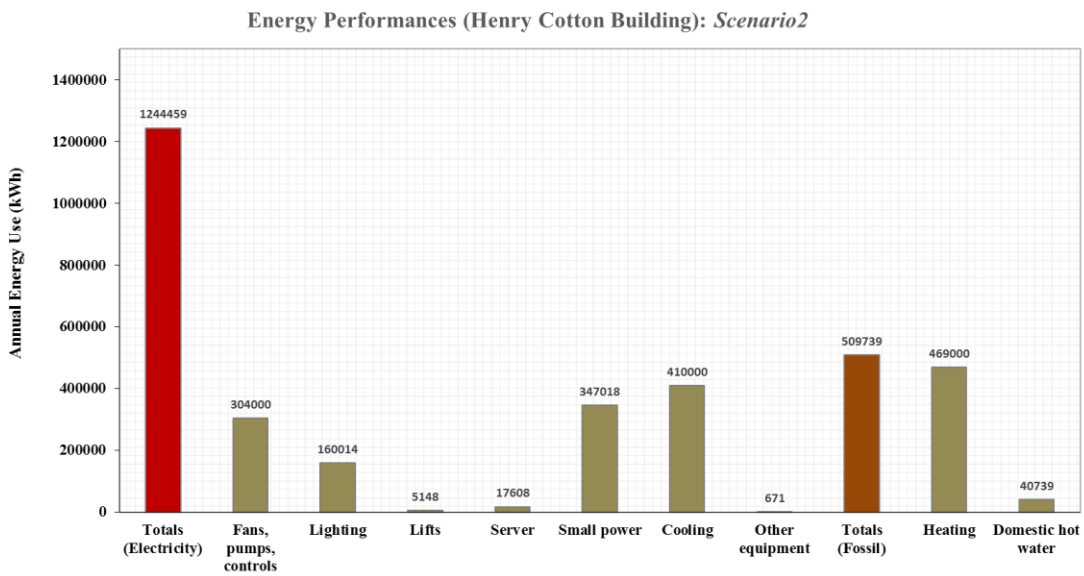

Figure4.16 Building services energy use: scenario 2: Henry Cotton.

Figure 4.16 (Scenario 2) has a similar characteristic to scenario1. Electricity remains the largest energy source. A situation in which there are less occupancy demands would lead to lower small power and domestic hot water use. A cooling load for buildings of this nature will be present for most of the year because much of the load is related to internal gains, though some free cooling could be designed into the system.

Figure 4.17 demonstrates the relationship between building services energy use for scenario 3. Although operational parameters have changed, the building energy use characteristic is similar. Again electricity is the highest energy user. This building includes some laboratory equipment, however data on its operation use is not available. In all scenarios laboratory equipment energy demand is small but this is based on observation and survey only.

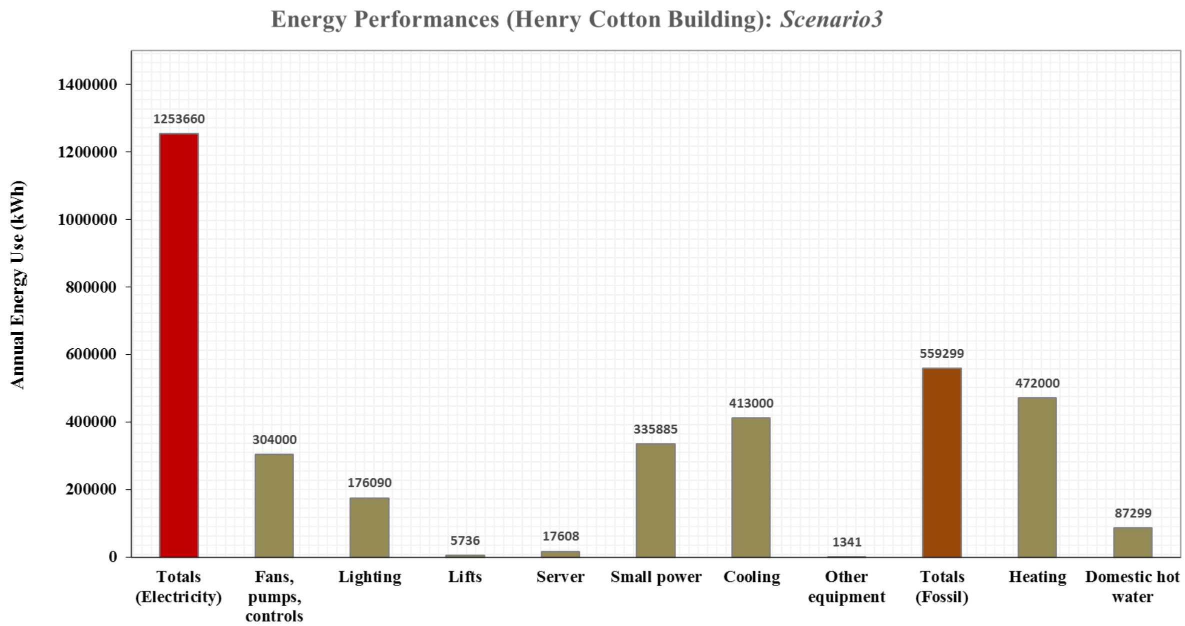

Figure4.17 Building services energy use: scenario 3: Henry Cotton.

Figure 4.18 depicts energy use in scenario 4. Again the cooling demand is secondary to heating, though the design relative humidity is tighter and creates a higher energy demand. Lifts for all scenarios has been deemed to be lightly used. This is based on a site survey. The lift installation at Henry Cotton is slow and much of the student access area are on the lower floors.

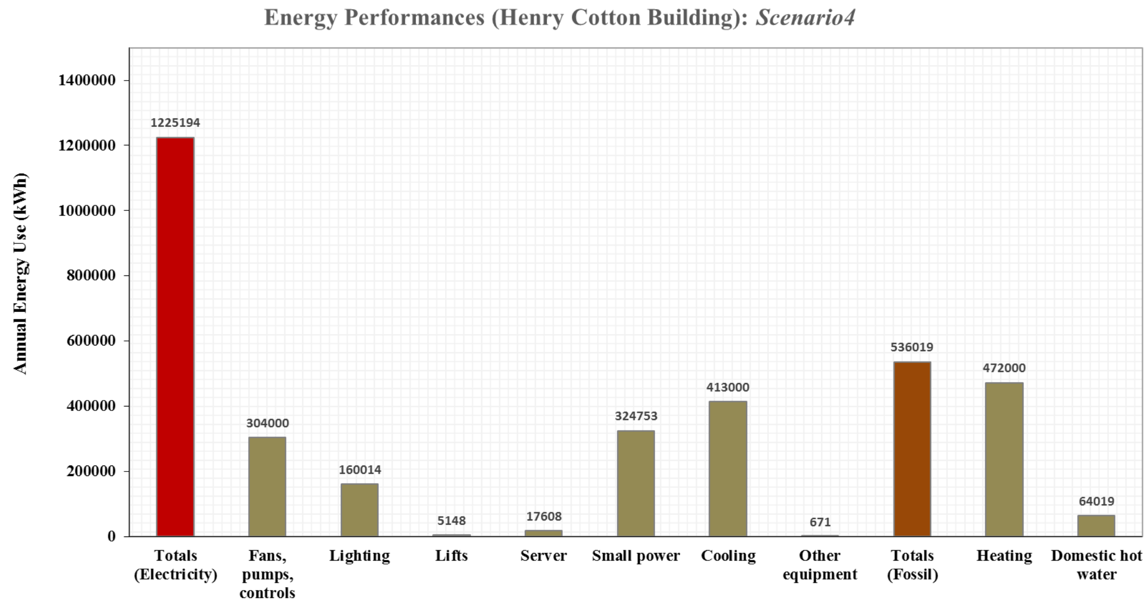

Figure4.18 Building services energy use: scenario 4: Henry Cotton.

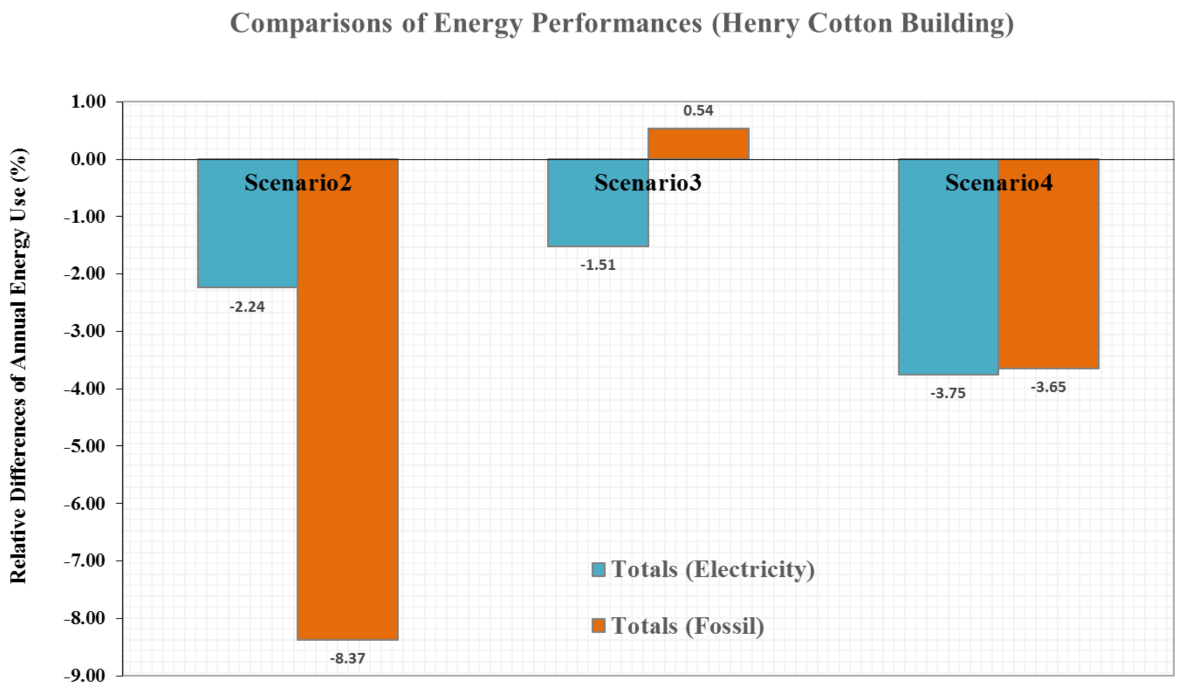

Figure4.19 Differences for energy use at different scenarios : Henry Cotton.

The Henry Cotton Building was constructed in accordance with 1992 Building Regulations and therefore would have lower thermal insulation values than more modern buildings. Whilst this leads to higher heat losses, the building is deep plan. This means that there is a lower ratio of external heat losing surfaces. Many of the indoor spaces have no exterior walls or windows and this will reduce heat loss. Nevertheless, fossil fuels are the most sensitive to changing scenarios (Figure 4.19). Although deep plan footprints can reduce heat losses, they will increase electrical energy use for lighting. The lifts are located at building entrance and compete with stairs. The lift are slow and this encourages a large proportion of occupants to use stairs, particularly since most lectures occur on the first floor. As a proportion of the total energy load cooling is comparable with heating. This is consistent with building deep plan space layout. This is despite the building being mixed mode.

The ratio of electricity and fossil fuel use for Henry Cotton is consistent across the scenarios (Table 4.5). Though operational factors vary, the building characteristic does not change. Also the deep plan nature of this building mean internal zones will be less affected by climatic changes. The scenarios have set realistic changes to design and occupational factors and therefore the relationship between fossil and electricity use should be stable. Occupational factors can have significant effects but these building population behaviour tends to considered as group patterns. This may not be the case but information from surveys may be less reliable than observed and logged data.

Table4.5 Percentage share of electrical or fossil energy at different scenarios: Henry Cotton

Percentage of building load (HC)							
Scenario 1		Scenario 2		Scenario 3		Scenario 4	
Elec	Fossil	Elec	Fossil	Elec	Fossil	Elec	Fossil
70	30	71	29	69	31	70	30

4.2.6 Engineering Workshop

Unlike other university buildings, the engineering workshops have a large amount of electrically powered machine tools and research equipment. Although energy use for this equipment is potentially high, it is not metered. Three scenarios were considered. The energy estimations for each scenario are demonstrated in Figures 4.20 to 4.22.

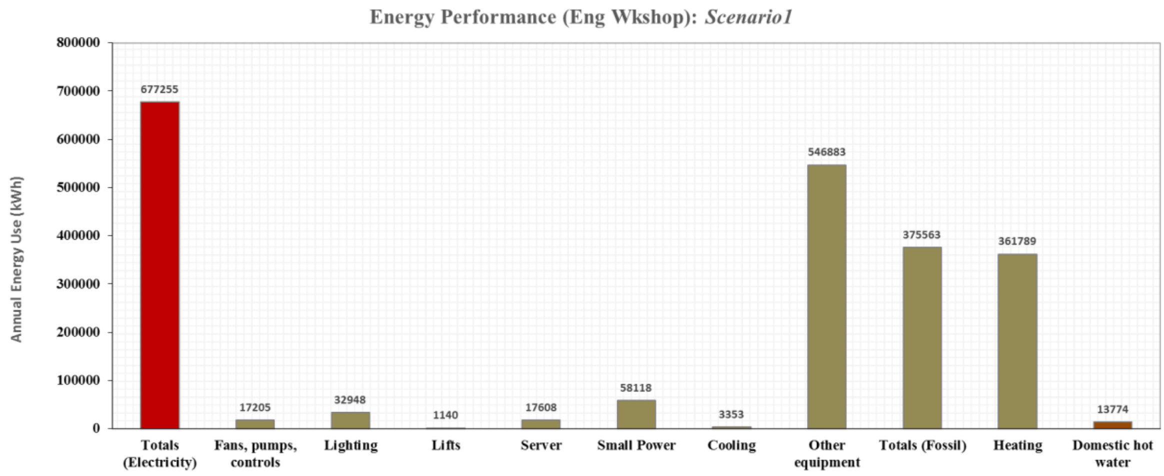

Figure4.20 Building services energy use: scenario 1: Engineering workshops

Figure 4.20 (scenario 1) depicts the situation for the Engineering Workshops in which there is a large electrical demand for laboratory equipment. As well as the laboratory equipment, this complex also includes a machine shop. Operational use for this equipment is not logged and estimates are based on surveys, observation and occupant interview. The small power load is comparatively low. This is consistent with the activities which take place in this building. The ratio of non-controllable energy is 8%.

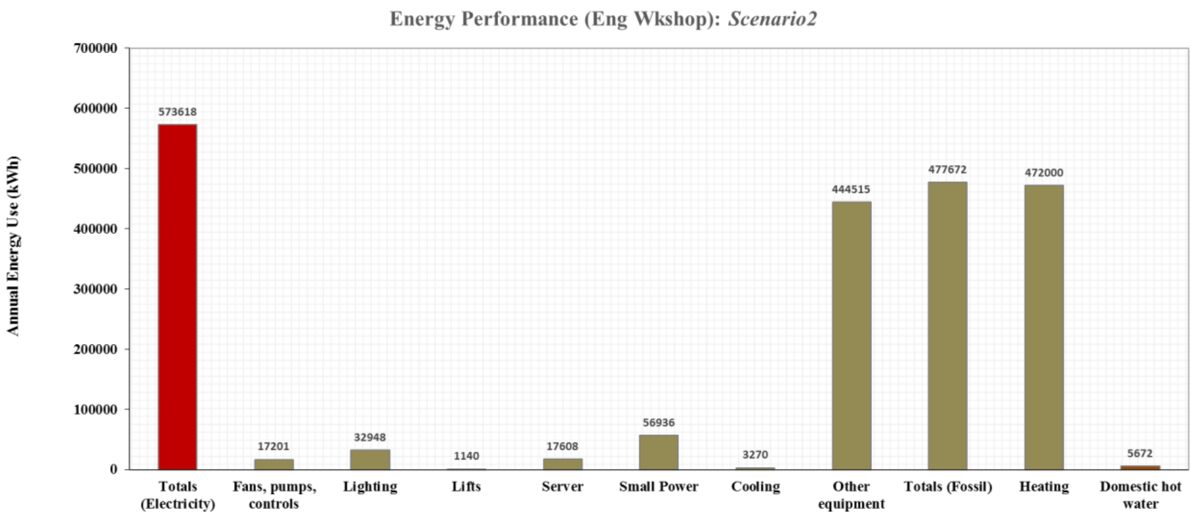

Figure4.21 Building services energy use: scenario 2: Engineering workshops

Figure 4.21 depicts scenario 2. Again laboratory equipment use is a major electrical energy user. This is building is an uncomplicated workshop area with straightforward services. Apart from a small split system air conditioning unit, the workshop's main building engineering service is heating, the energy for which is supplied from a central boiler plant. The lighting, small power, server and ancillary building services for this building are not major energy users in this building. The ratio of non-controllable energy is 9%.

Figure 4.22 considers scenario 3 in which there is lesser use of laboratory equipment. In this situation the heating energy requirement creates the highest energy demand. Lift energy values are based on a disabled persons' access lift which, according to survey is rarely used. Cooling energy relates to a small split system unit for the office section of the workshop. Investigation into operational demand for this cooling unit indicates that is infrequently required. The ratio of non-controllable energy is 10%.

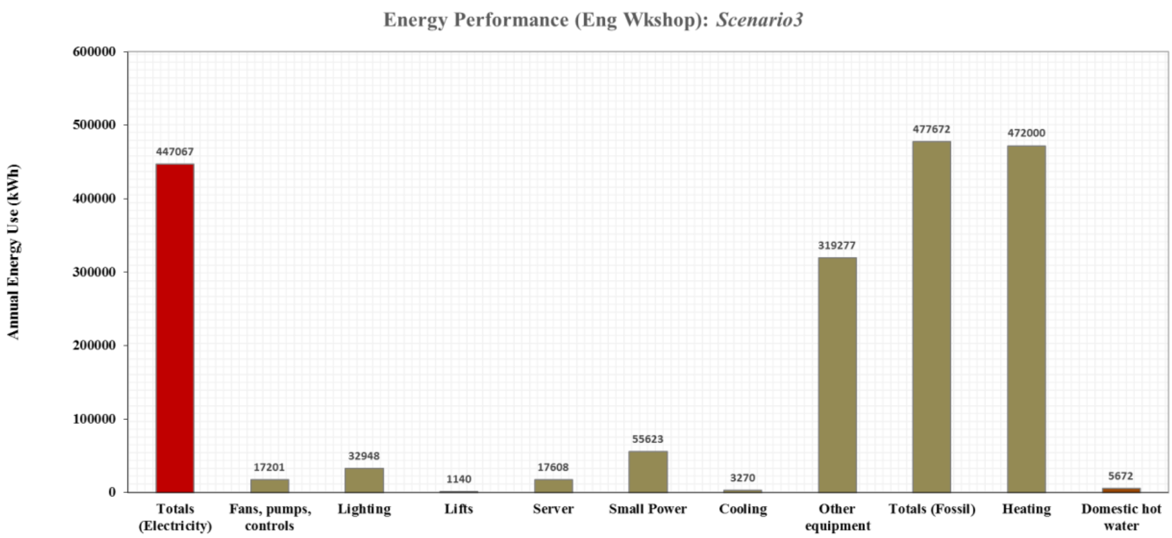

Figure4.22 Building services energy use: scenario 2: Engineering workshops

The engineering is a large factory style construction with an industrial style heating. Workshops are large with high roofs (no ceilings) and roller shutter doors. It would be expected that heating would be the largest energy load. However, there is a considerable amount of large specialist laboratory equipment. Almost all the laboratory equipment has a 230V or 400V supply. There is also a machine tool laboratory housing lathes, power saws, milling machines, shapers and pillar drills. None of the laboratory equipment is metered. Therefore the values of electrical power used for laboratory equipment has been estimated from a site survey and informal interviews with staff. On this basis the major form of energy used at the workshops is electricity. The sensitivity to changing scenarios appears to affect electrical loads slightly more than heating loads (Figure 4.23). However, it must be remembered that the values used in estimates for laboratory equipment were not based on form feedback data. The load share of electricity and fossil fuel mainly electrical for two of the three estimates.

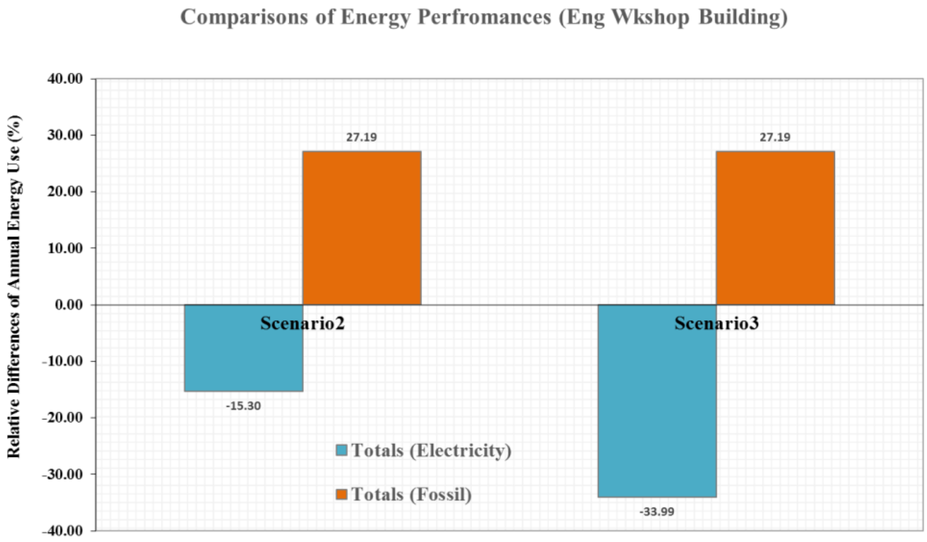

Figure4.23 Differences for energy use at different scenarios: Engineering workshops.

Table 4.6 indicates an instability in the ratio of fossil and electrical fuels for this building under different scenarios. Differences of this magnitude would ordinarily raise questions about building characteristics. However, in this case the major reason for this lack of consistency relates to the estimations for electrical energy use by laboratory equipment. The lack of logged data for the operation illustrates how the accuracy of estimation is directly related to the availability of reliable operational data.

Table4.6 Percentage share of electrical or fossil energy at different scenarios: engineering workshops

Percentage of building load (E W)					
Scenario 1		Scenario 2		Scenario 3	
Elec	Fossil	Elec	Fossil	Elec	Fossil
64	36	55	45	48	52

4.3 Energy Performance: Comparison with Benchmarks

A method of assessing the accuracy of the energy prediction process is to compare predicted values with benchmarks and actual energy use. Display Energy Certificates (DEC's) provide both actual recorded annual building energy use and benchmark information.

DEC's indicate how well a building performs and are required for public buildings. They should be displayed within the building in a location that is easily visible to occupants and visitors. The logic behind this approach is to raise awareness of building energy use. For buildings whose usable floor area exceeds 1000 m^2, DEC's must be renewed annually. This is the case for the buildings examined in this study. DEC's can be accessed through an electronic database (Uk Government, n.d.). The database is publically accessible and individual DEC's can be obtained if a reference number or address is known. DEC's can only be produced by energy assessors who are accredited through government-approved training schemes and numerous commercial organisations provide this service. The DEC's produced for the five buildings examined in this study have been compiled by several different energy assessor organisations.

Tables 4.7 to 4.11 demonstrate a comparison of the energy estimates for each of the case study buildings compared with benchmarks cited in their Display Energy Certificates. The availability of bench marks is linked with the age of each particular building.

Table4.7 Comparison of energy estimates with benchmarks (PJ)

Peter Jost Building		Annual energy use in kWh/m^2 floor area									
		Benchmark		Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate
		Heat	Elec	Heat	Elec	Heat	Elec	Heat	Elec	Heat	Elec
31/10/2011	30/10/2012	296	95	105	136	85	121	105	143	85	128
01/10/2012	30/09/2013	270	95	105	136	85	121	105	143	85	128
01/10/2013	30/09/2014	300	95	105	136	85	121	105	143	85	128
08/09/2014	07/09/2015	254	94	105	136	85	121	105	143	85	128
15/09/2015	14/09/2016	272	94	105	136	85	121	105	143	85	128
13/09/2016	14/09/2017	259	94	105	136	85	121	105	143	85	128

A comparison (Table 4.7) of benchmarks with estimated energy values for the Peter Jost Building reveals that heat energy use averages around 35% of the benchmark whilst electrical estimates average around 136%.

Table4.8 Comparison of energy estimates with benchmarks (TR)

Tom Riley Building		Annual energy use in kWh/m^2 floor area									
		Benchmark		Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate
		Heat	Elec	Heat	Elec	Heat	Elec	Heat	Elec	Heat	Elec
08/09/2014	07/09/2015	254	94	84	151	76	143	70	141	61	133
15/09/2015	14/09/2016	272	94	84	151	76	143	70	141	61	133
13/09/2016	14/09/2017	259	94	84	151	76	143	70	141	61	133

A comparison of benchmarks (Table 4.8) with estimated energy values for the Tom Reilly Building reveals that heat energy use averages around 27% of the benchmark whilst electrical estimates average around 151 %.

Table 4.9 Comparison of energy estimates with benchmarks (CB)

Cherie Booth Building		Annual energy use in kWh/m^2 floor area							
		Benchmark		Estimate	Estimate	Estimate	Estimate	Estimate	Estimate
		Heat	Elec	Heat	Elec	Heat	Elec	Heat	Elec
08/12/2008	07/12/2009	266	95	198	170	173	157	173	153
18/12/2009	07/12/2010	283	95	198	170	173	157	173	153
22/11/2010	21/11/2011	296	95	198	170	173	157	173	153
31/10/2011	30/10/2012	296	95	198	170	173	157	173	153
01/10/2012	30/09/2013	270	95	198	170	173	157	173	153
01/10/2013	30/09/2014	300	95	198	170	173	157	173	153
08/09/2014	07/09/2015	254	94	198	170	173	157	173	153
15/09/2015	14/09/2016	272	94	198	170	173	157	173	153
13/09/2016	14/09/2017	259	94	198	170	173	157	173	153

A comparison of benchmarks ((Table 4.9) with estimated energy values for the Cherie Booth Building reveals that heat energy use averages around 65% of the benchmark whilst electrical estimates average around 168 %.

A comparison of benchmarks ((Table 4.10) with estimated energy values for the Henry Cotton Building reveals that heat energy use averages around 25% of the benchmark whilst electrical estimates average around 169 %.

Table4.10 Comparison of energy estimates with benchmarks (HC)

Henry Cotton Building		Annual energy use in kWh/m² floor area									
		Benchmark		Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate
		Heat	Elec	Heat	Elec	Heat	Elec	Heat	Elec	Heat	Elec
30/10/2008	29/10/2009	275	95	72	164	66	161	72	162	69	158
30/10/2009	29/10/2010	287	95	72	164	66	161	72	162	69	158
30/10/2010	29/10/2011	296	95	72	164	66	161	72	162	69	158
30/10/2011	29/10/2012	296	95	72	164	66	161	72	162	69	158
01/10/2012	30/09/2013	270	95	72	164	66	161	72	162	69	158
01/10/2013	30/09/2014	300	95	72	164	66	161	72	162	69	158
08/09/2014	07/09/2015	254	94	72	164	66	161	72	162	69	158
15/09/2015	14/09/2016	272	94	72	164	66	161	72	162	69	158
13/09/2016	14/09/2017	259	94	72	164	66	161	72	162	69	158

Table 4.11 Comparison of energy estimates with benchmarks (EW)

Engineering workshops		Annual energy use in kWh/m² floor area							
		Benchmark		Estimate	Estimate	Estimate	Estimate	Estimate	Estimate
		Heat	Elec	Heat	Elec	Heat	Elec	Heat	Elec
31/10/2011	30/10/2012	211	120	221	398	281	337	281	263
01/10/2012	30/09/2013	226	130	221	398	281	337	281	263
08/09/2013	07/09/2014	226	111	221	398	281	337	281	263
08/09/2014	07/09/2015	226	111	221	398	281	337	281	263
15/09/2015	14/09/2016	243	111	221	398	281	337	281	263
15/09/2016	14/09/2017	231	111	221	398	281	337	281	263

A comparison of benchmarks ((Table 4.11) with estimated energy values for the Henry Cotton Building reveals that heat energy use averages around 121% of the benchmark whilst electrical estimates average around 153 %.

The heating values are better than benchmark values for the Peter Jost Building, Tom Reilly Building, Cherie Booth Building and Henry Cotton Buildings. Only for the Engineering Workshop (which is un-metered) are the actual recorded values near the benchmarks. For the better-performing buildings, some credit must go to the FM team for operational management. The lack of metering for the engineering workshops casts doubt on the validity of the actual energy use values.

The category benchmark used in DEC's is adjusted "according to the history temperature for the building location for the one year period over which the OR (Operational Rating) is to be calculated" (Department for communities and local government, 2008).

4.4 Energy Performance: Comparison with Actual Energy Use

Tables 4.12 to 4.16 demonstrate a comparison of the energy estimates for each of the case study buildings compared with actual energy use values cited in their Display Energy Certificates.

Table 4.12 Comparison of energy estimates with actual energy use (PJ)

Peter Jost Building		Annual energy use in kWh/m^2 floor area									
		Actual		Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate
		Heat	Elec	Heat	Elec	Heat	Elec	Heat	Elec	Heat	Elec
31/10/2011	30/10/2012	118	130	105	136	85	121	105	143	85	128
01/10/2012	30/09/2013	123	121	105	136	85	121	105	143	85	128
01/10/2013	30/09/2014	133	125	105	136	85	121	105	143	85	128
08/09/2014	07/09/2015	86	114	105	136	85	121	105	143	85	128
15/09/2015	14/09/2016	83	111	105	136	85	121	105	143	85	128
13/09/2016	14/09/2017	78	115	105	136	85	121	105	143	85	128

Average values for comparisons of energy estimates with actual energy use for Peter Jost indicate a good level of accuracy (Table 4.12). The average accuracy of heating estimates is 96% and the average accuracy for electrical energy is 110%.

Table 4.13 Comparison of energy estimates with actual energy use (TR)

Tom Riley Building		Annual energy use in kWh/m^2 floor area									
		Actual		Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate
		Heat	Elec	Heat	Elec	Heat	Elec	Heat	Elec	Heat	Elec
08/09/2014	07/09/2015	111	114	84	151	76	143	70	141	61	133
15/09/2015	14/09/2016	113	111	84	151	76	143	70	141	61	133
13/09/2016	14/09/2017	105	115	84	151	76	143	70	141	61	133

Average values for comparisons of energy estimates with actual energy use for Tom Reilly are: heating 67% and electrical energy use 125% (Table 4.13).

Table4.14 Comparison of energy estimates with actual energy use (CB)

Cherie Booth Building		Annual energy use in kWh/m^2 floor area							
		Actual		Estimate	Estimate	Estimate	Estimate	Estimate	Estimate
		Heat	Elec	Heat	Elec	Heat	Elec	Heat	Elec
08/12/2008	07/12/2009	164	125	198	170	173	157	173	153
18/12/2009	07/12/2010	176	128	198	170	173	157	173	153
22/11/2010	21/11/2011	148	135	198	170	173	157	173	153
31/10/2011	30/10/2012	118	131	198	170	173	157	173	153
01/10/2012	30/09/2013	123	121	198	170	173	157	173	153
01/10/2013	30/09/2014	134	125	198	170	173	157	173	153
08/09/2014	07/09/2015	86	114	198	170	173	157	173	153
15/09/2015	14/09/2016	83	111	198	170	173	157	173	153
13/09/2016	14/09/2017	78	115	198	170	173	157	173	153

A comparison of benchmarks with estimated energy values for the Cherie Booth Building gives values of 156% for heating energy and 130% for electrical energy (Table 4.14). It is noted that for the Peter Jost Building (Table 4.12) and the Cherie Booth Building (Table 4.13) there has been a clear decrease in annual heating demand. This does not correlate with heating degree days for these periods and is therefore not weather related. Although there has been some occupant “churn” for both of these buildings, reduced heating energy use must be attributed to better energy management by the FM team.

Table4.15 Comparison of energy estimates with actual energy use (HC)

Henry Cotton Building		Annual energy use in kWh/m^2 floor area									
		Actual		Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate
		Heat	Elec	Heat	Elec	Heat	Elec	Heat	Elec	Heat	Elec
30/10/2008	29/10/2009	74	119	72	164	66	161	72	162	69	158
30/10/2009	29/10/2010	68	115	72	164	66	161	72	162	69	158
30/10/2010	29/10/2011	86	92	72	164	66	161	72	162	69	158
30/10/2011	29/10/2012	90	96	72	164	66	161	72	162	69	158
01/10/2012	30/09/2013	78	91	72	164	66	161	72	162	69	158
01/10/2013	30/09/2014	99	86	72	164	66	161	72	162	69	158
08/09/2014	07/09/2015	89	76	72	164	66	161	72	162	69	158
15/09/2015	14/09/2016	84	79	72	164	66	161	72	162	69	158
13/09/2016	14/09/2017	74	75	72	164	66	161	72	162	69	158

The average accuracy of estimates for energy use at the Henry Cotton Building are 85% for heating and 155% for electrical energy use (Table 4.15).

Table4.16 Comparison of energy estimates with actual energy use (EW)

Engineering workshops		Annual energy use in kWh/m^2 floor area							
		Actual		Estimate	Estimate	Estimate	Estimate	Estimate	Estimate
		Heat	Elec	Heat	Elec	Heat	Elec	Heat	Elec
31/10/2011	30/10/2012	118	130	221	398	281	337	281	263
01/10/2012	30/09/2013	123	121	221	398	281	337	281	263
08/09/2013	07/09/2014	86	114	221	398	281	337	281	263
08/09/2014	07/09/2015	86	114	221	398	281	337	281	263
15/09/2015	14/09/2016	83	111	221	398	281	337	281	263
15/09/2016	14/09/2017	78	115	221	398	281	337	281	263

The Engineering Workshop electrical energy is not monitored, nor is the heating energy. The accuracy of heating and electrical estimates are 279% and 285% respectively (Table 4.16).

The benchmarks and actual energy use values vary from year to year. Therefore, average values were compared with averaged scenario values estimates. The Engineering workshops fuel supplies are not monitored and there is a large amount of experimental equipment and machine which are also un-metered. The Engineering Workshop actual energy use figures are considered to be unreliable and therefore this building is not considered to be representative. For the other buildings, all electrical estimates were closer to actual values than benchmarks. For heating energy, only the estimate for the Cherie Booth Building was outside of the benchmark value. These percentages are shown in Table 4.17.

Table4.17 Ratios of estimated energy to benchmark and actual values (%).

	Benchmark		Actual	
	Heating	Electrical	Heating	Electrical
Peter Jost	35%	136%	96%	110%
Tom Reilly	27%	151%	67%	125%
Cherie Booth	65%	168%	156%	130%
Henry Cotton	25%	169%	85%	155%
Engineering Workshop	121%	153%	279%	285%

Benchmark values reflect predicted building energy use under prescribed conditions. Although there is some flexibility built into the benchmarks systems (ref TM46), this does not explain the large variation between benchmarks and actual energy use. Benchmarks include the effect of climate variations (degree days). Therefore, it can be concluded that, although climate may affect energy use, other factors impinge on building how a building performs. The remaining influences on building energy use include occupancy patterns and behaviour, control strategy, plant operation and maintenance. Although controls and plant operation can have a facility for monitoring and logging, the relationship between occupant behaviour and building energy use require further investigation.

4.5 Discussion

4.5.1 Performance gap discussions

The performance gap is normally quoted in terms of total (heating and electrical) building energy. Tables 4.18-4.22 for the case study buildings indicate the percentage error of estimate compared to actual energy use. There are three or four estimates for each building based on table 3.9 (see section 3.4.2). These are compared to the annual energy totals for the years for which DEC's are available. The discrepancy between actual energy use and estimated energy use is not a single value. Building characteristics change over time and climate conditions are not identical from year to year. The data in table 4.18-4.22 are also illustrated graphically (Appendix CH4-2).

Table4.18 Percentage error between energy estimates and actual energy use (2011-2016): Peter Jost Building

P Jost		Gap 1	Gap 2	Gap 3	Gap 4
		%	%	%	%
31/10/2011	30/10/2012	-3	17	9	14
01/10/2012	30/09/2013	-1	16	7	13
01/10/2013	30/09/2014	-7	20	12	17
08/09/2014	07/09/2015	21	-3	-13	-7
15/09/2015	14/09/2016	24	-6	-16	-10
13/09/2016	14/09/2017	25	-7	-17	-10

Table4.19 Percentage error between energy estimates and actual energy use (2014-2016): Tom Reilly Building

Tom Riley		Gap 1	Gap 2	Gap 3	Gap 4
		%	%	%	%
08/09/2014	07/09/2015	4	-3	-6	-14
15/09/2015	14/09/2016	5	-2	-6	-13
13/09/2016	14/09/2017	6	-1	-4	-12

Table4.20 Percentage error between energy estimates and actual energy use (2008-2017): Cherie Booth Building

Cherie Booth		Gap 1	Gap 2	Gap 3
		%	%	%
08/12/2008	07/12/2009	27	14	13
18/12/2009	07/12/2010	21	9	7
22/11/2010	21/11/2011	30	17	15
31/10/2011	30/10/2012	48	33	31
01/10/2012	30/09/2013	51	36	34
01/10/2013	30/09/2014	42	28	26
08/09/2014	07/09/2015	84	65	63
15/09/2015	14/09/2016	90	70	68
13/09/2016	14/09/2017	91	71	69

Table4.21 Percentage error between energy estimates and actual energy use (2008-2016): Henry Cotton Building

Henry Cotton		Gap 1	Gap 2	Gap 3	Gap 4
		%	%	%	%
30/10/2008	29/10/2009	22	19	21	18
30/10/2009	29/10/2010	29	26	28	24
30/10/2010	29/10/2011	33	29	31	28
30/10/2011	29/10/2012	27	24	26	22
01/10/2012	30/09/2013	40	36	38	34
01/10/2013	30/09/2014	28	24	26	23
08/09/2014	07/09/2015	43	39	42	38
15/09/2015	14/09/2016	45	41	44	39
13/09/2016	14/09/2017	58	54	57	52

Table4.22 Percentage error between energy estimates and actual energy use (2008-2016): Engineering Workshops

Engineering workshops		Gap 1	Gap 2	gap 3
		%	%	%
31/10/2011	30/10/2012	150	149	119
01/10/2012	30/09/2013	154	153	123
08/09/2013	07/09/2014	210	209	172
08/09/2014	07/09/2015	210	209	172
15/09/2015	14/09/2016	219	219	180
15/09/2016	14/09/2017	221	220	182

For the case of the buildings examined in this study, the estimating process has demonstrated accuracies of between +221 % and -17% (Table 4.23). These are the two extreme values for a range of 117 estimates spread over several years. If the discrepancy percentages for the case studies are compared with performance gaps cited by Menezes (200%-500%) (Menezes, A. 2012) and Innovate UK (350%) (Palmer, J. et al), they are an improvement in accuracy. For this study, this indicates that energy estimation based on the CIBSE TM54 method is more effective. It also demonstrates that the performance gap for any building is not a constant value.

However, factors which provide context to the estimation accuracies are:

- Energy supplies (fossil and electricity) to the engineering workshops are derived from central plant and not metered.
- The Cherie Booth building and the Peter Jost Building share gas and electricity meters

- There is no data available for the energy used by laboratory equipment in the engineering workshops.

Table4.23 Maximum and minimum performance gaps for the case study buildings

Range of performance gaps		
	Max %	Min %
Peter Jost Building	25	-17
Tom Riley Building	6	-14
Cherie Booth Building	91	7
Henry Cotton Building	58	18
Engineering Workshops	221	119

Reducing or eliminating the performance gap for new buildings is partly about improving estimating accuracy. It is also necessary to ensure that the building operates efficiently. Design stage estimates, which are too high or too low, may have implications for project viability and business case development. Incorrect estimates may skew design decisions.

4.5.2 Alternative methods for the determination of plant sizes and annual heating energy use

4.5.2.1 Plant sizes

Software design packages provide convenient and rapid systems for building services design calculations. However, it is important that some method of evaluating the accuracy of software outputs can be applied to ensure that outputs are realistic. In this section, alternative methods have been used to determine heat losses and consequent heating plant loads.

Boiler sizes have been determined from manual heat loss calculations (see appendix CH4-3) and BSRIA “Rules of thumb” for each of the LJMU case study buildings, which have boilers on site (Table 4.24). The calculated boiler plant sizes are compared with installed plant ratings (Figure 4.24). The engineering workshops are heated from a central boiler plant. Domestic hot water is generated separately for all case study buildings.

Table 4.24 Boiler sizes determined by alternative methods.

Boiler Sizes based on calculated heat losses			
Cherie Booth Building	***Watts***	***Henry Cotton Building***	***Watts***
Heat Loss	99723.4	Heat Loss	479252.3
Emissions (10%)	109695.7	Emissions (10%)	527177.5
Plant ratio (1.2)	131634.9	Plant ratio (1.2)	632613
Peter Jost Building		***Tom Reilly Building***	
Heat Loss	389995.5	Heat Loss	627936.7
Emissions (10%)	428995.1	Emissions (10%)	690730.37
Plant ratio (1.2)	514794.1	Plant ratio (1.2)	828876.44
Boiler Sizes based dynamic simulation (chapter 5)			
Cherie Booth Building	140 000	*Henry Cotton Building*	805 000
Peter Jost Building	550 000	*Tom Reilly Building*	*1 162 000*
Boiler Sizes based rule of thumb (87 W/m²)			
Cherie Booth Building	99 000	*Henry Cotton Building*	741 000
Peter Jost Building	306 000	*Tom Reilly Building*	*793 000*
Installed (actual) Boiler Sizes			
Cherie Booth Building	179 000	*Henry Cotton Building*	800 000
Peter Jost Building	600 000	*Tom Reilly Building*	*1 308 000*

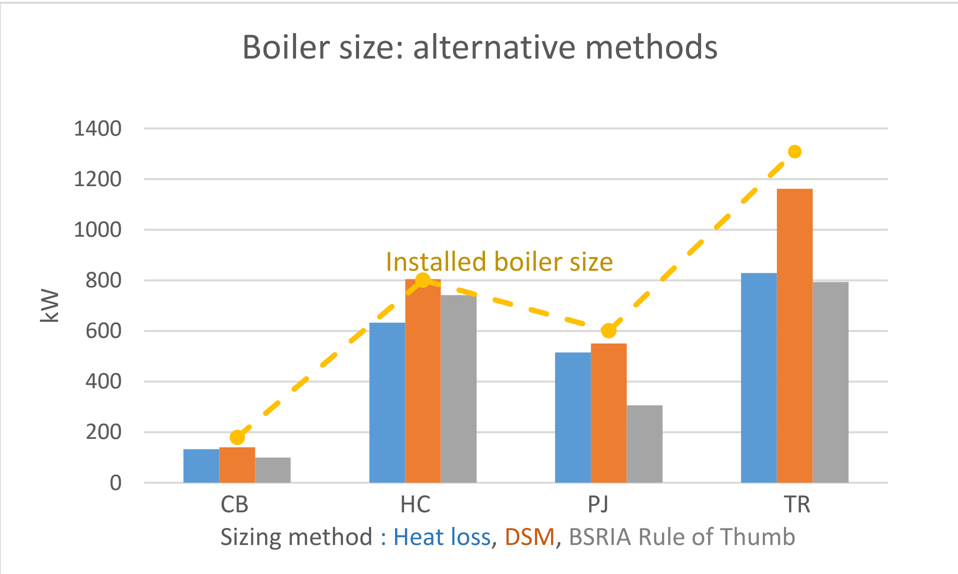

Figure 4.24 Alternative boiler sizes for Cherie Booth, Henry Cotton, Peter Jost and Tom Reilly buildings.

According to Figure 4.24, the different sizing techniques have resulted in different boiler plant sizes and only one estimate matches the installed plant size (Henry Cotton). For Cherie Booth, Peter Jost and Tom Reilly buildings, comparison with estimates indicates that installed plant has been sized conservatively, though these buildings have modular boilers or, in the case of Tom Reilly and Cherie Booth two boilers. If the estimates are compared to the appropriate load characteristics (Table 4.25) then plant sized based on dynamic simulation or manual heat loss calculations could be deemed satisfactory for Cherie Booth building, Peter Jost Building and Henry Cotton buildings. The load characteristics for the Tom Reilly building indicate that boiler plant sized by the manual heat loss method would not meet the load for approximately 20 hours during the heating season. This equates to 1.8% of the heating season and therefore, it could be argued that this would also be acceptable. This could infer that boiler plant based on DSM calculations are over-sized.

Table 4.25 Boiler output and demand.

Periods when boiler output falls below demand (hours and % of heating season)								
	CB	**%**	**HC**	**%**	**PJ**	**%**	**TR**	**%**
Heat loss	0	0	0	0	0	0	20	1.8
Act	0	0	0	0	0	0	0	0
DSM	0	0	0	0	2	0.2	2	0.2
ROT	25	2.3	0	0	20	1.8	50	4.5

4.5.2.2 Annual heating energy

Another benefit of thermal modelling software is that it can produce annual energy use values as well as data for plant sizing. Despite the convenience of this facility it is valuable to be able to assess how realistic these outputs are. In this section, alternative methods are used to determine annual heating loads for the Cherie Booth building and the Tom Rielly building.

For the Average Temperature Method, The maximum building heat loss is proportional to the design temperature difference between inside and outside. This is normally considered a worst-case situation and for most of the heating season outside temperatures will be greater than the design value. Consequently, the actual building heat loss will be less that the design figure. If the building load (kW) through the heating season is deemed proportionate to the actual temperature difference, then it can be calculated as an appropriate fraction of the design value. The actual temperature difference for each day of the heating season has been determined from ASHRAE weather data (Manchester TRY ASHRAEv5.0) from which a daily average inside/outside has been determined. This temperature difference is applied to the design day heat loss (Table 4.26). Calculations are included at appendix CH4-4.

Table 4.26 Annual heating energy (Average Temperature Method).

Annual heating energy at boiler efficiencies of 70, 80 and 90%. (Long hand)			
Cherie Booth Building	***kWh***	***Henry Cotton Building***	***kWh***
Annual Heat Losses	45122	Annual Heat Losses	216847
Energy input (90%)	50136	Energy input (90%)	240941
Energy input (80%)	56403	Energy input (80%)	271059
Energy input (70%)	64460	Energy input (70%)	309781
Peter Jost Building		***Tom Reilly Building***	
Annual Heat Losses	176461	Annual Heat Losses	320058
Energy input (90%)	196068	Energy input (90%)	355620
Energy input (80%)	220576	Energy input (80%)	400073
Energy input (70%)	252087	Energy input (70%)	475226

Table 4.27 Temperature difference frequency.

Calculation of values for $f(\theta_{base} - \theta_{bin})$						
Temperature bands		θ_{bin}	f_b	θ_{base}	$\theta_{base} - \theta_{bin}$	Σf_b
-11.9	-10	-10.95	0.01	22	32.95	0.3295
-9.9	-8	-8.95	0.01	22	30.95	0.3095
-7.9	-6	-6.95	0.07	22	28.95	2.0265
-5.9	-4	-4.95	0.21	22	26.95	5.6595
-3.9	-2	-2.95	0.69	22	24.95	17.2155
-1.9	0	-0.95	1.91	22	22.95	43.8345
0.1	2	1.05	4.23	22	20.95	88.6185
2.1	4	3.05	7.03	22	18.95	133.2185
4.1	6	5.05	9.49	22	16.95	160.8555
6.1	8	7.05	11.42	22	14.95	170.729
8.1	10	9.05	11.89	22	12.95	153.9755
10.1	12	11.05	11.72	22	10.95	128.334
12.1	14	13.05	11.97	22	8.95	107.1315
14.1	16	15.05	10.97	22	6.95	0
						$\Sigma f(\theta_{base} - \theta_{bin})$ = ***1012.238***

For the Bin method (CIBSE, 2006), instead of using average temperature values, another method for determining annual energy use is based on the frequency of occurrence of outside temperatures (CIBSE, 2002). For this method, the frequency values of outside temperature are listed within "defined bands" or bins. The values are derived for the nearest available location (Manchester) and are listed in Table 4.27. The heat loss coefficients have been determined from the calculated heat losses in appendix CH4-3 and Table 4.28.

Table 4.28 Heat loss coefficients.

Heat loss coefficients (H_T)			
Cherie Booth Building		***Henry Cotton Building***	***Watts***
Heat Loss	109.7 kW	Heat Loss	527.2 kW
Heat loss coefficient	4.39 kW/K	Heat loss coefficient	22.9 kW/K
Peter Jost Building		*Tom Reilly Building*	
Heat Loss	429 kW	Heat Loss	690.7 kW
Heat loss coefficient	17.2 kW/K	Heat loss coefficient	27.6 kW/K

From the heat loss coefficients, the annual heating energy use can be found in Table 4.29.

Table 4.29 Annual heating energy use.

Annual heating energy at boiler efficiencies of 70, 80 and 90%. (Bin method)					
	H_T	t_b	$\Sigma f_b\ (\theta_{base} - \theta_{bin})$	η	Q (kWh)
Cherie Booth	4.39	1104	1012.238	0.9	54509.7
	4.39	1104	1012.238	0.8	62323.4
	4.39	1104	1012.238	0.7	70083.9
Henry Cotton	22.9	1104	1012.238	0.9	284344.4
	22.9	1104	1012.238	0.8	319887.5
	22.9	1104	1012.238	0.7	365585.7
Peter Jost	17.2	1104	1012.238	0.9	213568.7
	17.2	1104	1012.238	0.8	240264.8
	17.2	1104	1012.238	0.7	274588.4
Tom Reilly	27.6	1218	1012.238	0.9	378091.1
	27.6	1218	1012.238	0.8	425352.5
	27.6	1218	1012.238	0.7	486117.2

4.5.2.3 Cherie Booth Building Heating and Cooling Calculations

This section will consider (software and explicit) methods used for the determination of heating and cooling loads for the Cherie Booth Building. The cooling loads for the Cherie Booth Building have been determined for the two spaces which are air-conditioned (lecture theatre and IT suite). Manual heat gain calculations are based on the methods for “practical load assessment” demonstrated by Jones (1998). Sensible transmission through glass can be calculated by the following equations:

$$Q_g = A_g * U_g * (t_o - t_r) \qquad (4\text{-}1)$$

Where

$Q_g = sensible\ heat\ gain\ through\ glazing \quad (Watts)$

$A_g = area\ of\ glazing\ (m^2)$

$t_o = outside\ design\ temperature\ (^0C)$

$t_r = inside\ design\ temperature\ (^0C)$

$$Q_{g\ IT\ suite} = 25.65 * 2.2 * (29 - 22) = 305\ Watts$$

$$Q_{g\ Lecture\ theatre} = 5.17 * 2.2 * (29 - 22) = 79.62\ Watts$$

Solar heat gain (glazing)

$$Q_{sg} = F_c * F_s * q_{sg} * A_g \qquad (4\text{-}2)$$

Where

$Q_{sg} = cooling\ load\ (Watts)$

$F_c = air\ node\ correction\ factor$

$F_s = shading\ factor$

$q_{sg} = tabulated\ cooling\ factor\ (W/m^2)$

$A_g = area\ of\ glazing\ (m^2).$

The solutions to the cooling load brought by solar gains can be found in Table 4.30. The maximum cooling load (glazing) for the lecture theatre occurs in October (2575.87 W). The optimum simultaneous cooling load through glazing for both spaces occurs in July (10397.57 + 688.69 W).

Table 4.30 Maximum cooling load through glazing.

IT Suite October 12:30					
Orientation	***Area (m²)***	***Fc***	***Fs***	***Qsg (W/m²)***	***Qsg (Watts***
North	1.74	0.86	N/A	70	104.75
South	2.28	0.86	N/A	576	1129.42
East	21.63	0.86	N/A	105	1953.19
				Total	3187.36
IT Suite October 14:30					
Orientation	***Area (m²)***	***Fc***	***Fs***	***Qsg (W/m²)***	***Qsg (Watts***
North	1.74	0.86	N/A	143	214
South	2.28	0.86	N/A	376	737.26
East	21.63	0.86	N/A	193	3590.15
				Total	451.41
IT Suite July 8:30					
Orientation	***Area (m²)***	***Fc***	***Fs***	***Qsg (W/m²)***	***Qsg (Watts***
North	1.74	0.86	N/A	96	143.65
South	2.28	0.86	N/A	154	301.96
East	21.63	0.86	N/A	535	9951.96
				Total	10397.57
Lecture Theatre October 12:30					
Orientation	***Area (m²)***	***Fc***	***Fs***	***Qsg (W/m²)***	***Qsg (Watts***
South	5.2	0.86	N/A	576	2575.87
				Total	2575.87
Lecture Theatre July 8:30					
Orientation	***Area (m²)***	***Fc***	***Fs***	***Qsg (W/m²)***	***Qsg (Watts***
South	5.2	0.86	N/A	154	688.69
				Total	688.69

Table 4.31 & 4.32 show the internal heat gains in IT suite and lecture theatre respectively.

Table 4.31 Internal heat gains in IT suite.

IT Suite Occupants			
Persons	Heat gain (W/m^2)		Total (Watts)
62	81	Sensible	5022
62	45	Latent	2790
It Suite Lighting			
Fluorescent lamps & high frequency ballasts (8 W/m^2)			
Floor area 92 m^2			736 Watts

IT Suite Equipment			
Item	Number	Heat output (W/unit)	Watts
PC	60	77	4620
Monitor	60	32	1920
Projector	1	77	77
Printer	2	137	274
		Total	6891

Table 4.32 Internal heat gains in Lecture Theatre.

Lecture theatre Occupants			
Persons	Heat gain (W/m^2)		Total (Watts)
124	81	Sensible	10044
124	45	Latent	5580
Lecture theatre Lighting			
Fluorescent lamps & high frequency ballasts (8 W/m^2)			
Floor area 148 m^2			1184 Watts

Lecture theatre Equipment			
Item	Number	Heat output (W/unit)	Watts
PC	1	77	77
Monitor	1	32	32
Projector	1	77	77
		Total	2417

Fabric heat gain was calculated by this equation (4-3):

$$Q_{fabric} = AU\,[(t_{em} - t_r) + f(t_{eo} - t_{em})] \qquad (4\text{-}3)$$

Where

$A = area\ of\ wall\ (m^2)$

$U = thermal\ transmittance\ of\ wall\ (W/m^2K)$

$t_{em} = 24\ hour\ mean\ value\ of\ sol\ air\ temperature\ (\,^0C)$

$t_{eo} =\ sol\ air\ temperature\ at\ the\ time\ heat\ entered\ the\ outside\ surface\ (\,^0C)$

$f = decrement\ factor\ for\ wall$

$t_r = inside\ design\ temperature\ (^0C)$

Table 4.33 & 4.34 indicate the fabric heat gains in IT suite and lecture theatre respectively.

Table 4.33 Fabric heat gains in IT suite.

IT Suite fabric							
	A (m^2)	U (W/m^2K)	tem $(\,^0C)$	tr $(\,^0C)$	f	Teo (^0C)	Q (Watts)
North	0.86	0.35	24.9	22	0.39	12.2	-0.61795
South	1.28	0.35	30.4	22	0.39	12.2	0.583296
East	14.52	0.35	30.9	22	0.39	12.2	8.166774
West	25.2	0.35	30.6	22	0.39	12.2	12.55968
						Total	20.7

Table 4.34 Fabric heat gains in Lecture Theatre.

Lecture theatre fabric							
	A (m^2)	U (W/m^2K)	tem $(\,^0C)$	tr $(\,^0C)$	f	Teo (^0C)	Q (Watts)
South	3.75	0.35	30.4	22	0.39	12.2	1.708875
East	57.52	0.35	30.9	22	0.39	12.2	32.17214
West	56	0.35	30.6	22	0.39	12.2	27.9104
						Total	61.8

The calculations of ventilation/Infiltration heat gains were based on the equation (4-4).

$Q_{inf}(sensible) = 0.33\ N\ V\ (t_0 - t_r)$ (4-4)

Where

$N = air\ changes\ per\ hour$

$V = room\ volume\ (m^3)$

$t_o = outside\ temperature\ (\ ^0C)$

$t_r = inside\ temperature\ (^0C)$.

Then, the calculations of the heat gains in two spaces are: $Q_{inf}\ (\ IT\ Suite\ S) = 0.35 * 0.33 * 257.5 * (29 - 22) = 208.2\ Watts$; $Q_{inf}\ (\ Lecture\ theatre\ S) = 0.35 * 0.33 * 592 * (29 - 22) = 478.6\ Watts$.

Based on the calculations above, the total sensible heat gains are listed in Table 4.35 & 4.36.

Tables 4.35 Total sensible heat gains in IT suite.

IT Suite sensible heat gains (Watts)							
Q_g	Q_{sg}	*Occupants*	*Lighting*	*Equipment*	*Infiltration*	*Fabric*	*Total*
305	10397.57	5022	736	6891	208.2	20.7	23580.47

Tables 4.36 Total sensible heat gains in Lecture Theatre.

Lecture theatre sensible heat gains (Watts)							
Q_g	Q_{sg}	*Occupants*	*Lighting*	*Equipment*	*Infiltration*	*Fabric*	*Total*
79.62	2575.87	10044	1184	2417	478.6	61.8	16840.89

The calculations of latent heat gains was achieved from the equation (4-5).

$Q_{inf}(latent) = 0.8\ NV\ (g_0 - g_r)$ (4-5)

Where

$g_o = outside\ moisture\ content\ (g/kg)$

$g_r = inside\ moisture\ content\ (g/kg)$.

Thus, the results of latent heat gains are in Table 4.37 & 4.38.

Tables 4.37 Total latent heat gains (IT suite).

IT Suite latent heat gains (Watts)		
Occupants (W)	*Infiltration (W)*	*Total (Watts)*
2790	288.4	3078.4

Tables 4.38 Total latent heat gains (Lecture Theatre).

Lecture theatre latent heat gains (Watts)		
Occupants (W)	*Infiltration (W)*	*Total (Watts)*
5580	663.4	6243.4

Similarly, the calculations of heat losses in IT suite and lecture theatre are shown in Tables 4.39-4.43.

Tables 4.39 Fabric Heat Loss in IT Suite.

IT Suite fabric loss				
Surface	Area (m^2)	U Value (W/m^2K)	Δt (^{0} C)	Heat loss (Watts)
glass E	21.5	2.2	25	1182.5
glass S	1.753	2.2	25	96.415
glass N	1.753	2.2	25	96.415
door 1	3	2.1994	5	32.991
door 2	3	2.1994	5	32.991
floor	102.21	2.2826	0	0
Ceilng	102.21	2.2826	0	0
Int wall N	20.3	1.9585	5	198.7878
Int wall S	25	1.9585	5	244.8125
Ex wall W	28	0.35	25	245
Ex wall E	14.65	0.35	25	128.1875
			Total	2258.1

Tables 4.40 Infiltration Heat Loss in IT Suite.

IT Suite infiltration loss			
$Q_{inf} = 0.33 * N * V * (tr - to)$			
Air Change rate	Room Volume (m^3)	Δt (⁰C)	Q inf (Watts)
0.5	286.18	25	1180.5

Tables 4.41 Fabric Heat Loss Lecture theatre.

Lecture theatre fabric loss				
Surface	Area (m^2)	U Value (W/m^2K)	Δt (⁰ C)	Heat loss (Watts)
Glazing	5.224	2.2	25	287.32
door 1	3	2.1994	5	32.991
door 2	3	2.1994	5	32.991
floor	156.25	0.25	25	976.5625
Ceilng	156.25	2.2826	0	0
Int wall N	29.25	1.9585	5	286.4306
Int wall S	16.6	1.9585	5	162.5555
Ex wall N	8.56	0.35	25	74.9
Ex wall S	7.66	0.35	25	67.025
Ex wall E	56.36	0.35	25	493.15
Ex wall W	56.12	0.35	25	491.05
			Total	2904.976

Tables 4.42 Infiltration Heat Loss Lecture theatre.

Lecture theatre infiltration loss			
$Q_{inf} = 0.33 * N * V * (tr - to)$			
Air Change rate	Room Volume (m^3)	Δt (⁰C)	Q inf (Watts)
6	625.017	25	30938

Tables 4.43 Total heat losses (manually calculated).

Total heat loss			
	Fabric	***Infiltration***	***Total***
IT Suite (6 ac/h)	2258.1	14166	16424
IT Suite (0.35 ac/h)	2258.1	1180.5	3439
Lecture Theatre (6 ac/h)	2904.976	30938	33843
Lecture Theatre (0.35 ac/h)	2904.976	1805	4710

The comparisons between manually calculated and simulated heat losses and cooling loads in IT suite and lecture theatre are shown in Tables 4.44 & 4.45.

Table 4.44 Comparison of explicit and DSM heat loss calculations.

Long Hand and DSM Heat losses			
	Long hand(W)	***IES (W)***	***Hevacomp (W)***
IT Suite (6 ac/h)	16424	15236	14165
IT Suite (0.35 ac/h)	3439	3307	3142
Lecture Theatre (6 ac/h)	33843	39352	43809
Lecture Theatre (0.35 ac/h)	4710	5084	6601

Table 4.45 Comparison of explicit and DSM heat gain calculations.

Long Hand and DSM Heat Gains (sensible)			
	Long hand(W)	***IES (W)***	***Hevacomp (W)***
IT Suite	23580.47	19384	20217
Lecture Theatre	16840.89	22629	24419

According to the results above, the comparisons of long-hand and DSM methods for determining heating and cooling loads indicate that, not only are there discrepancies between long-hand and DSM results, but there are also differences between different DSM applications. The range of difference obtained in this case study, though arithmetically significant must be considered in a present-day practical design context. Apart from the temptation of designers to add margins to calculated values, the process of selecting commercially available heating and cooling plant will almost certainly mean that installed equipment is rated above theoretically design values. Additionally, it has been demonstrated in chapter 5 that the practice of designing for a "design day load" means that heating and cooling plant is actually over-sized for most of it operational life. Consequently, the risks associated in commercial HVAC commercial practice are more likely to be related to over-sizing than under-sizing. Beattie and Ward (1999) state that air conditioning equipment sized by long-hand (admittance) methods "will not be under-sized", however they also point out that " the possibility of identifying over-sizing in most cases does not arise". In commercial terms, Beattie and Ward's comments demonstrate that designers and clients are willing to manage over-sized equipment providing it will always meet the load demand.

Energy modelling software systems use powerful algorithms which can perform design calculations rapidly and conveniently. Although CIBSE Guide A (2015) indicates that thermal modelling is an appropriate design tool for detail design applications, another CIBSE (Limitations of energy modelling, AM 11 2015) publication discusses the limitations of modelling software. These include simplified approaches to heat transfer and standard weather data sets based on historic data. Perhaps a more important limitation for thermal modelling is an imperfect knowledge of the actual construction and future operation of the proposed building.

Therefore, dynamic simulation models are not, in themselves, a panacea to all design problems. Long-hand calculations have their use, particularly for early design stages. For the process of sizing and selecting heating and cooling plant CIBSE guidance sizing (2016) recommends applying steady state calculations.

4.6 Summary

This chapter has considered the process of estimating building energy use by applying a method based on the CIBSE TM54 technique. The study included an assessment of the energy used by the various building services systems in five university campus buildings.

To determine the total building energy load involves using a combination of simulation modelling for dynamic loads and spreadsheet techniques for loads which are more related to occupant behaviour. The estimations have found that, for this study the greater amount energy use is related to occupant behavioural items. These items tend not to be monitored in existing buildings and, at design stage tend to quantified in "standardised" terms.

For designers of new buildings, unless an exactly similar building is available to study, estimates are compared with bench marks. The estimates determined in this study were compared with bench marks and comparisons indicated that estimates for heating were frugal and electrical estimates generous (apart from the engineering workshop). This could be a concern for design consultant who sees under-sizing of equipment as a contractual risk. A risk – averse designer, in this situation may also apply a rule-of-thumb technique, in which case the function of the DSM would be one of compliance. Applying rule-of-thumb figures would also create a wider performance gap between design and actual energy use.

The estimates were also compared with actual energy use values and heating and electrical values were closer, apart from the engineering workshop. The engineering workshops contain lots of unique specialist equipment which has the potential for high energy use. None of this equipment is monitored and therefore energy estimations require intelligent approximations. The lack of metering for this building means that it is unrepresentative. It does however, highlight the importance of metering and monitoring.

Performance gaps are normally quantified against total building energy use. On this basis, estimates were also compared with building total energy. These comparisons were more accurate, but of course only comparing total energy use will not reveal how heating and electrical ratios can vary for individual building services systems.

Chapter 5:

Building Service Appraisal: Fans, Pumps, Boilers and Chillers

5.1 Introduction

This chapter will review how decisions taken at design stage affect the energy performance of individual items of building services equipment. The study will involve case study information taken from several sources.

Data for the operation of fans has been obtained from consultant specifications, contractor's specifications and commissioning engineer's results for a large hospital project which is currently under construction. Data regarding the operation of pumps has been obtained from maintenance information and record drawings for case study buildings referred to in Chapter 4. Based on the data obtained for pumps and fans, methods have been developed for preparing a preliminary, design-stage assessment of the potential energy use of fans and pumps.

This chapter will also compare the heating and cooling loads for the case study buildings with installed plant sizes.

5.2 Building Service System: Fans

This section focuses on ventilation systems which are part of the building services engineering systems for a large hospital project (see section 3.5).

5.2.1 Case Study: Hospital Project

Technology has an important role in the operation of modern hospitals. Parts of that technology are the building services engineering systems which control environments and ensure safe and hygienic conditions. The air –handling requirement for a large project, currently under construction include, comprises more than 85 air – handling units. Each of these units contains one or more fans.

The consultant's schedule (appendix CH5-1) for air-handling equipment designates the hospital zone application, the technical specification as well as the margins applied to supply and extract flow rates and supply and extract system resistances. Part copies of the supply and extract specifications are shown in Tables 5.1 and 5.2. The external components are those sections of the duct system, which are not part of the air-handling unit. The ductwork designer determines the external losses. The system flow rates and resistances shown in these tables are inclusive of the applied margins. Figure 5.1 is a fan/system characteristic for one of the specified air handling units. This characteristic was obtained from manufacturer's publically accessible software. The characteristic demonstrates the operating point, fan efficiency, fan speed and fan power. However, these values are based on flow rates and system pressure drops which have added margins.

Table 5.1 Hospital Project AHU Supply Fans.

AHU Supply	m^3/s	External static (Pa)	Total static (pa)	AHU component (Pa)	Power (kW)
HB-AHU-03-NE-17	3.18	652	1050	398	4.70
HB-AHU-03-NE-16	4.14	658	1012	354	5.70
HB-AHU-03-NW-05	3.84	634	959	325	5.00
HB-AHU-03-NW-06	6.42	634	1107	473	10.40
HB-AHU-03-SE-12	7.51	564	977	413	10.00
HB-AHU-03-SW-01	4.53	508	946	438	5.80
HB-AHU-03-SW-10	3.67	425	806	381	4.03
HB-AHU-03-SW-11	1.96	564	1004	440	2.74

Table 5.2 Hospital Project AHU Extract Fans.

AHU Extract	m^3/s	External static (Pa)	Total static (pa)	AHU component (Pa)	Power (kW)
HB-AHU-03-NE-17	3.18	648	836	188	3.6
HB-AHU-03-NE-16	4.13	654	809	155	4.5
HB-AHU-03-NW-05	3.88	629	800	171	4.1
HB-AHU-03-NW-06	6.53	596	780	184	7.7
HB-AHU-03-SE-12	7.7	526	759	233	7.9
HB-AHU-03-SW-01	4.52	496	710	214	4.7
HB-AHU-03-SW-10	3.67	408	654	246	3.68
HB-AHU-03-SW-11	1.45	522	699	177	1.52

The image *originally presented here cannot be made freely available via LJMU E-Theses Collection because of copyright. The image was sourced at "Flakt-Woods fan selector* [*www.flaktwoods.com*](http://www.flaktwoods.com)

Figure 5.1 Manufacturer's fan performance characteristic (Flakt Ltd.)

Figure 5.2 illustrates the power for the hospital air handling fans at design condition and with margins to flows and pressure drops. This indicates that designers are not completely confident in the accuracy of design ratings. Omitting the margins reduces power requirements.

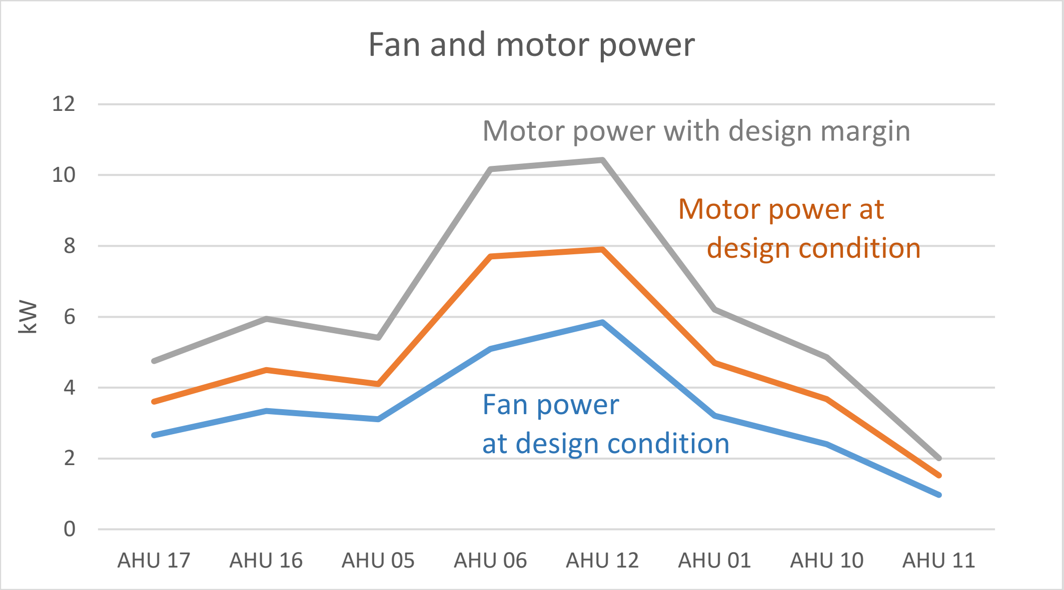

Figure 5.2 Power for supply fans at design condition and condition and with added flow and pressure margins

5.2.2 Fan Energy Prediction at Early Design Stage

This section will set out an early design stage method for estimating fan energy use based on the length of duct work index run and the following parameters:

- Allowable specific fan power
- Approximate route/length of duct run
- Approximate air flow rates
- Sketch designs for building layout, orientation and plant space locations.

It is proposed that this method be applied in conjunction with the CIBSE TM54 energy evaluation process. As part of the TM54 process, the application of the dynamic simulation will provide heating and cooling loads. The supply volume flow rates can be determined from the sensible heat gain formula (5-1). Constant 356 is determined from air density corrected for temperature multiplied by the specific heat capacity of air (1.2 kg/m3 * 294 K * 1.01 kJ/kg K). Extract volumes are normally equal to supply. For specialist situations, such as clean room air conditioning, extract systems tend to be greater than supply to create negative pressures within the space. Details on specialist requirements should be included in the client's brief.

$$Volume\ flow\ \left(m^3/_s\right) = \frac{Sensible\ heat\ gain\ (kW)}{(t_r - t_s)} + \frac{(273+t_s)}{358} \tag{5-1}$$

Where

$t_r = room\ temperature$ (^{0}C) and $t_s = room\ temperature$ (^{0}C)

Note: for heating applications, the temperature difference $(t_s - t_r)$ *is applicable*

The system for determining fan energy use involves comparing proposed duct length measured from design drawings with a duct length, which is allowable in compliance with specific fan power requirements. The method factors the following additional parameters into the calculation –

- Motor efficiency (2, 4, or 6 pole, IE2 or IE3)
- Fan efficiency
- Pressure loss in air handling plant (AHU factor)
- Percentage pressure loss due to duct fittings
- Straight duct design rate of pressure loss
- Fan type (forward curve, backward curve, axial)

The formula the determine allowable index run duct length-

$$Length\ of\ index\ run = \frac{[(SFP * motor\ \eta * Fan\ \eta) * (1 - AHU\ Factor)]}{(\Delta P/m)} \tag{5-2}$$

Where

$SFP = specific\ fan\ power\ in\ W/m^3$

$AHU\ factor = internal\ AHU\ pressure\ loss\ ratio$

$\Delta P/m = straight\ duct\ pressure\ loss\ (plus\ fittings\ allowance)$

The regulations regarding electric motors are discussed in chapter 2. The International Electrotechnical Commission (IEC) standard has been adopted as a UK standard (BS EN 60034-30:2009). The efficiencies for electric motors applicable to this standard are demonstrated graphical form in appendix CH2-1.

Fan efficiencies are closely related to the accuracy of specified operating points. The consultant's design schedule for the hospital project includes margins for supply and extract volumes (7.5-10%) (Hoare Lea, 2017) and external pressure drops (10-21%) (Hoare Lea, 2017). On this basis, it would be impractical to specify Best Efficiency Point. Practical fan efficiency values for application in equation 5-2 are shown in Chapter 2 (Figure 2.2-2.4). The AHU factors to be applied in equation 5-2 are also available in Chapter 3 (Table 3.15).

Recommended pressure drop rates for straight duct are from 0.8 Pa/m to 1.2 Pa/m. Clearly additional frictional losses occur for fitting and bends. In order that the system is straightforward, it is proposed that additional pressures created by fittings are accounted for by increasing the rate of pressure drop for straight duct. The straight duct pressure losses (Table 5.3) were applied to the fan systems for the hospital case study project. Calculated allowable duct lengths were compared with design drawing duct lengths (by measurement).

Table 5.3 Example rates of pressure drop applied in equation 5.2

Straight duct pressure drop						
ΔP/m (Pa/m)+ allowance fittings	1.2	1.4	1.6	1.8	2	2.2

The results of the duct length comparison are shown in Figure 5.3. The frequency curves indicate which values for rates of duct pressure loss are most likely to coincide with actual pressure installed duct length values. The most suitable rates of pressure drop for straight duct which accounts for additional losses in bends and fittings is between 1.8 and 2.2 Pa/m. Note: this an approximate method based on the consultant's specification at design stage.

The consultant's duties for the hospital project involve completing the design as far as RIBA stage 4, Technical Design. After this stage, preparing working drawings in accordance with consultant's design intent becomes the responsibility of the installation contractor. The effect of this change can be seen in the contractor's schedule of air handling equipment (appendix CH3-2) which differs from the consultant's schedule. Further changes can be made during installation and this can be seen from the commissioning engineer's report at appendix CH3-2.

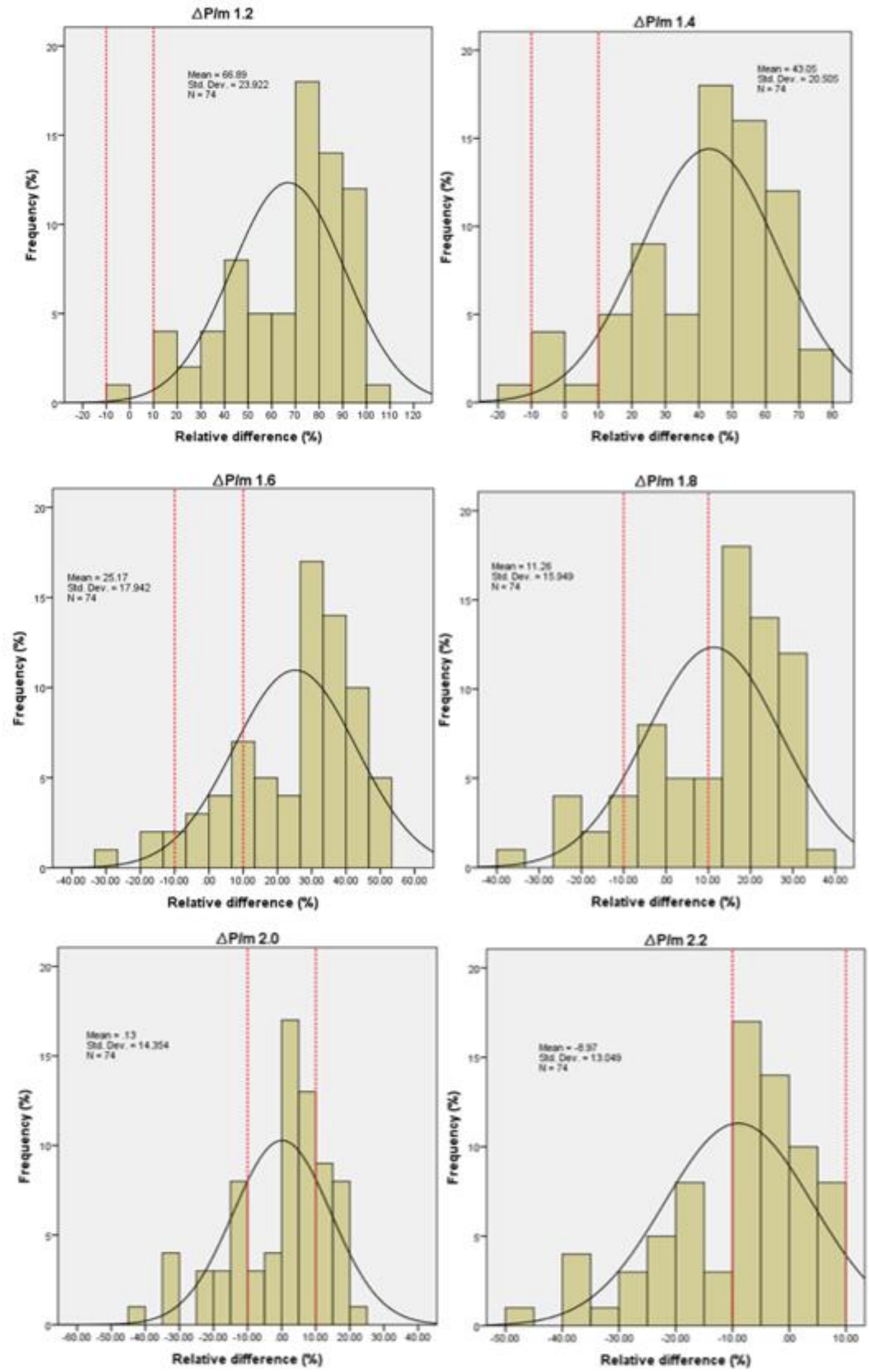

Figure 5.3 Rates of duct system pressure drop (Pa/m) which account for fittings losses.

5.3 Building Service System: Circulating Pumps

5.3.1 Introduction

Whereas the case study information for fans was obtained from the design data for a hospital project which is presently in construction, the case study which has been investigated for circulating pumps performance is the Tom Reilly building. The design values for the heating and chilled water pumps have been determined by the project consultant engineers and can be found the design specifications for the Tom Reilly Building. Further data on pump performance has been obtained from record drawings and maintenance information. Circulating pumps used to for transferring heating or cooling energy in buildings services applications do not deliver water from one source to another, instead the fluid circulates within the system exchanging heat at appropriate points. This means that the pump duty is based on overcoming the frictional resistance of the pipework only.

This section will consider secondary heating and chilled water circulating pumps. Primary pumps for heating and chilled water systems circulate fluid around the central boiler or chiller system from which secondary pumps derive fluid and circulate to the emitters located in the treated spaces.

5.3.2 Case Study: Tom Reilly Building

5.3.2.1 Specification and Maintenance Documentation for Pumps

There are two sets of documentation available for this building. One set of documentation sets out the design specification. The other documents include the record drawings and maintenance information which represent the installed condition of the building engineering services.

Comparison of design and commissioned performance values for circulating pumps for the heating and cooling systems at the Tom Reilly Building reveals the energy implications of design strategies. Table 5.4 & 5.5 list the design values for circulating pumps. It can be seen that the (operational) commissioned values for CP03 & CP04, HP04 & HP05, and for CP06 and CP07 are less than the specified values. The design margins represented by these values are shown in Tables 5.6 and 5.7.

Table 5.4 Design values for circulating pumps

	Flowrate (L/s)	Head (kPa)	Pump Efficiency (%)	Pump + Motor Efficiency (%)
CP03	11.6	150	74	65
CP04	11.6	150	74	65
CP06	11.6	150	74	65
CP07	11.6	150	74	65
HP01	7.9	75	65	60
HP02	7.9	75	65	60
HP04	7.6	150	64	59
HP05	7.6	150	64	59

Table 5.5 Commissioned values for circulating pumps.

	Flowrate (L/s)	Head (kPa)	Pump Efficiency (%)	Pump + Motor Efficiency (%)
CP03	8.1	73	64	58
CP04	8.1	73	64	58
CP06	9.5	101	70	60
CP07	9.5	101	70	60
HP01	7.9	75	65	60
HP02	7.9	75	65	60
HP04	6.8	121	62	56
HP05	6.8	121	62	56

Table 5.6 Pump design margins (flow rates)

CP03	$\left({}^{11.6}/_{8.1}\right) * 100$	+43%
CP06	$\left({}^{11.6}/_{9.5}\right) * 100$	+22%
HP04	$\left({}^{7.6}/_{6.8}\right) * 100$	+12%

Table 5.7 Pump design margins (system resistance)

CP03	$\left({}^{150}/_{73}\right) * 100$	+ 105%
CP06	$\left({}^{150}/_{101}\right) * 100$	+49%
HP04	$\left({}^{150}/_{121}\right) * 100$	+ 24 %

Pump efficiency is related to its operating point (flow rate and pressure). The change in pump performance characteristic between design and operational parameters has negatively affected pump efficiency. Although the reductions in flow rate and pressure drops decreases the overall power requirement for pumps, the margins have meant that, at operational conditions overall pump performances fall short of best efficiency point (BEP). Table 5.8 demonstrates the electrical input power to pumps at design and commissioned parameters.

Table 5.8 Electrical input power to circulating pumps at Tom Reilly Building

		Water power (Watts)		Electrical power (Watts)	
CP03	Design	$11.6 * 10^{-3} * 150 * 10^3$	1740	$1740/0.65$	2677
CP03	Commission	$8.1 * 10^{-3} * 73 * 10^3$	591.3	$591.3/0.58$	1019.5
CP06	Design	$11.6 * 10^{-3} * 150 * 10^3$	1740	$1740/0.65$	2677
CP06	Commission	$9.5 * 10^{-3} * 101 * 10^3$	959.5	$959.5/0.6$	1599.2
HP04	Design	$7.6 * 10^{-3} * 150 * 10^3$	1140	$1140/0.59$	1932.2
HP04	Commission	$6.8 * 10^{-3} * 121 * 10^3$	822.8	$822.8/0.56$	1469.3

Figure 5.4 graphically illustrates how, for a single pump achieving the best operational efficiency point requires that pumps are accurately sized. Where commissioning necessitates fluid volume regulation, speed control is an excellent and straightforward technique for this process. However, adjusting pump speeds too far from the best efficiency point reduces the energy benefit from speed control. Running pumps outside of the recommended operational range creates noise and additional wear (Chemical Engineering, 2015).

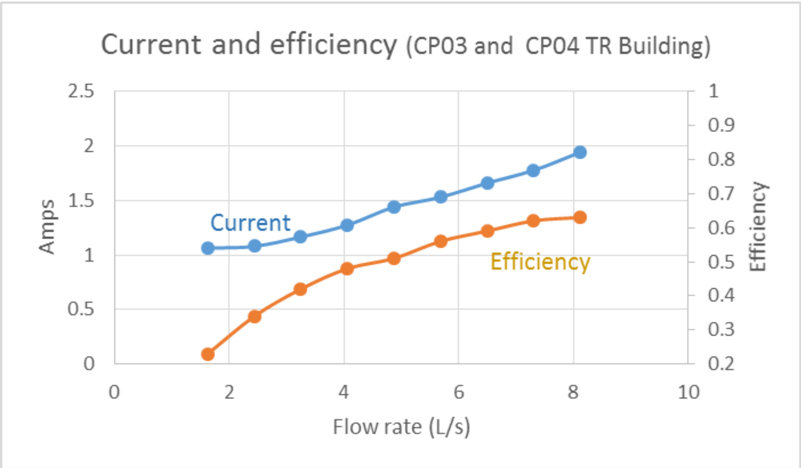

Figure 5.4. The relationship between current and efficiency chilled water pumps at Tom Reilly (CP03 and CP04)

5.3.2.2 Pump Speed Control: Constant Pressure

The circulating pumps at the Tom Reilly Building all have variable speed motors. This not only facilitates the commissioning process, but also enables the pump speed to be controlled in response to load. The relationship between impeller speed and pump power means that the significant savings can be obtained by speed reduction ($Power \approx speed^3$). Speed control is applied to the circulating pumps at the Tom Reilly Building.

Control of heating and cooling equipment in the Tom Reilly Building is achieved by means of two port control valves. As load decreases, the control response causes the valves to close and this increases system pressure, which initiates a change in pump speed. A constant pressure speed control system has been designed and installed at the Tom Reilly Building. This method of control matches flow rate to demand by re-positioning the pump operating point, which is the point at which the pump characteristic meets the system characteristic. By controlling pump speed so that the pump maintains a constant pressure at some fixed point within the circuit (system). This has the effect of shifting the system characteristic so the pump characteristic intersects it at the required speed.

Levermore (2000) explains the energy advantage of specifying two port modulating valves instead of the traditional three port control valves. Three port control valves maintain a constant flow in the circuit, whereas two port valves regulate the flow of hot (chilled) water according to the load. Therefore they allow the pump speed to be slowed at lower loads. Formulae (5.3) demonstrate how pumping power is related to volume flow and systems pressure drop.

$$Power\ to\ transmit\ fluid\ (Watts) = Volume\ flow\ (m^3/s) * Pressure\ drop\ (N/m^2)$$

$$Pumping\ power = \frac{Power\ to\ transmit\ fluid}{pump\ and\ motor\ efficiency} \qquad (5\text{-}3)$$

The pump speed can be controlled from a pressure sensor located at the pump (most manufacturers include this facility as part of the pump equipment). Alternatively, a constant pressure sensor can be located at a remote location on the pump index run. Guidance indicates that a remote sensor located two thirds along the index run provides a valid representation of pressure conditions. In practical installations, remote sensors should be determined as part of both design and commissioning processes.

The maintenance documentation states that constant pressure pump speed control for the circulating pumps at the Tom Reilly Building responds to remote sensors. The documentation describes the location of these sensors as being “two thirds along the index run”. However, from a site survey it has been found that constant pressure speed sensors for circulating pumps at the Tom Reilly Building are actually located at the pumps. This has implications for pump energy use. Given that pumping power is equal to the product of flow rate and system pressure drop, maintaining a constant pressure remotely from the pump will mean that at lower flow rates, the pump pressure will be reduced.

5.3.2.3 Constant pressure speed control (pumps CP03 and CP04) (sensor at pump)

Figure 5.5 illustrates the differential pump pressures for the circuit which forms the index run for pumps CP03 and CP04. The pump pressure is equal to the total resistance of the index run which is 94 kPa and is the pressure which is maintained by the pump speed control system installed at Tom Reilly. Figure 5.6 illustrates how the index run system characteristics vary with a speed control system which maintains a constant pressure of 94 kPa at the pump. As load reduces the pump speed reduces to provide an appropriate flow rate. Since the pressure remains constant, water power is equal to the product of the fluid flow rate and the constant pump pressure. Though this offers energy savings the overall pump efficiency will vary (Chemical Engineering, 2015).

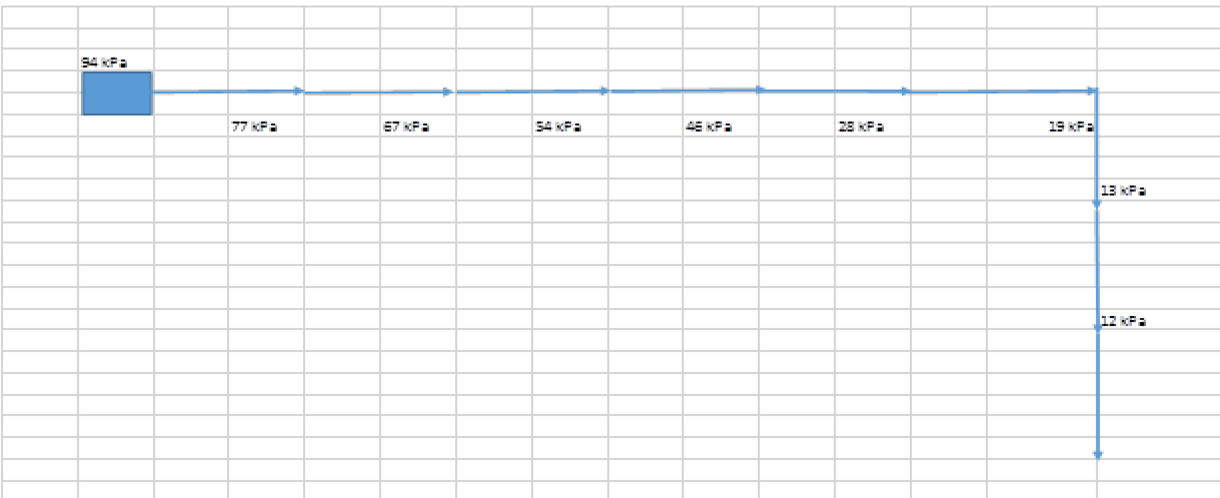

Figure 5.5 Differential pump pressures for index run served by pumps CP03 and CP04 (Tom Reilly Building)

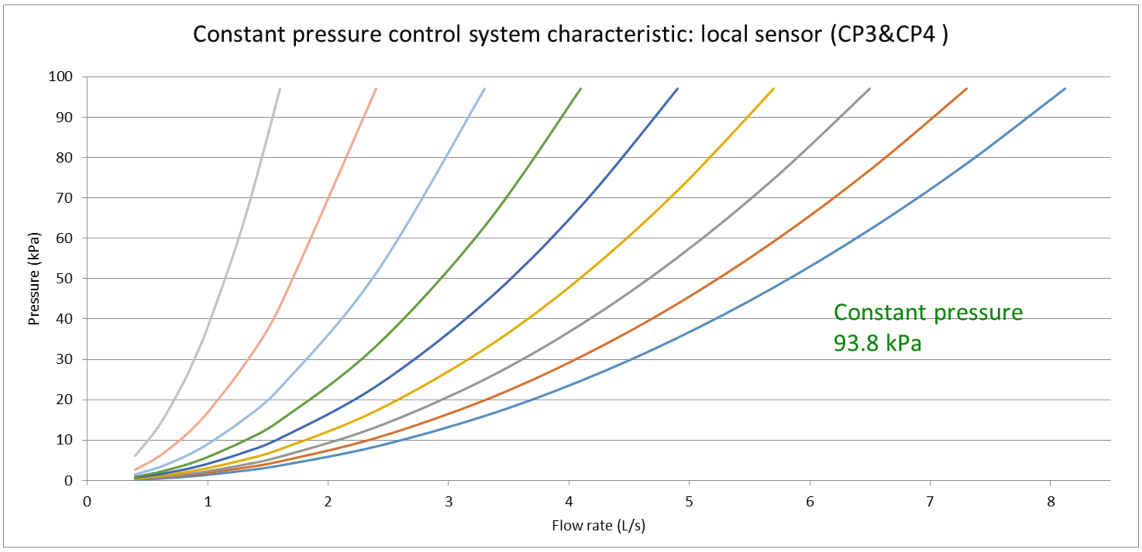

Figure 5.6 Index run system characteristics for constant pressure speed control with pressure sensed at pump location (CP03 and CP04 Tom Reilly Building)

5.3.2.4 Energy Savings from speed reduction for pumps CP03 and CP04 (pressure sensor at pump)

The maintenance documentation for the Tom Reilly Building states that pump speed control should regulate fluid flow rate to 25% of full load (8.12 L/s).

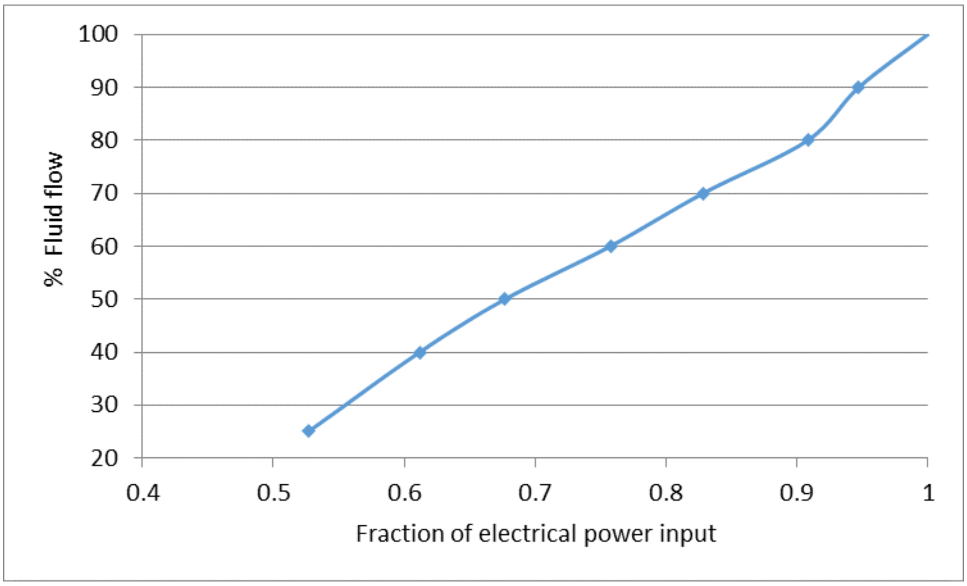

Figure 5.7 Relationship between electrical power input and fluid flow at constant pressure control with sensor located at pump: pressure sensor at pump (Tom Reilly Building).

Figure 5.7 illustrates how electrical power required to drive pumps (CP03 and CP04) reduces as fluid delivered reduces. The cause of this power reduction is related to the changing pressure drop in the pump circuit pipe work. Figure 5.8 graphically illustrates the how pump pressure reduces along the circuit length. From this diagram it can be seen that as fluid flow reduces the rate of pressure drop within the pipe system also reduces. Consequently, although the pump pressure remains constant, branch pressures increase at flows which are less than full load.

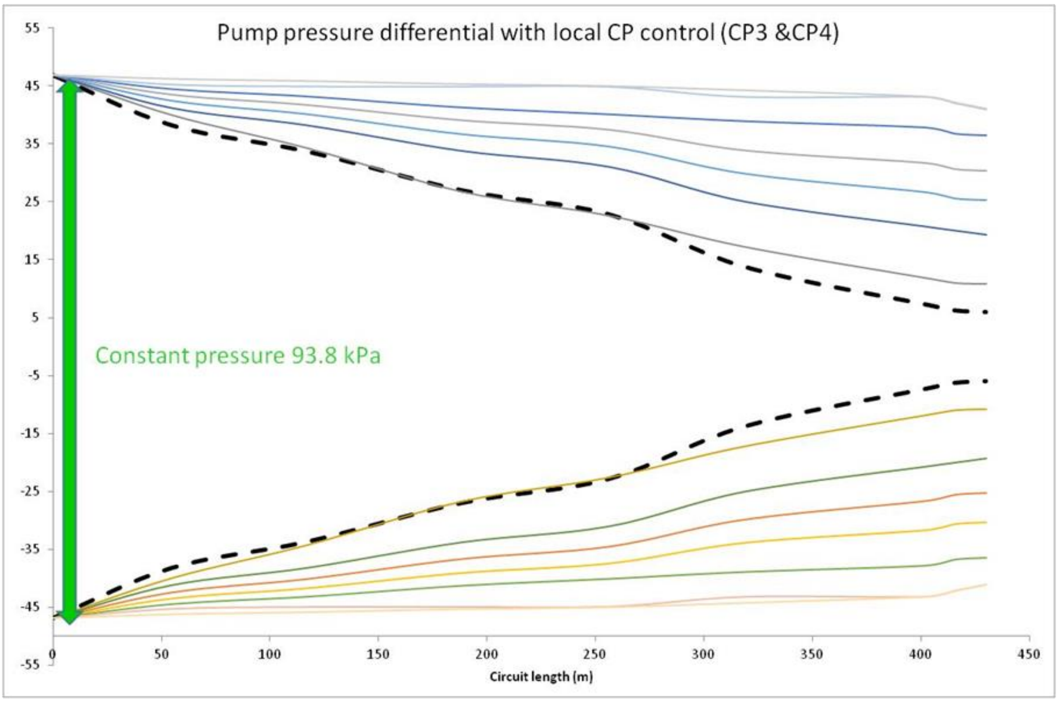

Figure 5.8 Pump pressure distribution along index circuit for constant pressure control with sensor at pump (CP03 and CP04 at Tom Reilly Building).

Table 5.9 demonstrates the electrical input power to the pumps at varying flow rates under constant pressure speed control. The energy benefit that should be available reduces because changing flow rates negatively affects pump overall efficiencies.

Table 5.9 Electrical input power to pumps CP03 and CP04 at constant pressure and reduced flow rates with sensor located at pump.

Flow rate (m^3/s)	% of full load	Pump Pressure (Pa)	Pump & motor efficiency	Electrical input power (Watts)
0.00812	100	93800	0.59	1290.942
0.0073	90	93800	0.56	1222.75
0.0065	80	93800	0.52	1172.5
0.0057	70	93800	0.5	1069.32
0.0049	60	93800	0.47	977.9149
0.0041	50	93800	0.44	874.0455
0.0032	40	93800	0.38	789.8947
0.00203	25	93800	0.28	680.05

5.3.2.5 Pump affinity laws

Pump manufacturer's information tends to apply the pump affinity laws to varying flow rates. For example, Figure 5.9 demonstrates the changing characteristic that would occur if the pump speed control law is applied to the heating pump at Peter Jost (design 3.4 L/s at 58 kPa). It is noted that the change in pump speed affects both flow rate and pressure. This would not be the case under a constant pressure speed control arrangement. Since the net pump power is the product of volume flow rate and pressure drop, the relationship between power and flow rate for a constant pressure controlled speed controlled pump is linear (see Figure 5.7).

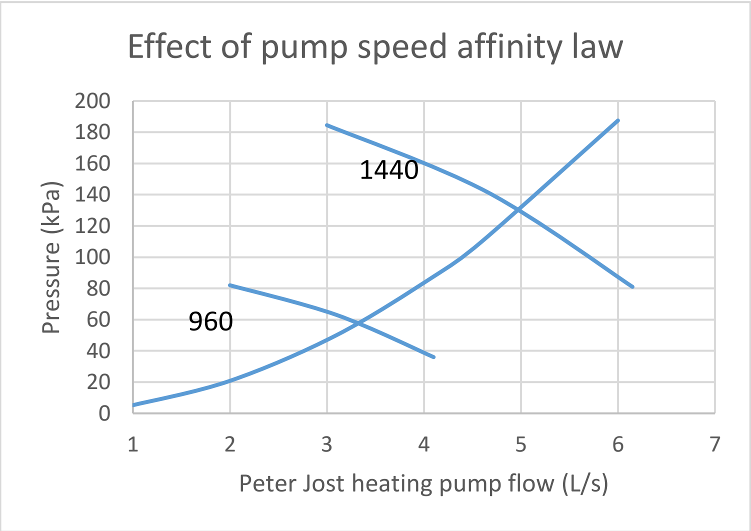

Figure 5.9 Peter Jost heating pump characteristic at varying speed.

Flow rates for the heating system at the Peter Jost Building were monitored via the LJMU building management system during January and February 2019 (1st Jan - 8th Feb).The monitoring intervals (set by BMS contractor) meant flow rates were recorded every 23 minutes during plant operation. The pumps serving this system are variable speed units responding to constant pressure control (Grundfoss Magna 40-100FN) and system design conditions are 3.4 L/s at 58 kPa. Although pressure control is located at pump, the pressure is not monitored by the BMS. Pumping power has been determined from from the product of flow rate and system pressure drop, factoring in pump/motor efficiency. The results are based on a system pressure drop of 58 kPa. Pressure control tolerances are not measured or included. Although flow rates vary between 0.2 L/s and 3.9 L/s (Figure 5.10) for the whole period, daily pump flow modulation tends to be small. Similarly, daily variations in pump and motor efficiencies are also small. Consequently if sampled flow rates are all operate at a constant pump pressure of 58 kPa, the resulting power characteristic will be linear.

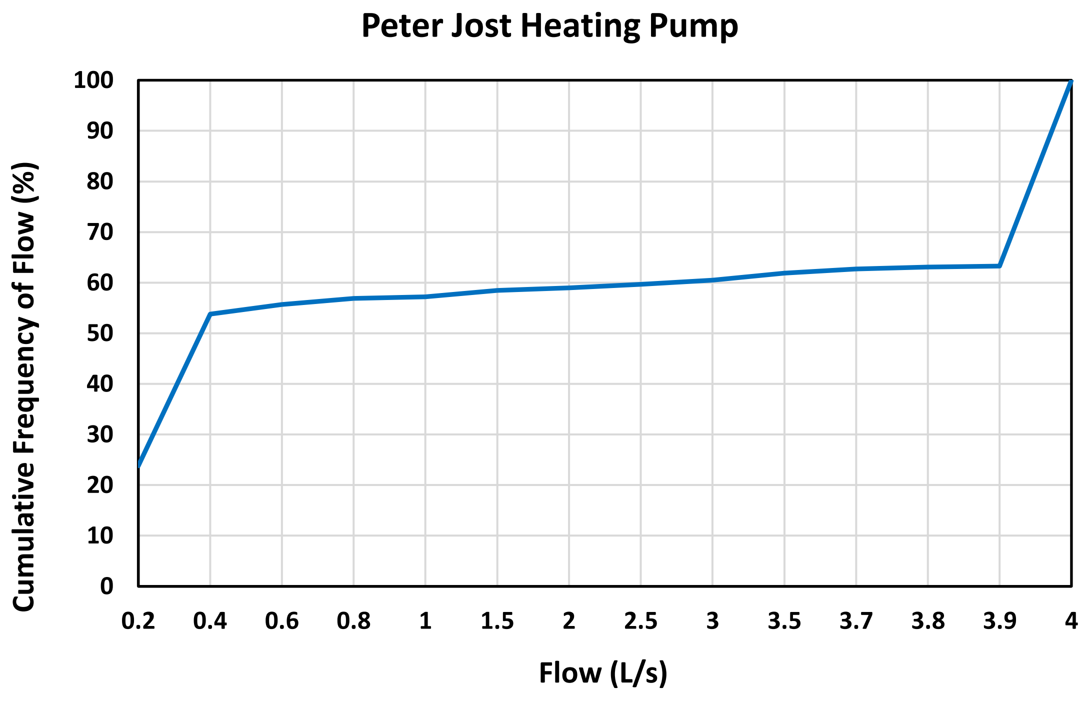

Figure 5.10 Peter Jost heating pump monitored flow rates (Jan 2018).

5.3.2.6 Constant pressure speed control (pumps CP03 and CP04) (remote sensor)

Figure 5.11 illustrates a comparison of power inputs to pumps (CP03 and CP04) responding to constant pressure sensors which are located at the pump or remotely along the pumped circuit index run. However, it can be seen from figure 5.9 that at low loads, the pressure available at branches is reduced.

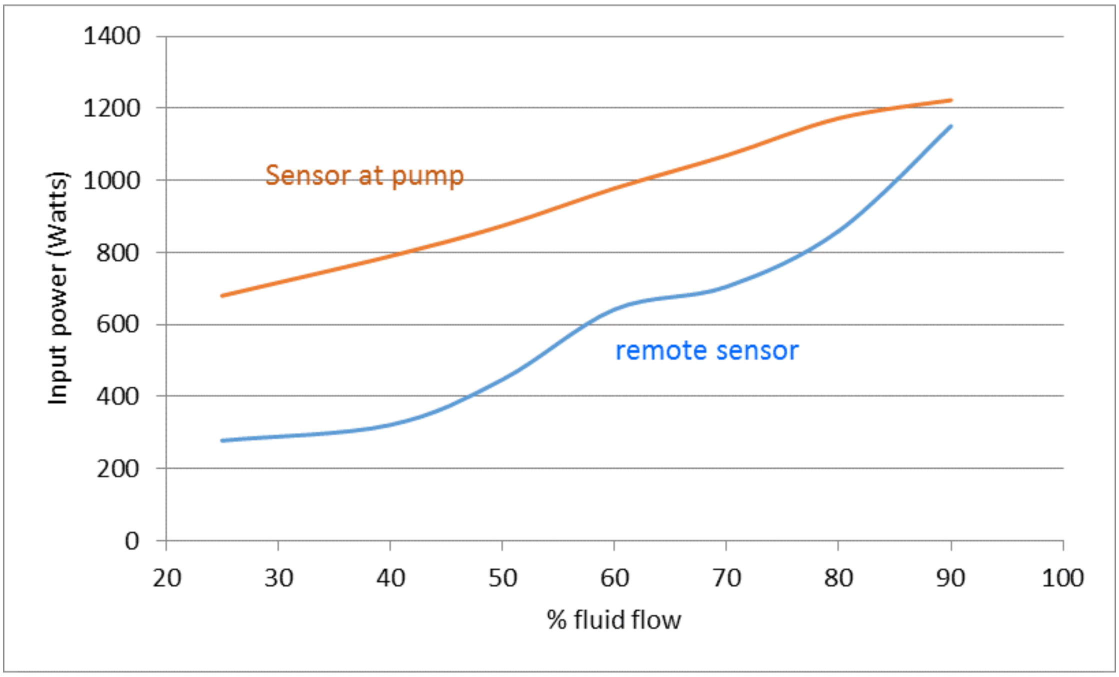

Figure 5.11 Power input to pump for constant pressure speed control for sensors at pump and remote sensors (CP03 and CP04).

Figure 5.12 illustrates the system characteristics for pump systems CP03 and CP04 where the pressure is sensed remotely at a point 256 m along the index run. The differential pressure at this point is 13.8 kPa (see Figure 5.13). By setting a control system to maintain a constant pressure at this point in the index circuit, it can be seen from the diagram that the pump pressure reduces as the fluid flow rate reduces. Therefore, this arrangement offers greater potential for energy reduction. Table 5.10 demonstrates that electrical power input requirements for remote sensor constant pressure speed control. Although reduced flowrates negatively affect pump overall efficiency, by maintaining constant pressure downstream, the pump pressure can reduce and this can improve energy performance.

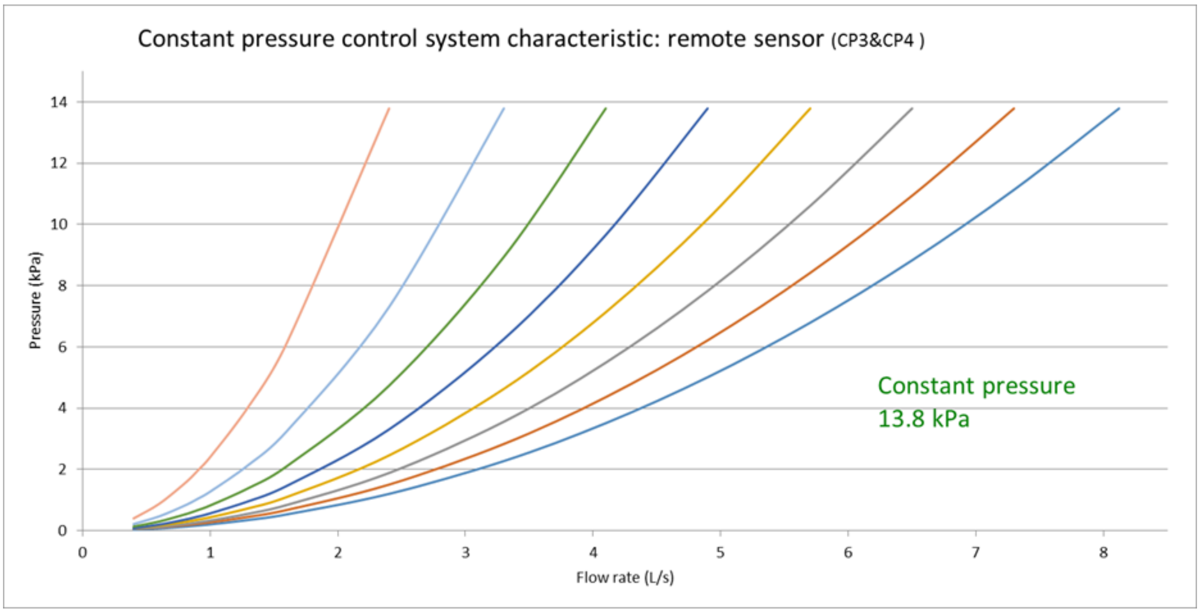

Figure 5.12 Index run system characteristics for constant pressure speed control with remote pressure sensing (CP03 and CP04 Tom Reilly Building).

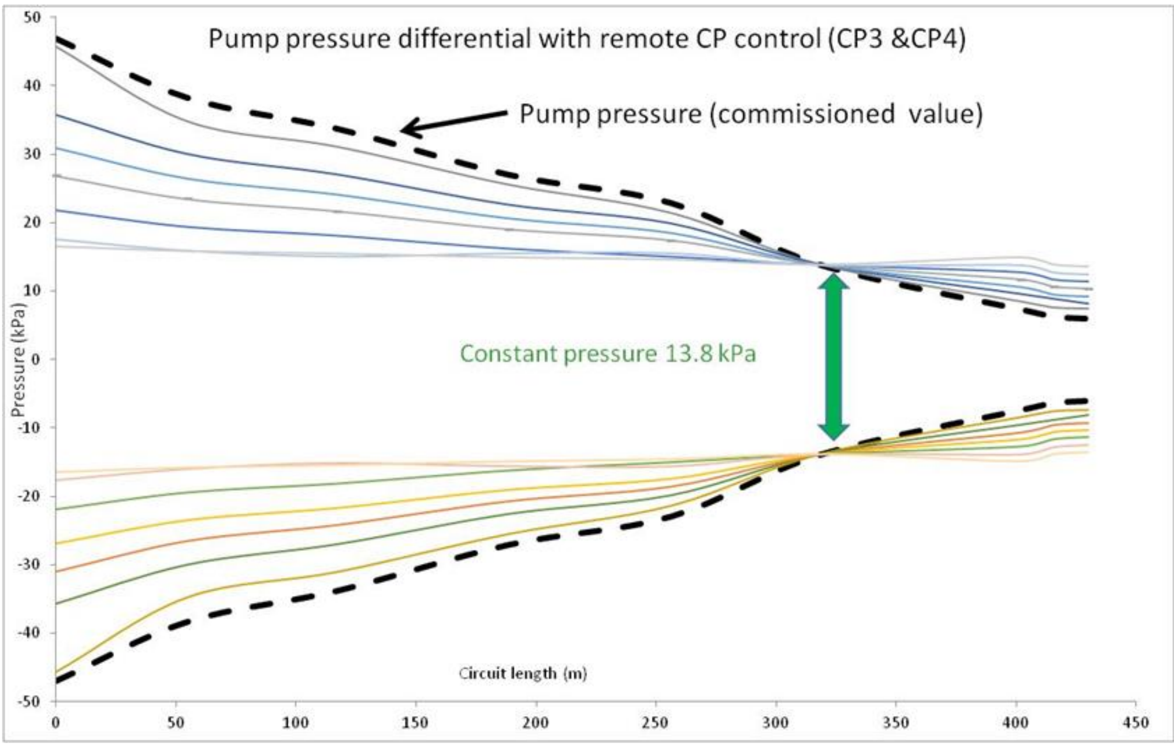

Figure 5.13 Pump pressure distribution along index circuit for constant pressure control with remote pressure sensing (CP03 and CP04 Tom Reilly Building).

Table 5.10 Electrical input power to pumps CP03 and CP04 at constant pressure and reduced flow rates with remote pressure sensor (Tom Reilly Building).

Flow rate (m^3/s)	% of full load	Pump Pressure (Pa)	Pump & motor efficiency	Electrical input power (Watts)
0.00812	100	93800	0.59	1290.942
0.0073	90	91424	0.58	1150.68
0.0065	80	71432	0.54	859.83
0.0057	70	61842	0.5	705.00
0.0049	60	57648	0.44	641.99
0.0041	50	43640	0.4	447.31
0.0032	40	35160	0.35	321.46
0.00203	25	32860	0.24	277.94

5.3.2.7 Speed control for pumps HP04 and HP05 with constant pressure sensed at pump

The schematic representation (Figure 5.14) of the index run served by pumps HP04 and HP05 illustrates the circuit which will create the required pump pressure. The pressure changes with flow rate/speed. Figure 5.15 illustrates the pumped system characteristic which results from pump speed control where the pressure sensor is located at the pump. Table 5.11 demonstrates the pump energy requirements at various fluid flows.

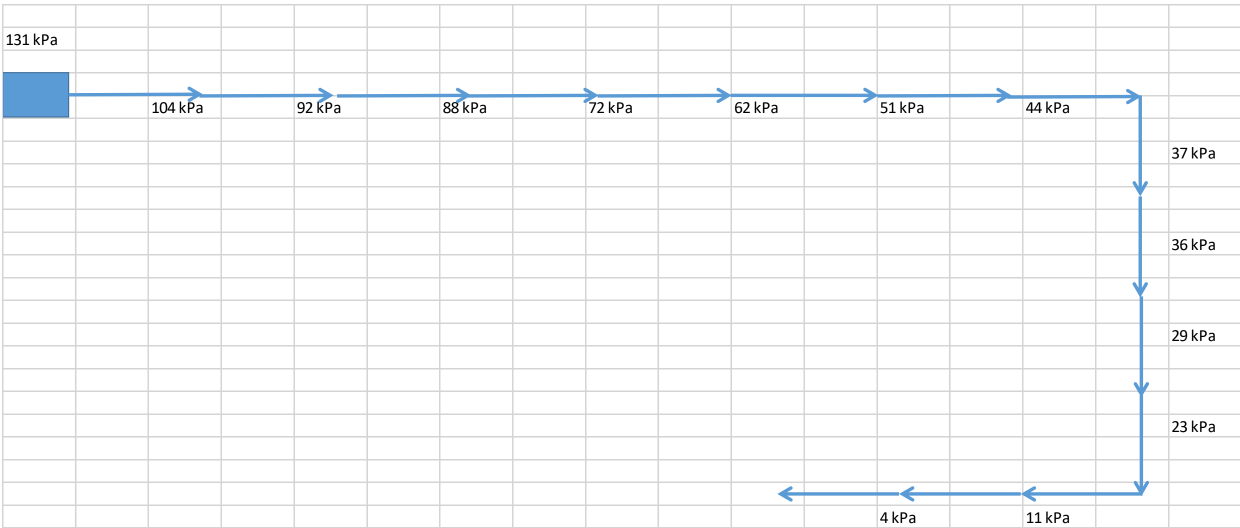

Figure 5.14 Index run served by pumps HP04 and HP05 (Tom Reilly Building).

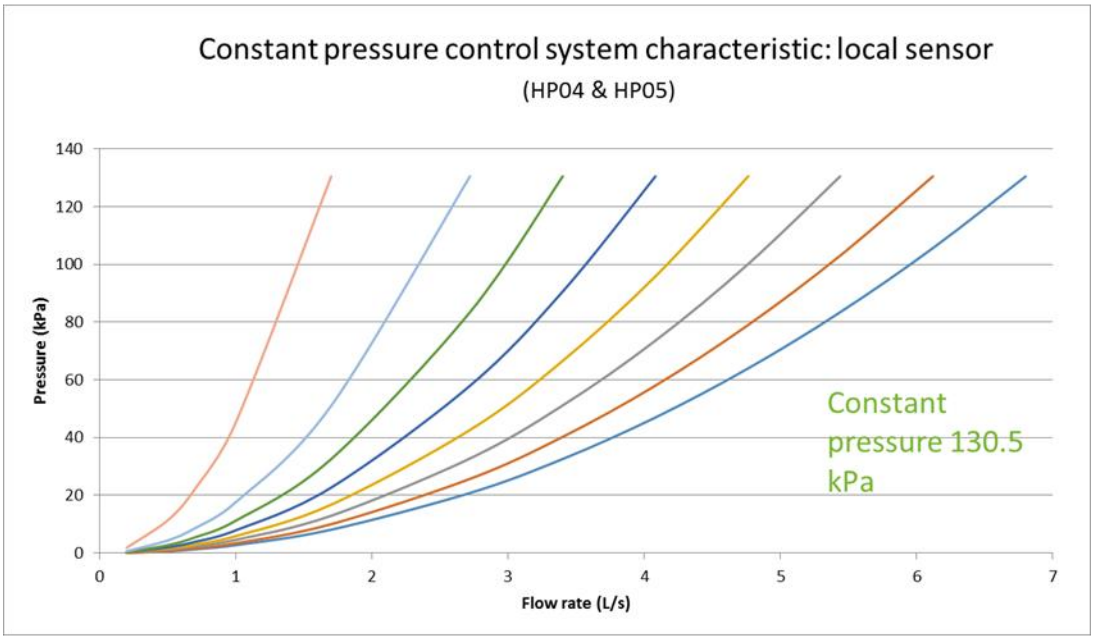

Figure 5.15 Index run system characteristics for constant pressure speed control with pressure sensed at pump location (HP04 and HP05 Tom Reilly Building).

Table 5.11 Electrical input power to pumps HP04 and HP05 at constant pressure and reduced flow rates with sensor located at pump.

Flow rate (m^3/s)	% of full load	Pump Pressure (Pa)	Pump & motor efficiency	Electrical input power (Watts)
0.0068	100	130500	0.58	1530.00
0.00612	90	130500	0.52	1535.88
0.00544	80	130500	0.48	1479.00
0.00476	70	130500	0.45	1380.40
0.00408	60	130500	0.40	1331.10
0.0034	50	130500	0.36	1232.50
0.00272	40	130500	0.32	1109.25
0.0017	25	130500	0.22	1008.41

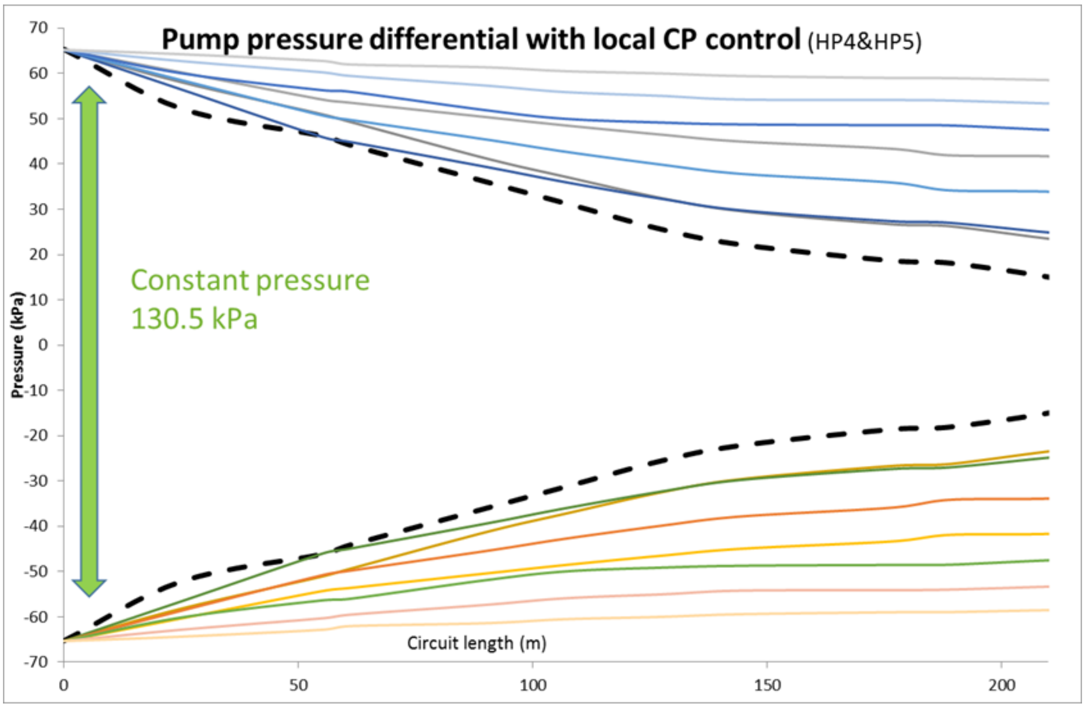

Figure 5.16 Pump pressure distribution along index circuit for constant pressure control with sensor at pump (HP04 andHP05) at Tom Reilly Building).

Figure 5.16 illustrates the pump differential pressure variations along the index run with constant pressure controlled at the pump (130.5 kPa). This diagram demonstrates how this control arrangement creates higher pressures at branch points. (it is noted that chilled water and heating pumps characteristics each have different design characteristics for pressure drop and flow rate).

5.3.2.8 Speed control for pumps HP04 and HP05 with constant pressure sensed remotely

Table 5.12 demonstrates the energy input required for pumps HP04 and HP05 at various fluid flows. Again the potential energy benefits are affected by reduced overall pump efficiencies. It is unlikely that the pump will always be at 100% load and, at design stage, it may be possible to determine the operating condition which would achieve the greatest efficiency for the majority of the time.

Table 5.12 Electrical input power to pumps HP04 and HP05 at constant pressure and reduced flow rates with sensor located at pump.

Flow rate (m^3/s)	% of full load	Pump Pressure (Pa)	Pump & motor efficiency	Electrical input power (Watts)
0.0068	100	130500	0.58	1530
0.00612	90	116000	0.52	1365.23
0.00544	80	112000	0.52	1171.69
0.00476	70	96000	0.5	913.92
0.00408	60	82000	0.48	697.00
0.0034	50	70600	0.44	545.55
0.00272	40	596000	0.42	385.98
0.0017	25	496000	0.37	227.89

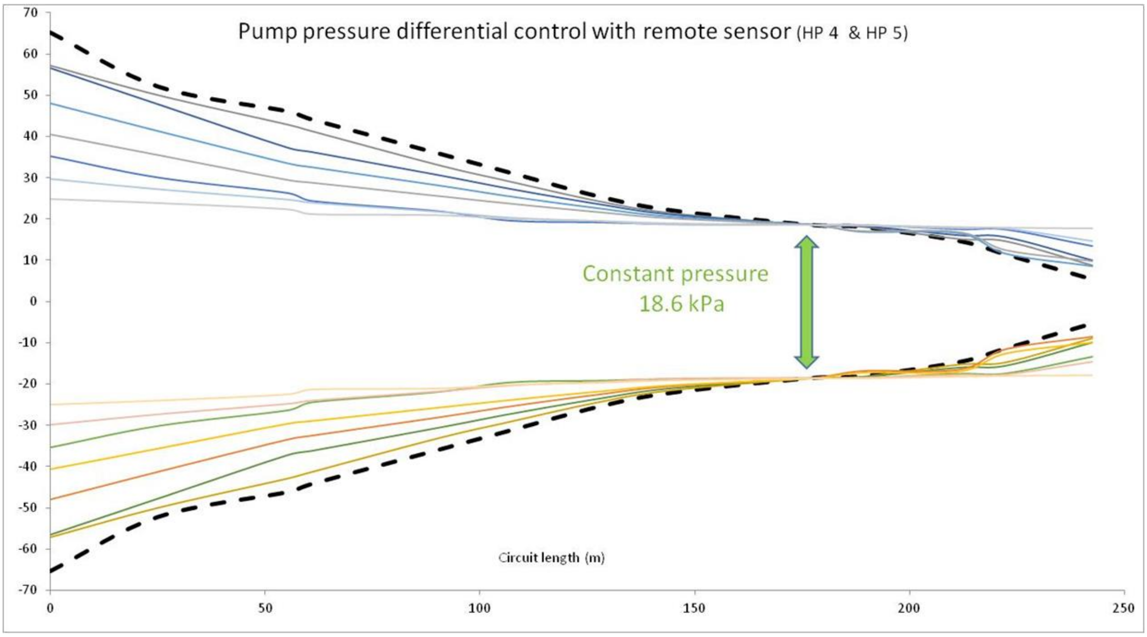

Figure 5.17 Pump pressure distribution along index circuit for constant pressure control with remote pressure sensing (HP04 andHP05 Tom Reilly Building).

Figure 5.17 demonstrates that at fluid flow which are less than design (100%) the rate of pressure drop in the pipe system reduces. Therefore, whilst a constant pressure is maintained at the remote sensor point, the pressure at branches is reduced. It is important that designers ensure that there is always sufficient pressure available at the branch to ensure that fluid will be delivered to all parts of the system. The varying pressure regimes could affect the system balance and it is necessary to install PICV (pressure independent) control valves at the branches to offset this problem.

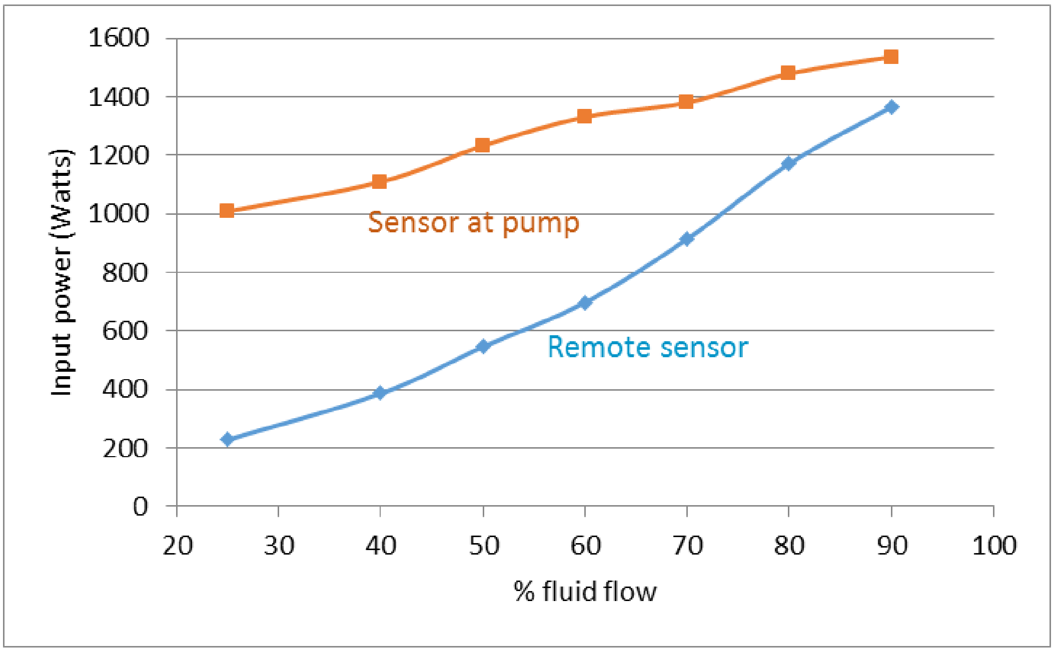

Figure 5.18 Power input to pump for constant pressure speed control for sensors at pump and remote sensors (HP04 and HP05).

Figure 5.18 indicates how the energy input requirements for pumps HP04 and HP05 are affected by the location of the constant pressure sensor. It graphically illustrates the power input benefit of constant pump speed control responding to a remote sensor compared to a sensor located at the pump. It can be seen that the curves converge as the fluid flow increases and power requirements will be equal at design (100%) flow. Where a constant flow pump system is specified there would no benefit in specifying speed control apart from facilitating the commissioning process.

Figure 5.19 compares the actual energy used by pumps (pumps CP03, CP04, HP04 and HP05) at the Tom Reilly Building with the potentially reduced energy that would be needed if the constant pressure control system had been installed in compliance with the project specification. This is based on a 12 hour plant schedule for a typical educational year.

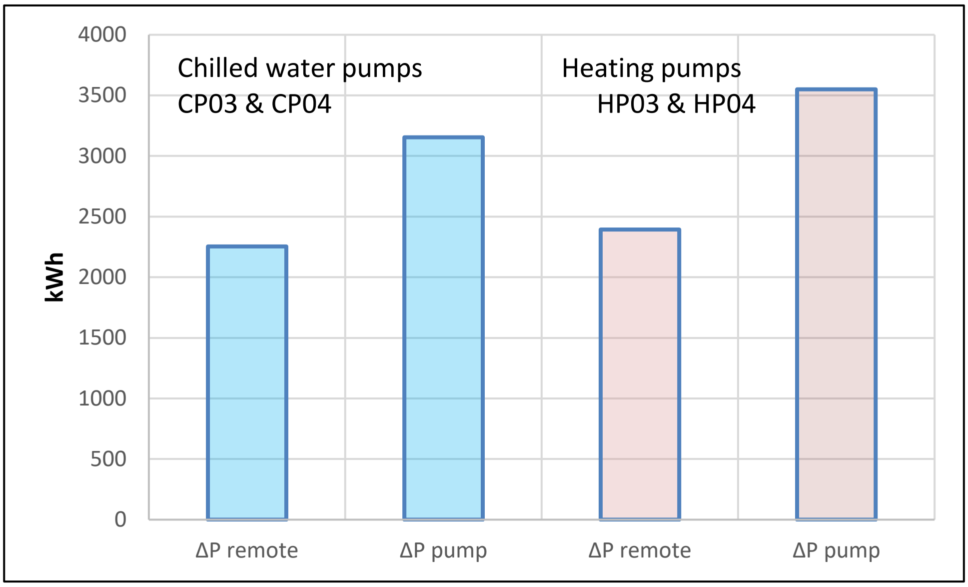

Figure 5.19 Annual energy input requirements (kWh) for pumps (CP03, CP04, HP04 and HP05, Tom Reilly Building).

The estimates for annual pump energy use have been determined from –

$$Monthly\ energy\ (kWh) = \frac{\dot{V} * WAF * \Delta P * operational\ hours}{pump/motor\ efficiency\ (\%) * 1000} \quad (5\text{-}4)$$

Where

$\dot{V} = volume\ flow\ (m^3/s)$

$WAF = weather\ control\ factor\ (Table\ 5.13)$

$\Delta P = system\ resistance\ (Pa)$

The volume flow rates, system pressure drops and motor/pump efficiencies applied in equation (5-4) have been developed from Tables 5.9, 5.10, 5.11, and 5.12.

The estimates indicate that the energy savings available from constant pressure control from a remote sensor are significant in comparison with pressure control at pump location (29% for chilled water pumps and 33% for heating pumps). Chilled water and heating pumps characteristics each have different design characteristics for pressure drop and flow rate.

Although the project specification called for pump speed CP sensors to be located remotely, the inspection of the installation revealed that the CP sensors were located at the pump. Investigation into why this installation did not comply with the specification revealed several causes.

- BMS contractor/installer did not understand the reasons for remote sensor location
- BMS contractor/installer based installation on previous experience of CP pump speed control
- Location of sensor was not inspected at project handover
- BMS controls considered overly complicated by facilities managers.
- Pumps operated satisfactorily other than at less than optimum efficiency.

5.3.3 Pump Energy Prediction at Early Design Stage

This process sets out a method of determining pump energy use from an estimate of length of the pump index run and space heating or cooling load. The level of estimation accuracy is obviously dependent on the firmness of available design data. However, it proposed that this system will produce estimates which are appropriate for inclusion in a TM54 exercise.

The volume flow rate of pumped fluid is related to the heating or cooling load in kW and the system temperature difference. Heating and cooling flow rates for temperature differences of 10, 20 and 6 degree C are listed in appendix CH5-2.

The rate of pressure drop selected should include an allowance for the additional resistance offered by fittings and equipment. Selecting an appropriate rate of pressure drop requires some engineering judgement. In order to determine a practical range of pressure drop values, the performance of pumps used the recently constructed case-study building were examined. Pump input power is related to the energy which is required to be delivered to the fluid and from this relationship it was possible to determine the pump motor power at design conditions from equation 5-5.

$$Power = \frac{\dot{V} * \Delta P}{pump\ and\ motor\ \eta} = \sqrt{3} * 400 * \ I_L * PF \qquad (5\text{-}5)$$

Where

$$\dot{V} = volume\ flow\ (m^3/s)$$

$$\Delta P = system\ resistance\ (Pa)$$

$$\eta = \ pump/motor\ efficiency\ (\%)$$

$$I_L = pump\ motor\ current\ (Amps)$$

$$PF = motor\ power\ factor$$

Pump motor current demand commissioned conditions was compared with manufacturer's information to determine which rate of system pressure drop co-ordinated with manufacturer's current flow data. The unknown in this case was the margin applied to system resistance by the designer. The curves in figures 5.20 and 5.21 demonstrate the range of system pressure drops at which the installed equipment current values intersect with manufacturer's current values. This indicates that a pressure drop rate of between 340 and 460 Pa/m would be appropriate.

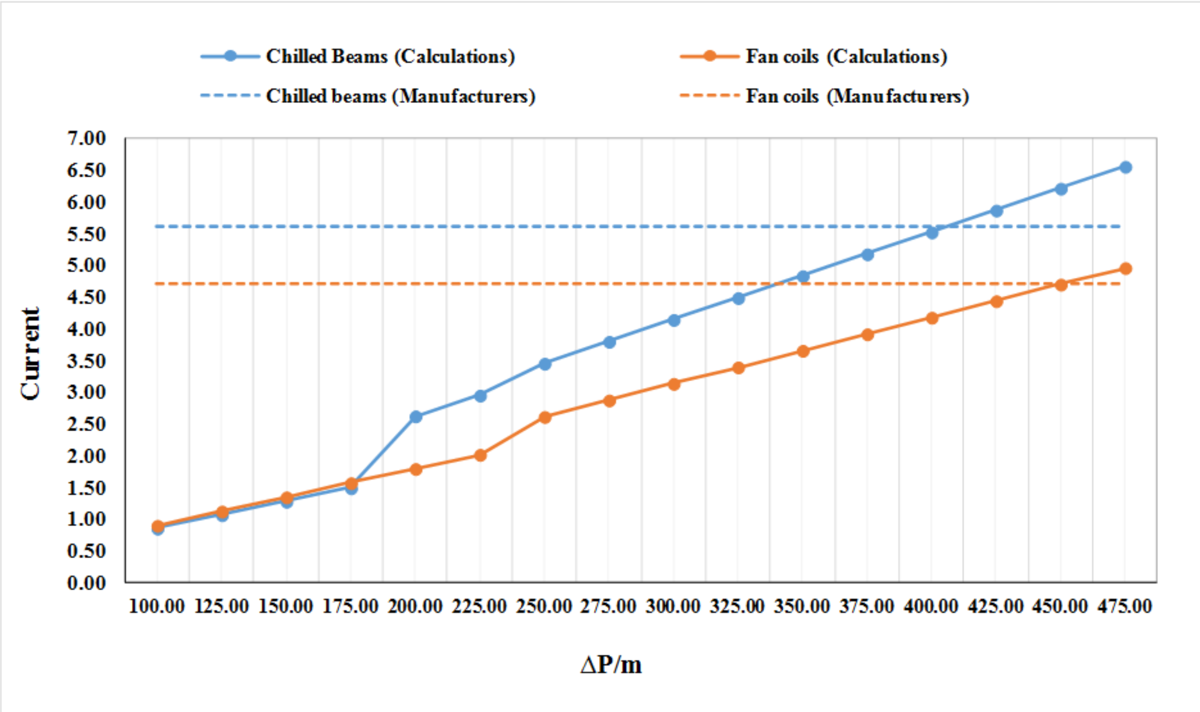

Figure 5.20 Comparison between Actual Pump Current and Manufacturers' data (Chilled Beam & Fan Coils)

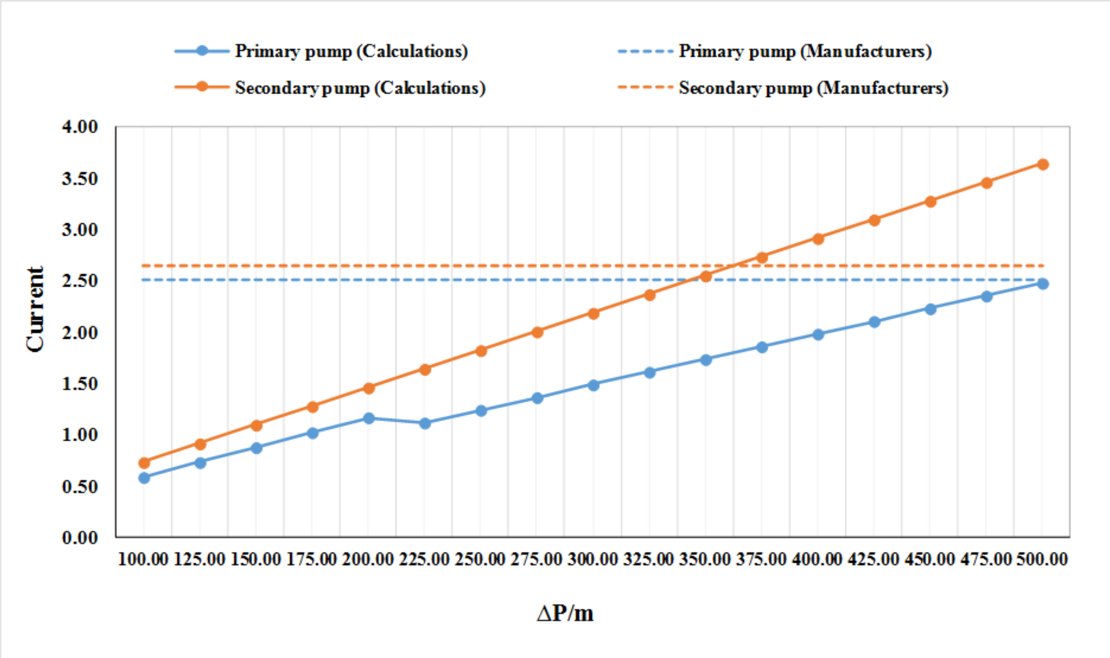

Figure 5.21 Comparison between Actual Pump Current and Manufacturers' data (Primary & Secondary Pump).

The rate of pressure drop for primary pumps is largely associated with boiler or chiller resistance since much of the pipework forms a low-loss header.

$$Pump\ Energy\ (kW) = \frac{volume\ flow\ (m^3/s) * index\ run\ (m) * rate\ of\ pressure\ drop\ (Pa/m)}{pump/motor\ efficiency}$$

(5-6)

The pump/motor efficiency value can vary depending on design and actual conditions. The purpose of pump speed control is to match fluid supply (heating or cooling energy) to the load imposed on the zone or space. Pump energy input may therefore be related to heating or cooling degree days (Table 5.13) Weather adjustment factors).

$$Annual\ pump\ energy = pumps\ energy\ (kW) * \ operational\ hours * adjustment$$

(5-7)

Table 5.13 Weather Adjustment Factors for Pump Speed Control

	Cooling pump adjustment	Heating pump adjustment
January	0.36	1.00
February	0.33	0.91
March	0.45	0.83
April	0.54	0.65
May	0.77	0.35
June	0.91	0.13
July	1.00	0.07
August	1.00	0.07
September	0.85	0.18
October	0.72	0.40
November	0.50	0.71
December	0.48	0.79
	Factor based on averaged cooling degree day values from Jan 2014 – Oct 2017 (base temperature 0^{0}C)	Factor based on averaged heating degree day values from Jan 2014 – Oct 2017 (base temperature 15.5^{0}C)
Note: This is based on pumps running for all operational hours.		

Variable speed circulating pumps should be controlled so that volume flow and consequent pump speeds modulate in response to the heating or cooling load. For many building applications, there is a relationship between outside temperature and heating or cooling demand. It is noted, that in some cases this may be a less direct relationship for cooling applications, however prevailing outside climate conditions will almost always be part of the design process for air conditioning and cooling systems. Therefore, for preliminary approximate heating and cooling pump energy estimates, heating and cooling degree days represent the magnitude of the heating or cooling load which is related to outside temperature conditions. The degree day factors (table 5.13) have been determined from averaged heating and cooling degree day figure from 2014 to 2017 for Liverpool (Bizee Software Ltd. 2017). The maximum applicable degree day factor for heating or cooling indicates design load (100%) and further factors indicate proportionate plant loads.

5.4 Building Service System: Boilers and Chillers

Four of the case study buildings have boiler plant. The engineering workshops derive heat from a central plant. All of the case study building have air conditioning cooling plant. As part of the energy appraisal for the case study buildings the heating and cooling loads used to determine boilers and chillers sizes were assessed. Unlike annual energy estimates, plant duties are quoted in terms of kW instead of kWh. This instantaneous value is determined using dynamic simulation modelling. A comparison of boiler and chiller ratings with existing plant adds a further perspective on the accuracy of energy estimation. The DSM has also been used to determine operational periods at different plant loads.

Optimum sizing of plant contributes to its efficient operation. Boilers and chillers must cope with a range of loads. The powerful mathematics within DSM's enables designers to evaluate plant performance against all of these loads. The possibility of plant failing to meet the load is seen by designers as a risk. In many design situations engineers may offset this risk by over-riding DSM outputs and applying rules of thumb methods. This can this can contribute to over-sizing.

5.4.1 Peter Jost Building

The installed boiler plant at Peter Jost is rated at 600 kW. The rating determined by dynamic simulation is shown in figure and is 550 kW (Figure 5.22). The characteristic of plant operation (Figure 5.23) indicates that full load output only occurs briefly. Therefore, designer's plant selection is practical. The Peter Jost boiler plant is modular and can operate in steps of 50kW and therefore has been designed to cope with all loads.

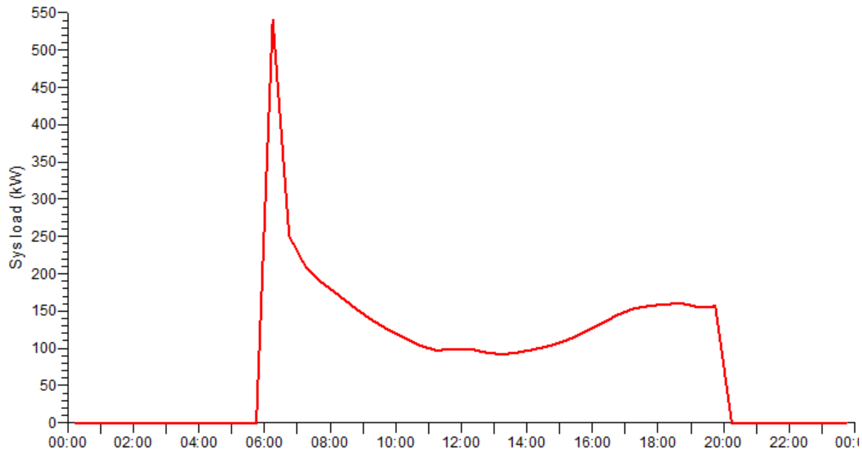

Figure 5.22 Boiler Heating Load (Peter Jost Building)

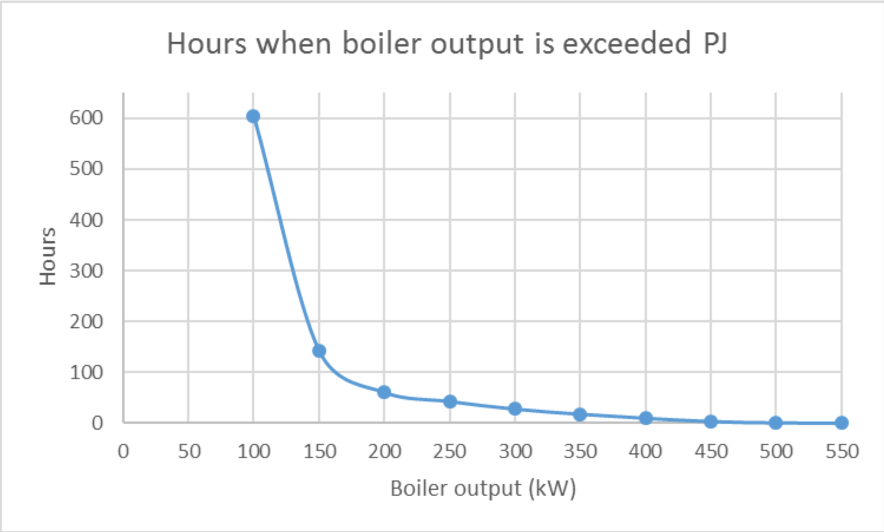

Figure 5.23 Boiler Output Demand Distributions (Hours; Peter Jost Building)

The DSM calculated chiller plant size is 130 kW (Figure 5.24). The installed plant is rated at 65kW. The operational characteristic indicates that 65kW of cooling capacity will not meet the cooling load for approximately 50 hours/year (Figure 5.25). Air conditioning at Peter Jost only serves the two lecture theatres. The rest of the building is naturally ventilated.

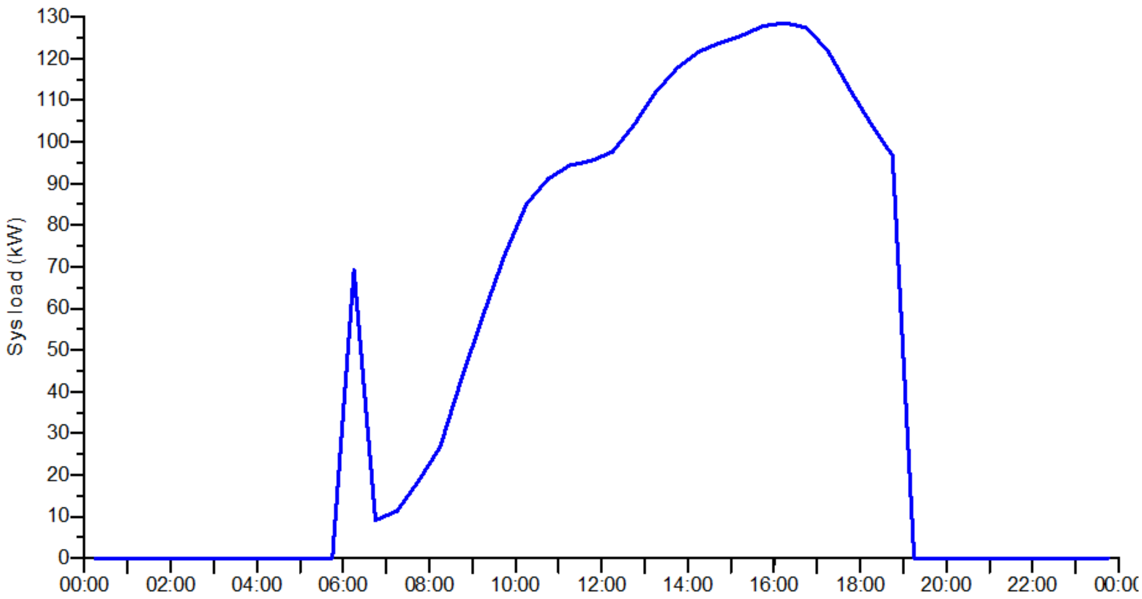

Figure 5.24 Chiller Cooling Load (Peter Jost Building)

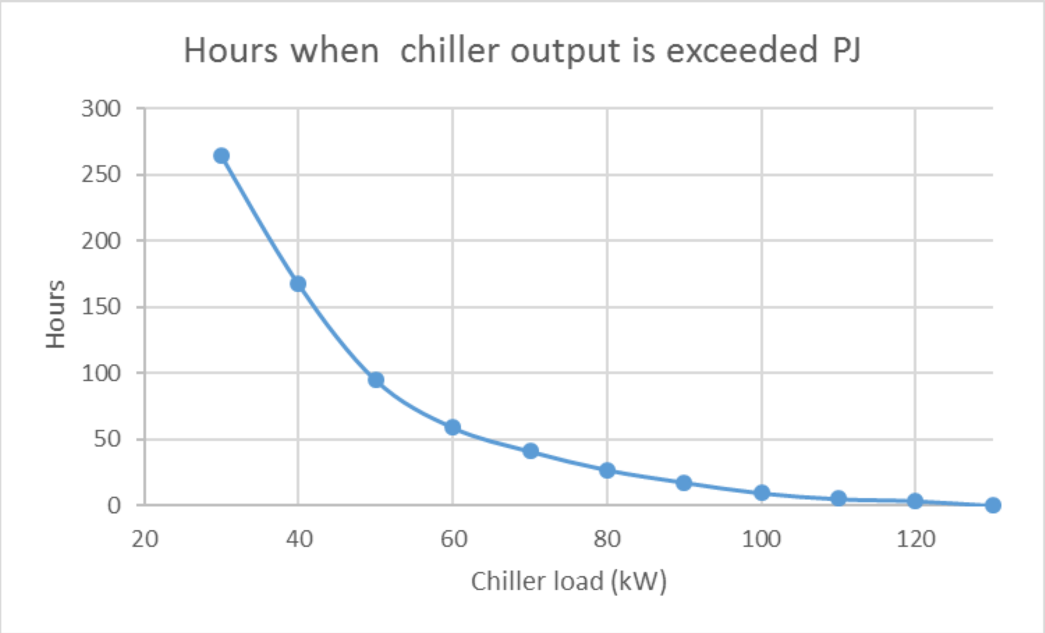

Fig 5.25 Chiller Output Demand Distributions (Hours; Peter Jost Building)

In comparison with DSM ratings, both the boiler and chiller plant are smaller (shown in Fig 5.22 & 5.24). In fact the cooling plant is only 50% of the DSM value. The boiler plant is rated at 91% of the DSM value. Conversely, occupant complaints have tended to refer to heating rather than cooling. This may be because the building is only partially cooled. It may also indicate poor commissioning of building services at handover. (Note: The under-rated chiller at Peter Jost resulted from poorly-planned and ad-hoc building modifications. This has now been replaced by a chiller plant rated at 140 kW. A short comfort survey was carried out amongst student occupants – results appendix CH5-3)

5.4.2 Tom Reilly Building

The boiler load determined by DSM is 1162 kW (Figure 5.26). The actual boiler plant is composed of two Remeha gas-fired low pressure hot water boilers each rated at a a maximum output of 654 kW. The project record document specifies that each boiler is rated at 66% of total duty. Although the boilers have been sized prudently, it is not clear why designers have specified each boiler to be rated to meet two thirds.

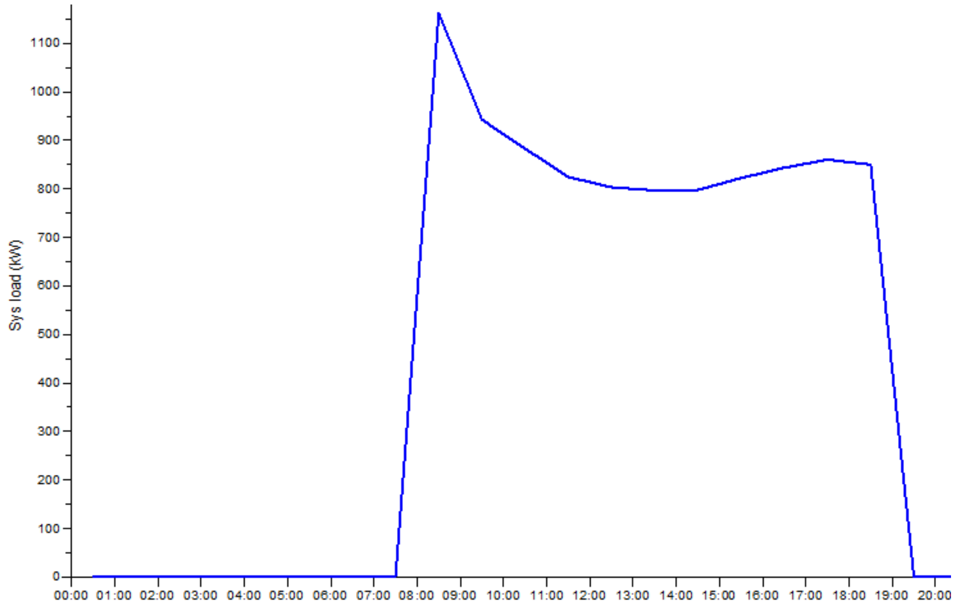

Figure 5.26 Boiler Heating Load (Tom Reilly Building)

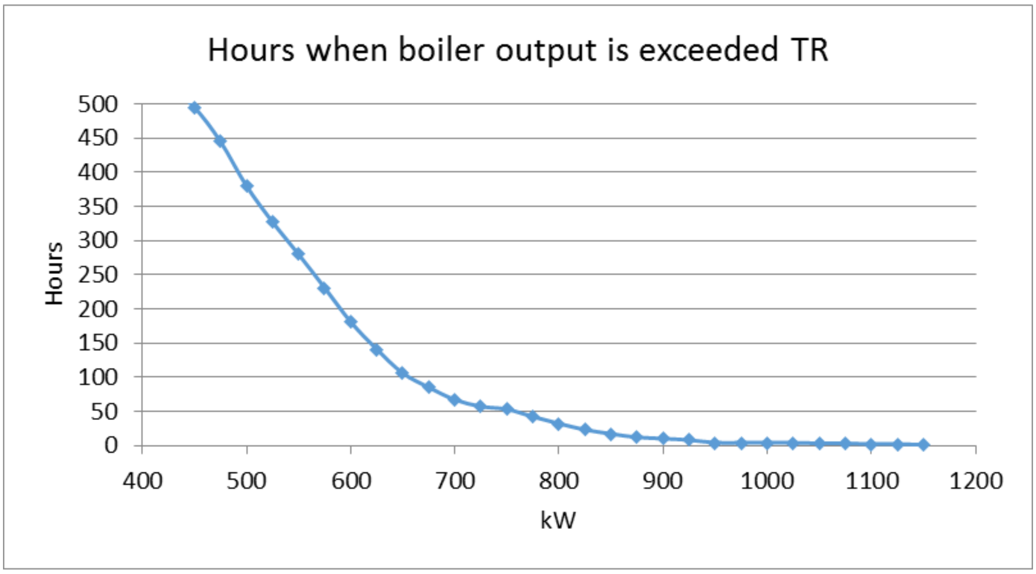

Figure 5.27 Boiler Output Demand Distributions (Hours; Tom Reilly Building)

From the boiler operational characteristic (Figure 5.27) full load from boiler plant will rarely be required. Both boilers will be required to operate simultaneously for only approximately 100 hours per year.

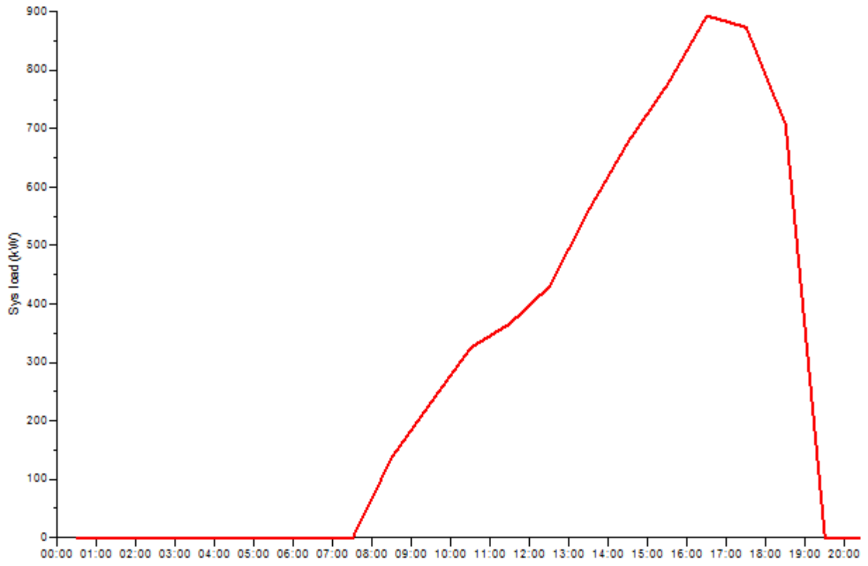

Fig 5.28 Chiller Cooling Load Tom Reilly Building

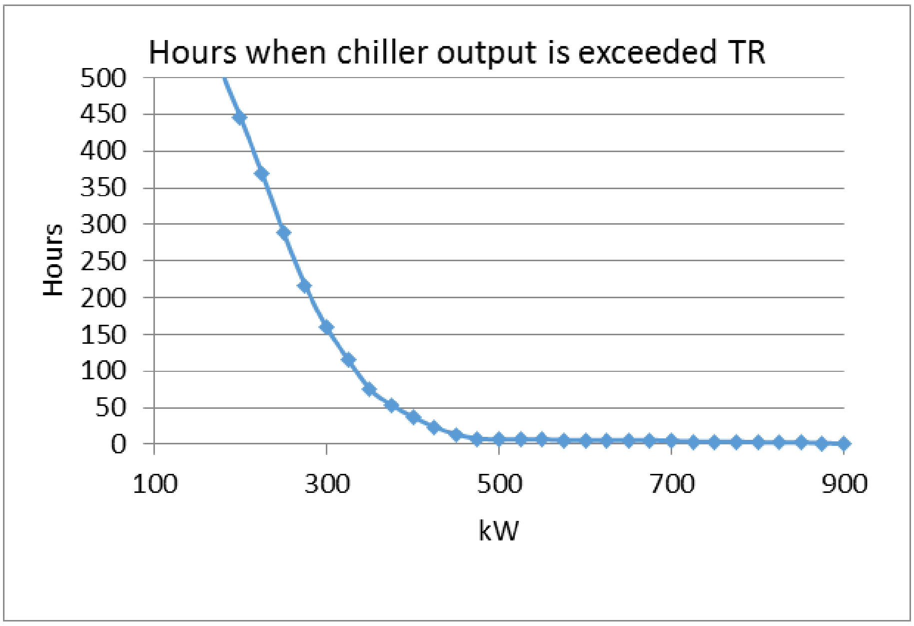

Fig 5.29 Chiller Output Demand Distributions (Hours: Tom Reilly Building)

The rating of chiller plant determined by DMS is 890 kW (Figure 5.28). The specification states that actual chiller total cooling output is 582 kW. The output is shared between two chillers each rated at 291 kW. By meeting the load with two equally sized chillers the designers have provided a system which can cope with some diversity. DSM simulation indicates that a chiller output of 582 kW would be sufficient to meet the cooling for all but five hours during the building operational period (5.29). The application of the DSM in this case proposes over-sized plant. As a percentage of DSM values boiler plant is 88% and chiller plant is 65%. There are no recorded significant occupant complaints about internal temperature.

5.4.3. Cherie Booth Building

The DSM determined that maximum boiler output was 140 kW (Figure 5.30). The actual plant installed comprises two boilers each rated at 89kW. Each of these boilers can deliver 64% of the load and therefore boiler plant is effectively over-sized.

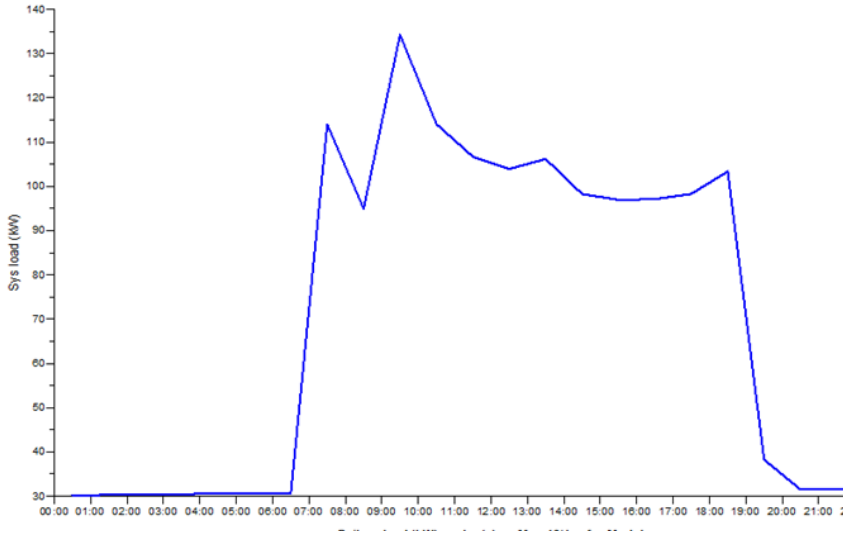

Fig 5.30 Boiler Heating Load (Cherie Booth Building)

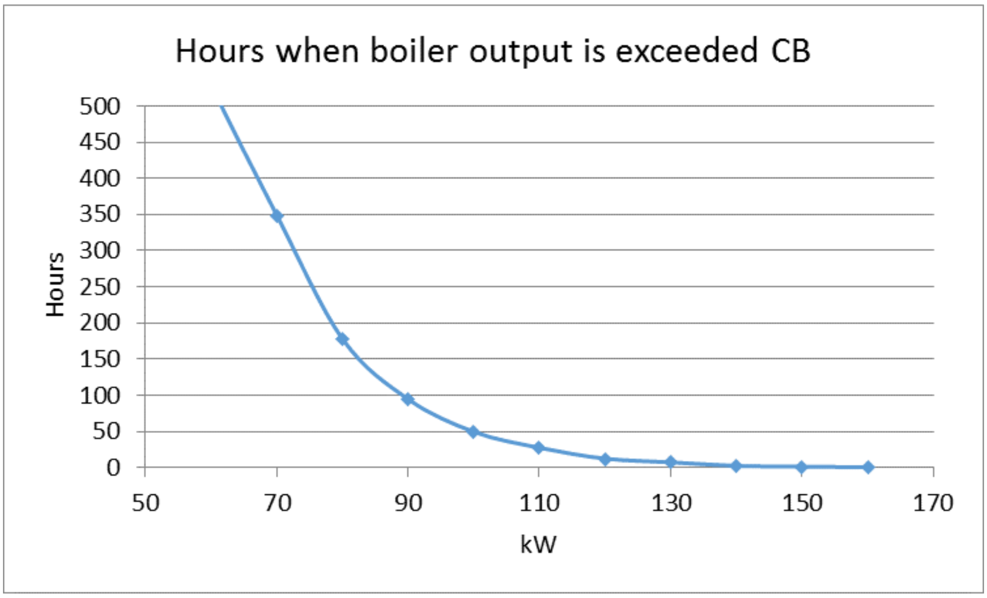

Fig 5.31 Boiler Output Demand Distributions (Hours: Cherie Booth Building)

Each boiler, at Cherie Booth is rated at two thirds of the heating load. This appears to indicate that a rule of thumb method has been applied to the calculated rating. It can be seen from DSM analysis (Figure 5.31) that 140kW of boiler heat output should be capable of meeting all building heat loads and one boiler should be capable of meeting all heating demands except for 100 hours of the heating season. The cooling plant is undersized compared to the DSM value. Whilst there are no occupant complaints about air conditioned areas, some deliberately non-cooled areas can overheat.

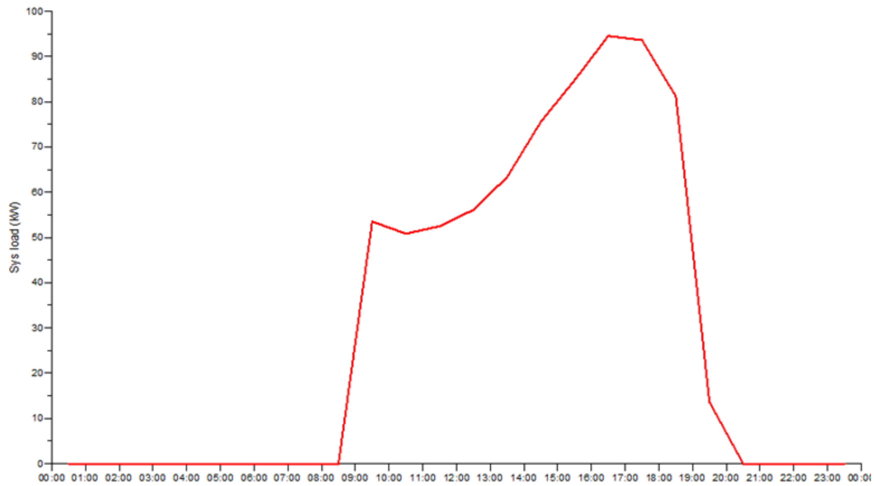

Figure 5.32 Chiller Cooling Load (Cherie Booth Building)

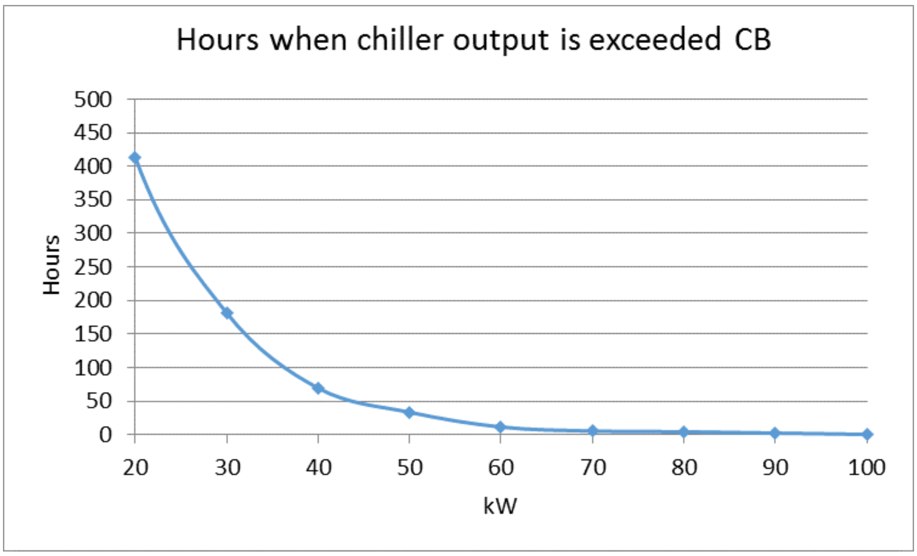

Fig 5.33 Chiller Output Demand Distributions (Hours: Cherie Booth Building)

The total cooling load determined by the DSM is 95 kW (5.32). The actual total cooling capacity for both the lecture theatre and the IT suite is 66 kW. From the DSM simulation chiller equipment with an output of 95 kW would meet cooling loads at all times. The actual cooling capacity installed would meet all cooling loads but for 6 hours (Figure 5.33). A significant fraction of the cooling load is generated by occupants, lighting and machinery. The concept of a cooling season is less appropriate since the theoretical cooling load is less dependent on weather. Plant sizing for smaller applications can be prone to over-size because of the ranges of commercial systems available

5.4.4 Henry Cotton Building

The DSM output of 805 kW (Figure 5.34) compares favourably with the existing plant size (800 kW). DSM load characteristic (Figure 5.35) indicates that the maximum boiler output is only required for worst case scenarios. The boiler plant in the Henry Cotton Building is modular and each module is rated at 100 kW. This should enable heating plant to operate at optimum efficiency.

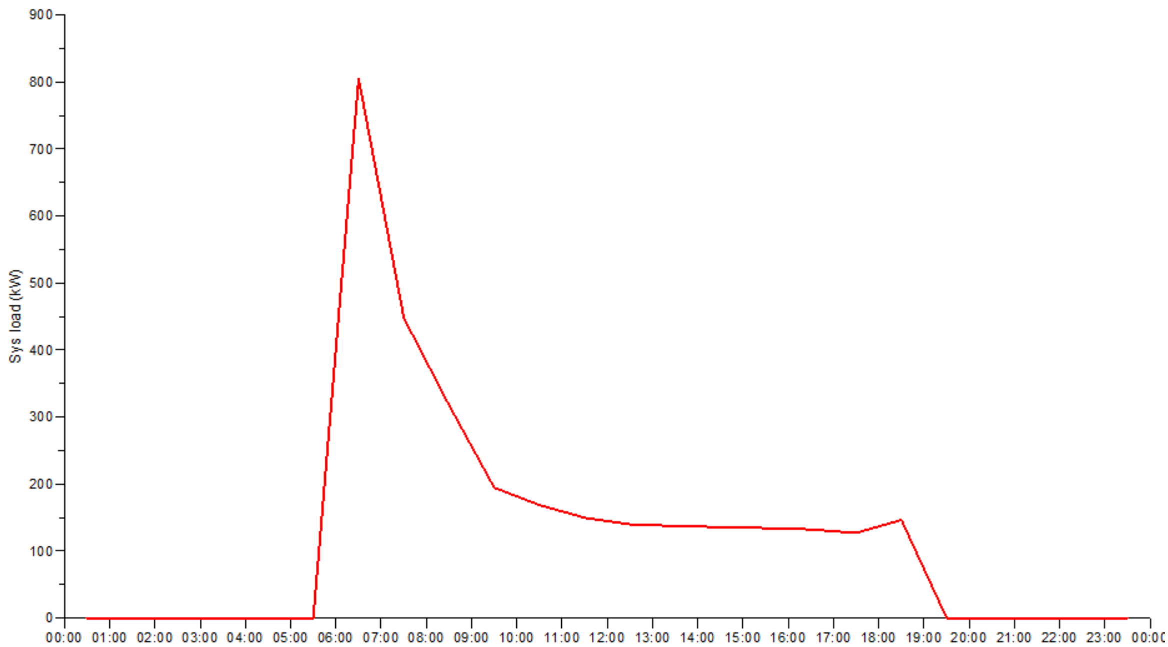

Fig 5.34 Boiler Heating Load (Henry Cotton Building)

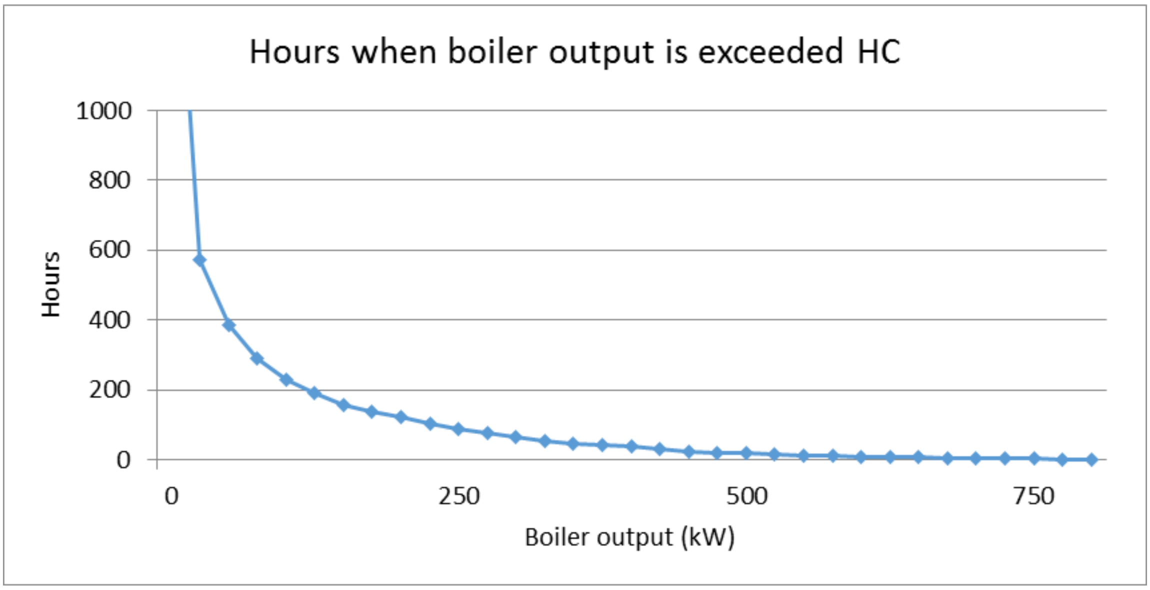

Fig 5.35 Boiler Output Demand Distributions (Hours: Henry Cotton Building)

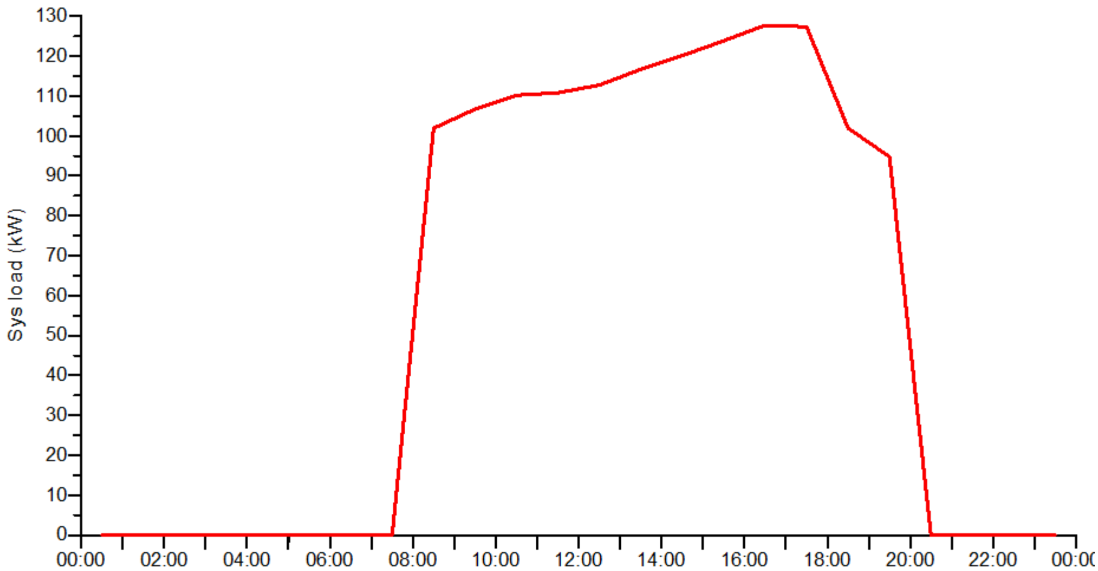

Fig 5.36 Chiller Cooling Load (Henry Cotton Building)

The DSM output indicates a cooling load of 130 KW (Figure 5.36). The chiller plant serving main air handling plant is rated at 160 kW. The operating characteristic (Figure 5.37) indicates that there is no time when a chiller rated at 160 kW will not meet the load. Refurbishments and modifications to other building locations have meant that an additional 30kW of cooling capacity has been installed.

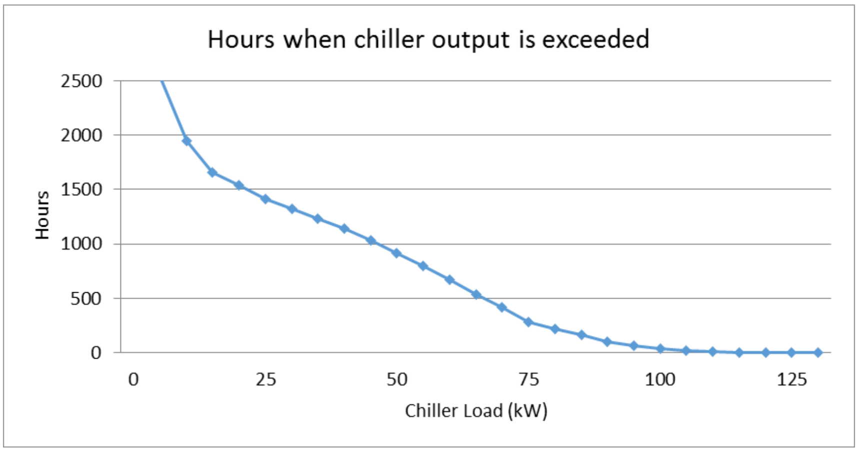

Fig 5.37 Chiller Output Demand Distributions (Hours: Henry Cotton Building)

The additionally installed cooling capacity uses split systems in various locations. Though the overall cooling power exceeds design demand, this offers an opportunity for coping with diversified load but adds to the difficulty of control and monitoring. BMS controls and monitoring for split system air conditioning is limited to on/off signals.

5.4.5 Engineering workshop

The engineering workshop heating requirement is derived from a central boiler plant. There is no designated boiler plant for this building. Cooling for the engineering workshop consists of a 10kW split system which treats the office area only. Although the DSM estimates a 12 kW (Figure 5.38) load, this occurs only temporarily. Similarly, the demand characteristic (Figure 5.39) infers that the worst case load is temporary.

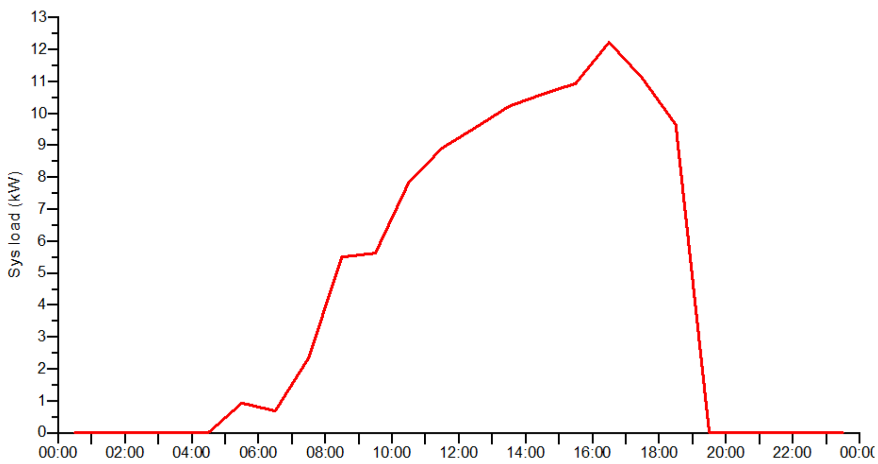

Fig 5.38 Chiller Cooling Load (Engineering workshops (office))

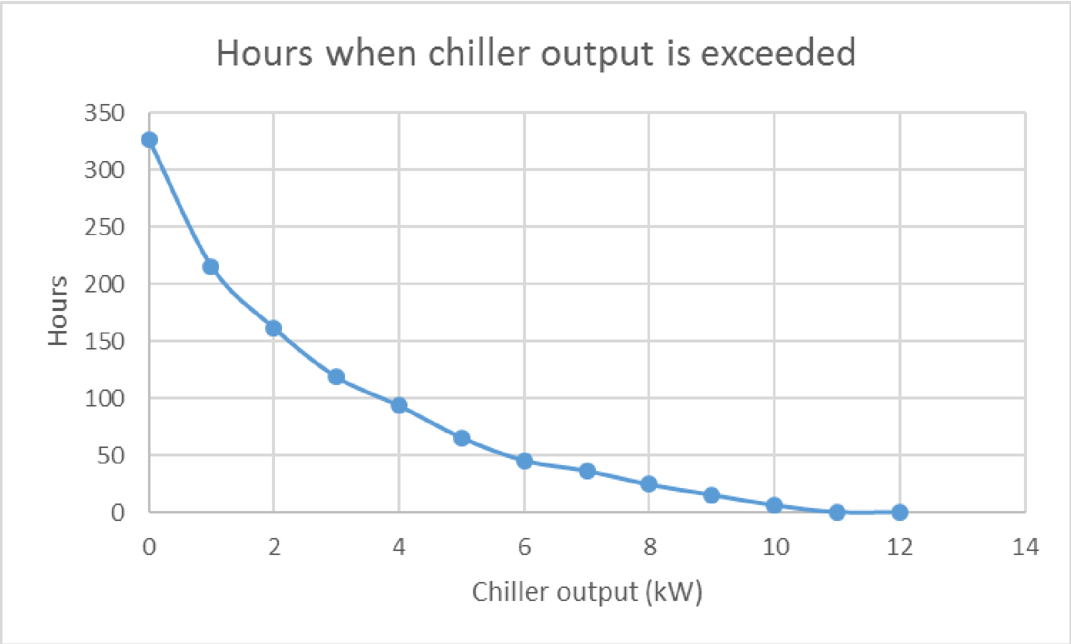

Fig 5.39 Chiller Output Demand Distributions (Hours: Engineering workshops (office))

5.4.6 Heating load characteristics

The boiler and chiller load characteristics (section 5.4) represent the simulated design-day energy load in KW, which occurs during the operational period. The profiles of these characteristics indicate how the heating (cooling) loads are modified by factors such as building construction, layout, shape coefficient and occupancy factors. Each of the buildings was constructed at different times and all are operated intermittently. For intermittently heated buildings, it is desirable that the boiler output can enable the heating system to achieve comfort temperature by the time the building is occupied. Figure 5.40 (Moss, 2003) illustrates the relationship between heating time and space temperature for a situation in which the building is unheated and cold at boiler start-up time.

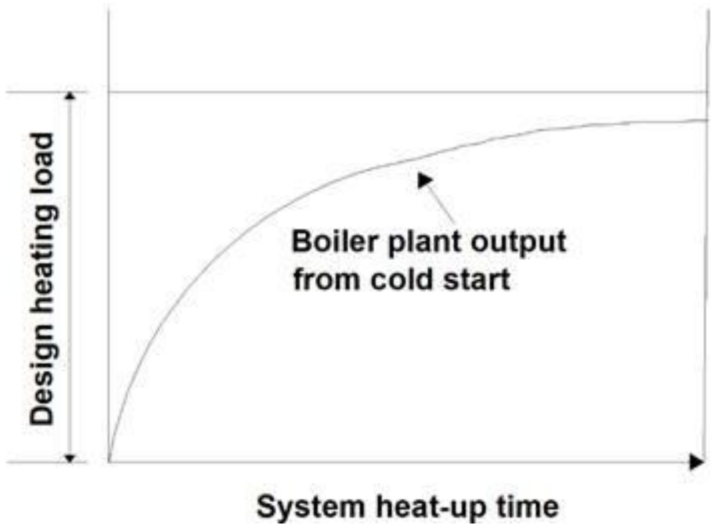

Fig 5.40 Intermittent boiler start- up characteristic

The simulated heating load characteristics (sections 5.4.1 to 5.4.4) reflect this effect, but since the simulation data sets a constant room temperature, start-up plant output is demonstrated as a "spike" in boiler load. The magnitude and duration of this spike varies for each building. The simulated charts do not identify specific causes, though design practice has recognised that the impact of thermal mass can be significant. There are three contributions to thermal mass: "the envelope and structural elements, the air volume and the fittings and furniture". (Reilly & Kinnane, 2017). The effect of these parameters can be a modification of the rate of heating and temperature change within the heated space. An ideal situation would be one in which the heat absorbed, from heating or external surfaces, is slowly released during unoccupied periods and consequently reduces the heating load. Despite this effect, the heating load simulation charts for each building indicate that start – up conditions require increased plant capacity for a short period. The length of time for which the increased load applies differs for each building and varies between one and four hours. However, for the Cherie Booth and Henry Cotton buildings the gradient of peak reduction is less acute and may be also be related to the rate of building heat requirement created by outside air temperatures. The difference between the peak load and the settled plant load also varies for different buildings. The Henry Cotton, Peter Jost and Cherie Booth buildings have start-up peaks that are approximately 360 %, 500% and 180% greater than the average operational load. Tom Reilly building start up peaks at approximately 130% of the operational load. Although this is a small sample, the building, which has been designed to be the thermally heaviest (Tom Reilly), has the lowest percentage peak at start up. This tends to comply with theoretical expectations.

One of the solutions to the problem of slow building heat-up is to pre-heat (start plant earlier). Figure 5.41 demonstrates simulated boiler loads at with different plant start times for the Tom Reilly building. The effect of pre-heating on the simulated loads is to reduce the start-up peaks, which will contribute to quicker space warm-up. However, this effect is not dramatic.

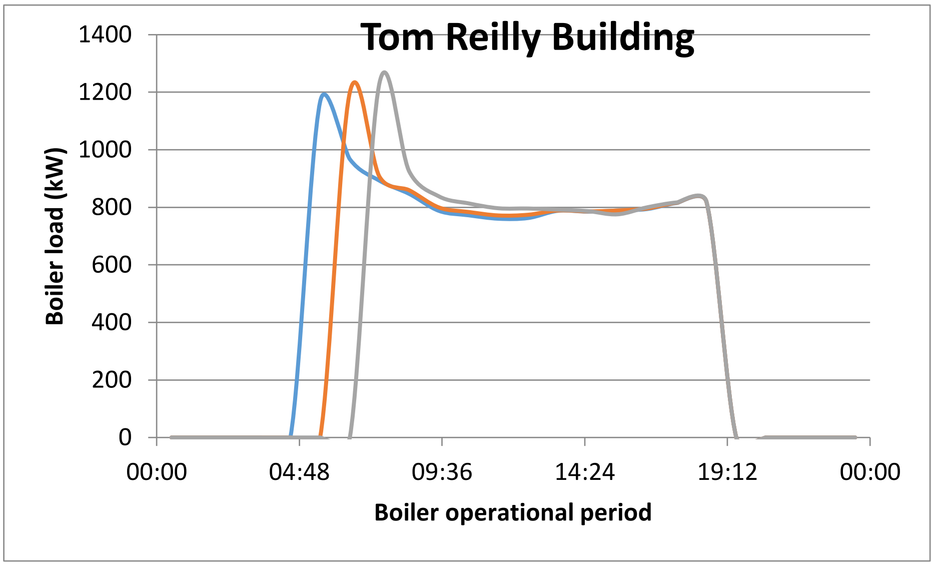

Figure 5.41 Boiler start – up characteristic at with different pre-heat.

Thermal mass also plays a part in the chiller load. Figure 5.42 (Tymkow, et al., 2013) illustrates how the heat storage capacity of room or zone influences how much of instantaneous heat gains can actually become a load on the air conditioning plant.

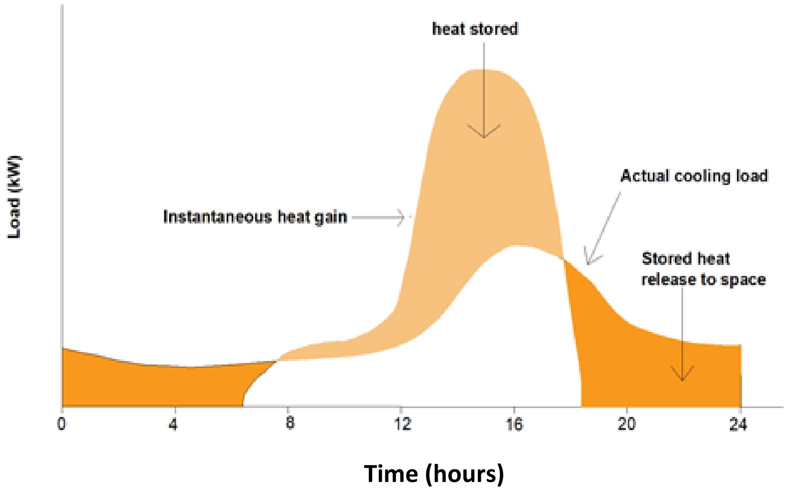

Figure 5.42 Heat storage and cooling load.

The simulated chiller load characteristics for the buildings in this study (Sections 5.4.1 to 5.4.4) buildings demonstrate the actual cooling loads which are to be offset by the air conditioning plant. For all four buildings the storage effects are recognisable in that the peak cooling load is delayed and occurs towards evening time. The Tom Reilly Building, which is the thermally heaviest building not only has a delayed peak cooling load, but also a slower rate of increase over the operational day. The other three buildings exhibit a sharp start-up load followed by a more gentle increase through the operational day. The start-up increase demonstrated for the Peter Jost building occurs briefly, before falling to a lower level and then commences a gentle increase. The space internal gains are entered into the software as a constant value. The air conditioned zone (lecture theatre) has a relatively small window which offers a variable instantaneous heat gain which may account for this characteristic. The Henry Cotton building cooling load characteristic demonstrates the largest start-up load followed by a gentle increase from an initially high condition. This characteristic indicates that this building has effectively the highest cooling load over the operational day. This is consistent with the characteristics of the building which is deep plan with a large amount of internal zones. The cooling load characteristic for the Cherie Booth Building has a similar high start-up characteristic, though this does represent as large a proportion of peak cooling as for Henry Cotton. This initial load is consistent with the large solar gain which would affect the window façade at that time in the operational day.

5.4.7 Design techniques

Each of the case study buildings have been built during different periods of statutory energy legislation. This has no discernible trend or effect in plant sizing strategies, though it appears that some “rule of thumb” techniques have been applied. For example, both Tom Reilly and Cherie Booth buildings have twin boilers each rated at 2/3 of the load, despite being built 12 years apart. All of the buildings, apart from the engineering workshops have been designed during a period when dynamic software was available but it is not known how this has been applied, particularly for the older buildings. Determining the accuracy of plant sizes would require logged data in order to compare performance to some threshold which can then form the basis of feedback to designers. This is a long-term process and, in the meantime it may fall to facilities managers to resolve these issues as part of maintenance and replacement duties. However, this also requires access to appropriate logged performance data.

5.5. BMS monitoring for key building services systems

The BMS inputs and outputs were found to be insufficient for some of the air conditioning systems and it was necessary to install temporary temperature sensors in some cases. Table 5.14 indicates findings.

Table 5.14 BMS monitoring for air conditioning systems

Primary air cooling coil: Tom Reilly chilled beam air conditioning	BMS monitoring only reports % signal to cooling coil control valve. This is unclear how this relates to cooling coils output. Poorly calibrated flow sensors report incorrect supply volume flow rate
Active chilled beams in Tom Reilly Building	Portable sensing indicates that, during summer condition, there is no temperature difference between primary air and supply air. This indicates that room coil (within chilled beam) is not required and primary air over-cools. This is not monitored by BMS
Heat recovery primary air handling units in Tom Reilly Building	Poorly located sensors prevent determination of heat exchanger effectiveness. Poorly calibrated flow sensors report incorrect supply volume flow rate
Split system air conditioning in Cherie Booth IT suite	Portable sensors indicate an acceptable COP. However, BMS only provides on/off control. Performance not monitored

5.6 Discussion

Although this chapter considered the implications of design decisions for building installations, the study revealed that the design of building services equipment and its subsequent installed operation are linked and inter-dependent. Where plant equipment design sizes are examined against system performance, it is commonly found that excessive margins are applied to plant ratings. Building services engineering design is an iterative process which must co-ordinate with all of the other professional disciplines involved in a project and this can create situations in which a safety-first approach to plant sizing is adopted. However, the efficiency of equipment such as fans and pumps is very sensitive to operating parameters (section 5.2.1 and section 5.3.2.1) and in order to obtain low energy performance, more accurate sizing of equipment is necessary. The forgiving and tolerant nature of building services performance can mean that acceptable conditions can be achieved with oversized plant and the additional energy costs. Poor efficiencies often go unnoticed by busy facilities managers. This situation has been identified for the speed control of pumps. In this case, the facilities managers were informed, by means of maintenance manuals (section 5.3.2.2), that outputs of heating and chilled water pumps were controlled by remote constant pressure sensors, however by survey and inspection it was found that pump speed control arrangement was a simpler and consequently more energy intensive arrangement. The likely cause of this discrepancy was probably poor communications between the building services designer and the controls/BMS installer. The nature of the procurement process for building services engineering systems can mean that the resolution of discrepancies and excessive margins falls to the facilities managers and may be described as legacy problems. Building services engineering systems normally require maintenance, replacement or upgrading within the life of the building. This means that facilities managers have an opportunity to correct these issues and enable building services engineering equipment to operate at peak efficiency. Therefore, facilities managers can provide a practical solution to the performance gap. A critical factor would be a strategic monitoring system which enabled facilities managers to measure system performance so that plant replacement can be accurately sized to meet the loads at peak efficiencies. Major plant item ratings for the case study buildings tend not to agree with DSM generated (section 5.4.7) values, however in all cases the plant sizes are large compared with typical loads. This has implications for plant control.

5.7 Summary

- The three types of fan which are normally used in centralized ventilation and air conditioning systems for non-domestic buildings are: axial flow, centrifugal backward curve and centrifugal forward curved fans. Each of these types is recognised within the industry to have a generic type of characteristic.
- The performance of a fan depends upon its operating point which is the condition at which the fan curve characteristic intersects with the system curve characteristic. Ideally, this should be at the maximum efficiency condition.
- However, the operating point is very sensitive to the relationship between flow rate and system pressure drop. Therefore, unless the duct system pressure drop is has been determined precisely it is likely that a fan will operate at less than maximum efficiency.
- Precise determination of system pressure drop is hampered by the sometimes inexact nature of the available pressure loss factors. Additionally, it is common for designers to apply safety margins to the design supply volume and system pressure drops. The design information for the large hospital project has been obtained from a leading international consultancy and their calculations in include additional safety margins for both volume and pressure
- Precise determination of system pressure drop is also hampered by the disjointed nature of the procurement process in which the design is effectively shared between the design/tender information prepared by the consultant and ductwork manufacture/installation details prepared by the ductwork sub-contractor
- Fan manufacturers provide fan selection software for their products. The fan characteristics obtained from these selection tools tends to indicate only that part of the fan curve which is not subject to stall or overload.
- The Building Regulations set specific fan power limits of between 1.6 W/L and 3 Watt/L of air flow. This must be checked at design stage and should be checked at commissioning stage. If applied safety margins mean that commissioning engineers reduce flow rates by adding resistance or by changing fan speed, this can also affect the fan efficiency characteristic negatively

- The consultant's design information from the Large Health Service development has been used to develop a design tool which will enable designers and facilities managers to assess fan energy use by from preliminary design drawings or record drawings.
- The pumps considered in the case study building (Tom Reilly) have all been specified with margins. As a contractual strategy this design approach is logical since it means that the pumps will always meet the load. Commissioning pump flow rates can be achieved by modifying impellor speed. The relationship between pump speed and power is proportional to the cube of the speed. Achieving reducing flow rates by speed control is a straightforward operation for speed reduction. Where speed is required to be increased the greater power requirement can have implications for the size of supply cables and associated switchgear.
- Although adding margins (over-sizing) pumps has benefits in terms of contractual risk, it also means that pump and motor efficiencies are almost always negatively affected.
- Pump speed control by constant pressure is a convenient and effective way of reducing energy use. However, some of the energy savings can be wasted if sensing and control systems are not properly designed.
- Constant pressure pump speed control from remote sensors instead of at pump location has, in the past meant additional wiring. Wireless sensors can now provide this function.
- The peak boiler and chiller loads are measured in KW and are therefore a "snapshot" of the peak building load. In some cases, for boilers this "worst-case" load is short-lived, meaning that they are over-sized for much of the heating season
- The DSM has the facility for determining the periods of time for which building loads vary from peak. Graphical representations of how often the boiler or chiller plant will operate at different loads can provide some guidance for control arrangements. The specification of modular boilers for the Peter Jost and Henry Cotton buildings co-ordinate plant operation with load schedules. As for the Tom Reilly and Cherie Booth boiler plant, coping with load variations

appears to have been met by superimposing a rule of thumb technique on top of dynamically determined loads.

Comparing DSM estimates for cooling plant loads with installed plant appears to indicate that this technique is prone to over-estimating. Unlike heating, cooling has a less strong correlation with outside temperature and care is necessary in assessing non-temperature related heat gains. Internal heat gains are related to occupancy.

Chapter 6:

Building Energy Management: a Proposed Method

6.1 Introduction

Previous work in this study has identified some important factors which characterise building services procurement. Chapters 2, 4 and 5 discuss how the scientific nature of the engineering process is affected by the practicalities imposed by the procurement process. Though dynamic simulation modelling has been a boon to the industry, the case studies in chapter 4 indicate that outputs must be viewed judiciously. The responsibility for design can shift between project phases, and participants, each of which may have their own definition of design intent. In order that designers progress projects, theoretical procedures and concepts have been developed into applied processes which contain the tolerances that are necessary for equipment to be designed, manufactured and installed in a commercial environment. In some cases these tolerances have led to plant margins which may be excessive, which leads to over-sized plant. The causes of over-sizing may be related to technical factors or may be a risk avoidance strategy, in which case the solution would be managerial. In either situation, over-sized equipment negatively affects the operational efficiencies of building services equipment. It can also increase noise output and wear, thereby requiring plant/equipment sooner than otherwise would be the case. It also means that building engineering systems use more energy and this has become to be known as the performance gap. Though an ideal situation is one in which competent designs are accurately translated into efficient operational systems, it must be accepted that in many cases this is not achieved and therefore a solution to reducing building energy use lies in the operational phase of projects. This chapter proposes that an improved building energy management system can make a significant contribution to reducing the performance gap as well as developing constructive feedback for designers.

Because operational energy data is a requirement for an accurate quantification of any performance gap, its assessment must normally be a retrospective exercise. Whilst the knowledge obtained from this type of assessment provides useful feedback for future projects, improving the energy performance of the particular project under examination becomes essentially an operational phase task. The operational phase a project's lifecycle may be 40 years, during which time building use may change, occupancy may vary, and systems will require upgrading, repair and replacement. Consequently, a project's operational phase offers the greatest opportunity for saving energy and therefore building energy management can have a significant effect on overall energy use. The underlying strategy for an energy- management scheme design should incorporate sensing and monitoring functions, which can enable improvements. This involves more than simply using energy management systems to support day-to-day operational requirements. Monitored data should be automatically compiled and presented in a manner which enables effective comparisons of individual building services systems and components with required levels of operation. By applying a planned methodology, data and information, which can pin point particular operational characteristics and performance is made available. It can also contribute to accurate retro-fitting, up-grading and replacement of equipment and systems.

6.2 A strategy for building energy management

6.2.1 Brief introduction to performance gap reduction

By comparing building energy estimations with actual energy use (Chapter 4), it can be seen that the performance gap for a building is not a constant ratio (Figure 6.1). The annual energy used by a building can change because of weather, occupation and the changing characteristics of the building. The effects of weather on building energy use can be complicated. For example, energy predictions based on a linear relationship between building energy use and typical weather year data may not be appropriate in all cases (Hacker and Capon 2009), though this has been common practice. The implications for predicted global temperature increase should also be considered. Levermore et al (2012)have developed robust methodologies for the development of weather data with which designers may account for future temperature effects. Also, annual energy data for buildings, in the majority of cases is only available in terms of total annual heating (fossil) and annual electrical totals. Building energy data in this form is a blunt instrument for energy managers because it is not sufficiently detailed to enable the performance of specific building services systems to be assessed. Given the approximations of the estimation process and the lack of detail in presently available building energy data, a building energy management system requires to be able to produce results which are targeted at individual systems and can achieve an appropriate level of precision relative to the stage of project development or building operation. It should also be capable of fine-tuning as improved data becomes available. Figure 6.2 illustrates this process.

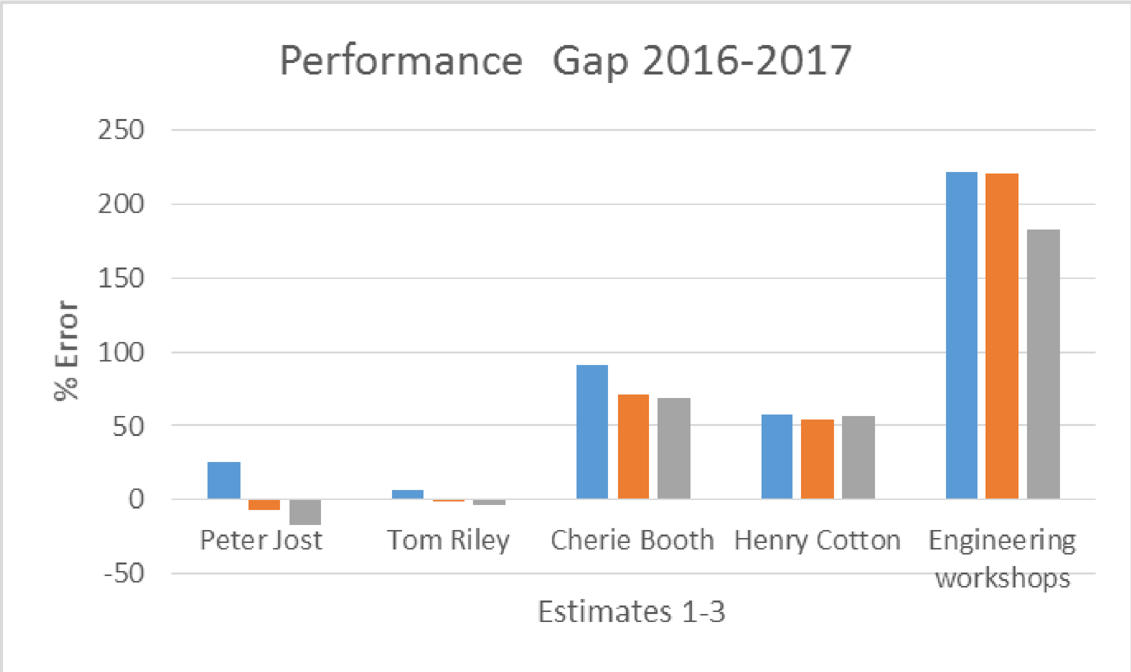

Figure 6.1 Performance gaps for case study buildings for the period 2016-2017

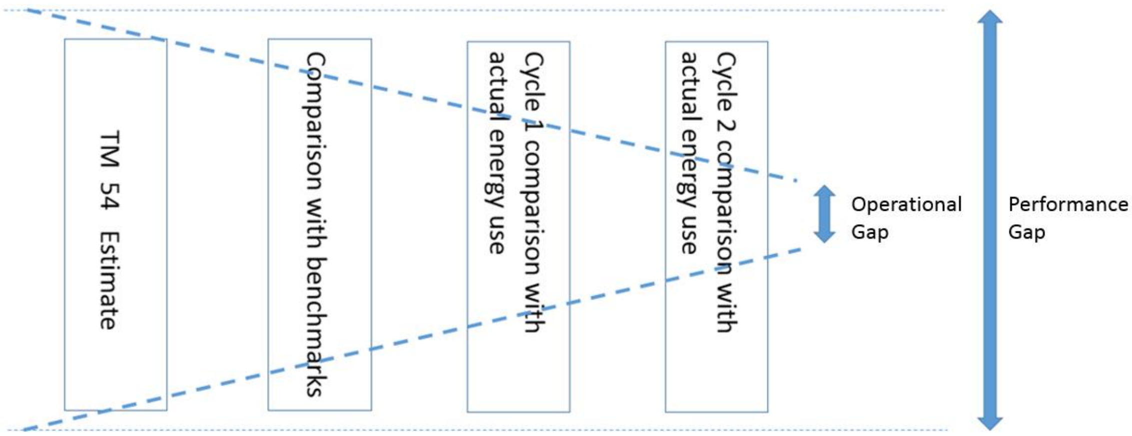

Figure 6.2. A strategy for estimating and refining individual system energy use

Although Figure 6.2 indicates two cycles of fine-tuning of energy estimates, it is proposed that this is an ongoing facilities management role.

6.2.2 Energy management for new and existing buildings

The strategy indicated in Figure 6.2 commences with a TM54 (or equivalent) estimate. Whilst this process has been developed for new buildings, the strategy is also applicable for existing buildings. The essential element is that preliminary energy data/estimations are prepared for individual plant items and a means of measuring and monitoring the energy use for that equipment is available. Typically, the method of monitoring/measuring will be by means of a building management system. This study (Chapter 5) has shown that building management systems do not necessarily measure appropriate parameters and it is therefore necessary that for new projects, the energy management strategy is developed at an early design stage. Where TM54 estimates are part of the early design process, the individual energy streams will be identified and should also appear in the list of sensing points proposed by the building management system designer/installer. For existing buildings this may require some retro-fitting. Care is necessary to ensure that plant items which include controls as part of the package have appropriate instrumentation facilities. In many cases, for this type of equipment, building management inputs are limited to on/off signals. For new buildings commissioning data should be available, but for older buildings it is common to find that maintenance documentation has been prepared perfunctorily and has not been stored with care.

Building services energy use should be monitored and logged under distinct individual headings so the energy streams can periodically logged and compared. The energy streams identified in the case studies (Chapter 4) are listed in Table 6.1.

Table 6.1 Individual headings for energy logging

Lighting
Small power
Lifts
Servers
Cooling
Pumps, fans and controls
Total electrical fuel use
Heating
Domestic Hot water
Total fossil fuel use

It should be noted that for the case study buildings, fans, pumps and controls were considered as one energy stream. However, it was found that energy use under this heading was significant. Also, it was not possible to accurately assess the operational efficiencies for fans and pumps. Chapter 5 includes simplified methods for determining early stage estimates for fan and pump energy use.

6.2.3 The nature of building management outputs

The outputs reported by the building management system are a necessary component of a building energy management regime. The data available from the building management system must deliver data which has a content and nature to provide effective information to the building facilities managers. It is important recognise the level of resource available to facilities management. It should not be assumed that all facilities managers are trained building services design engineers. Many facilities managers come from a surveying or commercial management background. Also, the term “building services engineer” covers a range of disciplines.

The data building management system presented to facilities managers should include typical parameters for temperature, start / stop times etc. It should also have a facility to present data in a form, which is presently unavailable. This will depends on the characteristics of each particular project. The parameters necessary to develop the TM54 type estimate into an operational management tool should be available. Also, data should inform facilities managers of the efficiencies of boilers, pumps and fans as well as the COP’s (coefficients of performance) for chiller plant.

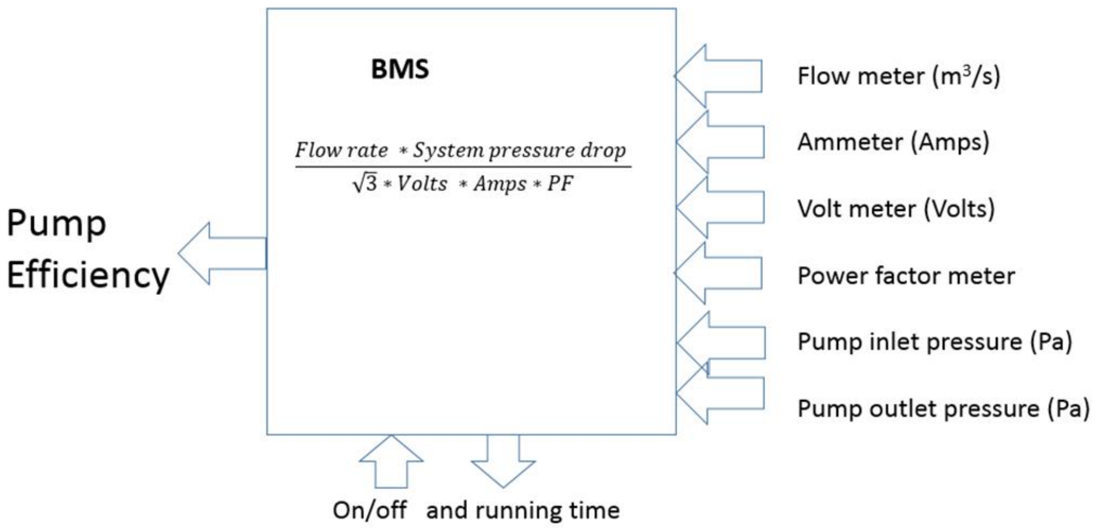

Figure 6.3.Building management inputs for analysis of pump efficiency.

Figure 6.3 illustrates a working diagram which identifies the data inputs necessary so that a building management system can report plant (in this case pump) efficiency. The diagram indicates how an algorithm within the BM software can be designed to convert input BMS input parameters into data, which is valuable to facilities managers.

In this case, the efficiency is determined from by comparing the power transferred to the fluid with the electrical input power.

$$Power\ transferred\ to\ fluid\ (Watts) = volume\ flow\ rate * pump\ pressure$$

$$Electrical\ input\ power\ (Watts) = \sqrt{3}\ * voltage * current * power\ factor$$

$$Pump\ efficiency\ (\%) = (Power\ transferred\ to\ fluid/Electrical\ input\ power) * 100$$

Where

$$Volume\ flow\ rate = fluid\ flow\ in\ m^3/s$$

$$Pump\ pressure = system\ pressure\ loss\ in\ N/m^2.$$

The interfacing of technologies involved in building management systems and building services can leave gaps (Chapter 5). It is necessary for the building services designers and the controls/building management specialists to liaise so that each party appreciates the detail and quality of the monitored output. Figure 6.2 & Table 6.1-6.3 set out a proposed method for this process. It should be noted that the two tables not only identify particular parameters, but they also specifye how the effect and implications of these parameters should be reported. Examples of performance monitoring reporting include factors such as boiler efficiency and heat exchanger effectiveness. By setting out how building services engineering equipment must be described in this method, should ensure that the appropriate parameters are monitored and measured. Additionally, although in the past this kind of assessment it may have been possible to calculate factors such as efficiency from monitored information, it was necessary for the facilities manager to have appropriate skill and knowledge. It was also necessary that all of the appropriate parameters had been monitored.

Table 6.2 Monitoring and Sensing Schedule

Plant	Sensing and monitoring	Units	Emissions	Formula
Boilers	Operational time	on/off		**Boiler efficiency**
	Fluid flow rate	kg/s		
	Fluid temperature difference	^0C		**Combustion efficiency**
	Fuel flow rate	m^3/s	CO2 emissions	
	Flue gas temperature	^0C		
	Flue gas analysis	O2 % and CO2 %		
Chillers	Operational time	on/off		**Coefficient of performance**
	Chilled water flow rate			
	Fluid temperature difference			
	Electric current	Amps	CO2 emissions	
	Evaporating temperature	^0C		
	Condensing temperature	^0C		
Pumps	Operational time	on/off		**Pump efficiency**
	Fluid flow rate	kg/s		
	System pressure drop	Pa		
	Electric current	Amps	CO2 emissions	
Fans	Operational time	on/off		**Fan efficiency**
	Fluid flow rate	m^3/s		
	System pressure drop	Pa		
	Electric current	Amps		
Cooling coils (chilled water)	Chilled water flow rate	kg/s		**Heat exchanger effectiveness**
	Chilled water flow/return temps	^0C		
	Air flow rate	m^3/s		
	Air on/off coil temperatures	^0C		
Heating coils (hot water)	Hot water flow rate	kg/s		**Heat exchanger effectiveness**
	Hot water flow/return temps	^0C		
	Air flow rate	m^3/s		
	Air on/off coil temperatures	^0C		

Table 6.3 Monitoring and Sensing Schedule (continuation)

Plant	Sensing and monitoring	Units	Emissions	Formula
Domestic hot water (calorifier)	Primary fluid flow rate	kg/s		**Heat exchanger effectiveness**
	Primary fluid flow and return temperature	0C		
	Cold feed flow rate	kg/s		
	Draw off flow and return temperature	^0C		
Direct fired calorifier	Fuel flow rate	kg/s	CO2 emissions	
Cross plate heat recovery	Supply flow rate	m^3/s		**Heat exchanger effectiveness**
	Extract flow rate	m^3/s		**Heat recovery effectiveness**
	Supply pressure drop	Pa		
	Extract pressure drop	Pa		
Split systems	Operational time	on/off		**Coefficient of performance**
	Electric current	Amps		
	Room temperature	^0C		
	Supply temperature	^0C		
	Evaporating temperature	^0C		
	Condensing temperature	^0C		
	Supply air volume	m^3/s		
	Electric current	Amps	CO2 emissions	
Lifts	Number of journeys / day	on/off		
	Operational time/journey	on/off		
	Lift current (operational)	Amps		
	Standby current	Amps		
Small power	Current	Amps		
	Operational time	On/off		
Lighting	Current	AMPs		
	Operational time	On/off		

6.2.4 Continuous commissioning

In parallel with the process of monitoring described in 6.2.3 of this chapter, the building energy management strategy should also incorporate a facility for continuous commissioning of building services engineering systems. Presently, the commissioning process for building services systems is a one-off event which is carried out towards the end of site operations for a construction project. The problems associated with this process are considered in chapter 2. Particular systems, or parts of systems are measured, regulated and set to work and, unless some event requires retro-commissioning they will be set for the buildings operational lifetime. Examples of this policy are the flow rates for water and air systems. Much of the instrumentation used at commissioning stage is portable and is removed from site when system are considered to be “signed off”. Given that fluid flows are the major media for delivering heating and cooling energy around buildings it is important that facilities managers have a real-time awareness of volume flows of water in pipe and air in ducts. These values are critical factors in determining, not only how much heat/cooling energy is transferred, but they are also related to fan and pump duties and system pressure drops. These parameters are vital for facilities managers when replacement or retro-fitting of building services equipment is necessary. Without access to this data, specifying replacement equipment is a case of exchanging like for like, in which case the problems created by excessive design margins will remain unresolved.

Because much of the instrumentation used by commissioning engineers is portable and removed from site when systems have been set to work, for continuous commissioning it is necessary to install additional permanent instrumentation. Figure 6.4 is an example of a permanently installed air flow grid. Instrumentation which is located within fluid flow systems can create an additional pressure loss and, therefore may increase fan or pump energy use. Alternatively, the relationship between pressure drop and flow rate can be exploited and air flow can be inferred if pressure sensors are more convenient. Ultra-sonic flow sensors can be simpler to incorporate unto fluid flow systems. Figure 6.5 illustrates a water flow ultra-sonic-sensor mounted externally on pipe work. Where continuous commissioning/monitoring is applied to electrical energy use, patterns of use can be determined. If sensing is intelligently located load characteristics can be identified and appropriate control actions can be instituted.

The ongoing commissioning data should be logged in similar fashion to the energy data described in section 6.2.3. The original commissioned data should form the basis of this procedure.

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Figure 6.4 Permanently installed air flow measurement grid

The *image* originally presented here cannot be made freely available via LJMU E-Theses Collection because of copyright. The image was sourced at https://micronicsflowmeters.com/product-category/energy-management-building/ultrasonic-flow-meters-energy-management-building/

Figure 6.5.Permanently installed ultra-sonic water flow meter

6.3 Summary

This chapter has set out a strategy for identifying the parameters which will reflect the energy used by individual building services plant and equipment. This strategy is a development of the TM54 process and therefore an energy accounting system will enable detailed analysis of individual building services equipment. For new buildings, the starting basis of the energy management strategy will be the design energy estimates. For existing buildings, similar estimates can be prepared and may benefit from operational knowledge. In both cases it is likely that estimated values for individual building services systems will not be precisely accurate. However, these initial approximations will provide a baseline from which to fine-tune energy use values.

Electronic building management systems (BMS) will have a critical role in this process. The selection of monitored parameters must obtain the data necessary so that system performance can be reported in terms which have relevance for facilities staff from a range of backgrounds. An example of this kind of performance assessment is combustion efficiency. This parameter is normally measured periodically using portable equipment. Permanent monitoring equipment would require to be specifically requested by consultant designers instead allowing such design decisions to be left to specialist sub-contractors.

Alongside and coordinating with energy management the system should incorporate a continuous commissioning procedure. This should also monitor and compare parameters. Permanent instrumentation will be required to be installed to measure those parameters which are traditionally only measured by portable equipment at the contract commissioning stage. The data obtained from this process will not only contribute to efficient operation and fault detection but will also provide the basis for accurate equipment sizing when replacement is necessary

The building energy management system should be developed to become a routine facilities management duty.

Chapter 7: Conclusions

Section 7.1 Introduction

This chapter summarises and reviews the outcomes which this study has revealed. The study was initiated by the need to find ways of improving the energy performance of buildings services engineering systems. The most recognised phenomenon of this energy discrepancy is termed the performance gap and this work aimed to contribute to the solution of this problem. The performance gap normally refers to new buildings but improvements in building services for existing buildings is also necessary, not least because existing building stock emits much more carbon.

Five of the six case study buildings used in this study are existing but each were built under different regulatory regimes. In response to the problem of the performance gap, CIBSE have developed an improved method for early design stage energy estimates for buildings. This method has been applied to the five existing buildings under various scenarios. The estimated values were compared with benchmarks and actual energy use values. This process indicated a range of performance gaps and also highlighted the importance of input data. Since building services are the active dynamic energy-using components of a building, the management and design of systems were considered. For building services the iterative nature of design plus contractual arrangements which encourage shifting design responsibility, can mitigate against technical accuracy. In fact, tolerances are standard practice. It was found that sometimes added tolerances become excessive. This can have negative effects on the operational efficiency of equipment: fans and pumps are in this category. Case studies were also used to examine the implications for the sizing and control of fans and pumps. This offered the opportunity to develop new methods for early-stage estimation of fan and pump energy use. Examination of variable speed circulating pumps for one of case study buildings found that the control installation did not comply with the specification with consequent effects on efficiency. Perhaps more concerning was that this was unnoticed by the building management system. Resolving performance gap issues in the design and installation phases of a building services engineering project can be hampered by contractual procedures. A consequence of this is that part of the solution to improving building energy efficiency sits with facilities management. This study proposes a strategy for managing the energy used in buildings.

7.2 Major Outcome1: design practice

According to the literature review in this thesis (Chapter 2), it has been recognised that inefficiencies can be created at all stages of building services development. Building services engineering is a term which covers a wide range of technologies and disciplines. The design, installation, operation and maintenance of these technologies is carried out by mechanical and electrical engineers. However, even these job descriptions can be sub-divided. Mechanical engineers deal with heating, air conditioning, ventilation, control systems, fire suppression, hot and cold water supplies and drainage. Electrical engineers deal with lighting, electrical power distribution, fire and security, lifts, generators and information technologies. Each of these sub-divisions demands a high level of knowledge and expertise. The situation is further complicated by the need to co-ordinate all of these disciplines within a larger project in which the building services engineers must inter-relate, not only with each other, but with architects, structural engineers, quantity surveyors and civil engineers. For a new project these various diverse teams may be brought together and exist only for the duration of that project.

The development of the project goes through several stages in which building services engineering designs are produced, refined or altered and reproduced until a solution is found which meets agreement with all other members of the design team. The point at which a building services engineering design is completed to a level for tender is described as "fully-co-ordinated", however contractual procedures will mean that the design must then incorporate the design goals of the various specialist sub-contractors. “Design-intent” is the thread which links the tender design with the working drawings to which the systems are installed and commissioned. There has been criticism that the silo-nature of the different disciplines affects design quality negatively. On the other hand, there is some agreement amongst construction experts that the expertise of specialist sub-contractors and suppliers can provide a valuable input to the technology and buildability of buildings services designs. The ideal situation would be to include this expertise into designs pre-tender rather post-tender. However, this would require innovative contractual arrangement whereby specialists can be remunerated for their work. Presently, most specialist sub-contractors are appointed post-tender and often through some financially competitive arrangement.

Building services engineering design solutions which have been developed using precise data and relevant calculations should naturally result in efficient systems. However, the nature of the industry means that designers cannot apply laboratory conditions to design outcomes. Systems must be practical, buildable and completed within acceptable periods. This is recognised by the learned bodies which produce data which is practically useful and accessible. Examples of this approach are the fluid mechanics factors and guidance offered by CIBSE for determinations of pipe and duct sizes and resistances. The documentation includes caveats and advice on approximations. This also requires designers to make judgements. Designers must be aware that theoretical calculations resulting in pressure losses measured in Pascals can be significantly affected by site practices and the selection of fittings from suppliers. This situation is recognised by the industry and tolerances are acceptable. However, tolerances can become margins and may become excessive. This can have serious implications for the operation equipment. This thesis has considered this effect for fans and pumps. Almost all fans and pumps now have variable speed motors which can offer considerable energy savings. However, they are sometimes seen as offering a commissioning solution to oversized fans and pumps. The motives behind over-sizing pumps and fans are understandable. Given that the power requirement is cubed as speed changes, if at commissioning stage a fan or pump was required to increase in speed the greater power requirement could affect the electrical distribution system supplying the equipment.

Building services engineering systems are the dynamic, energy using components of a building. The processes which link feasibility and design to the handover and operation of these are less than perfect. Therefore, facilities managers may be faced with challenges which have originated from design and installation. However, facilities managers can have far greater influence in building energy performance because their role inhabits the longest period of a project life cycle.

7.3 Major Outcome2: early-stage methods

In response to the concept of the performance gap, CIBSE have developed an improved method for estimating, at an early design stage, the operational energy that will be used by building services engineering systems. In Chapter 4 of this thesis, a method based on this procedure has been applied to the five case study buildings which are located within the LJMU campus. Whereas, the original intention for this process was for it to applied to new buildings, in this study all of the case study buildings are existing. The buildings vary in age and in construction method. There is also some variation in the nature of the occupant behaviour which relates to building use. In this thesis, several operational scenarios were considered for each case study building. These were developed from building surveys, access (most times limited) to record information and interviews with occupants. A great value of this technique is that the estimates are applied to individual building services equipment and systems. This level of detail is considerably more useful than the information available from previously developed estimation procedures. Up until now most of the information regarding building energy is framed in terms of total annual fossil (heating) energy and total annual electrical energy. Whilst this is useful, it can be seen as blunt instrument for building services engineers and facilities managers seeking to understand, not only how much energy is used, but also where, how and when it used.

An interesting feature of this technique was the ability to determine how energy is used by controlled building services systems and how much energy is used in response to occupant needs. Within this thesis, these are described as controlled and non-controlled respectively. For the case study buildings, the newer projects had higher ratios of non-controllable energy use. This corresponds with reduced controlled building energy use where statutory regulations have increased insulation and operational factors. Despite all buildings having gas-fired heating systems, the major fuel in most estimates was electricity, though for three of the buildings, fossil fuel use was most sensitive to scenario changes. The CIBSE estimation technique recommends that estimates are compared with benchmarks. This is logical in the case of new buildings but since the case study building exist, the estimates were also compared with actual energy use. Benchmarks were obtained from the Display Energy Certificates for each building for the years for which they were available. Accuracies varied from estimates being 169% to 25% of the total energy benchmark value. If this were the case at the design stage of a new project, the 25% value may trigger a re-examination of the design. The 169% should also trigger a reassessment but may not. Comparing energy estimates with actual energy use enabled performance gaps to be determined. In all case study buildings, except the engineering workshops, performance gaps which are smaller than the higher values quoted within the industry. This indicates that the TM54 process is certainly an improved estimation technique. However, perhaps more importantly, where estimates are compared to actual energy values over the life of a building, performance gaps change. The performance gap for a building is not a constant ratio. This raises a question about the validity and application of the concept of a performance gap. Though it is useful to have a number which can act as an index energy efficiency, it is necessary for value to have context. Building characteristics change. Buildings are affected by climate and aging. Building services systems performance may fall below optimum. The factor which probably has the greatest effect is that building occupants and what they do changes during a buildings operational lifecycle.

7.4 Major Outcome3: sizing and control

The energy estimates carried for the case study buildings indicated that fan and pump energy is a significant portion of total building energy use. In Chapter 5, commissioned values for pump duties were compared with specified values for the Tom Reilly Building. Therefore, it becomes apparent that designers have applied substantial margins. Since the efficiency for both pumps and fan is sensitive to the location of the operating point (flow rate and pressure drop), the circulating pumps in this building operate at a lower efficiency than was specified, even though these are variable speed pumps.

Examination of the record and maintenance documentation sets a constant pressure control strategy for the circulating pumps. Controls guidance indicates that this strategy offers greater energy savings if the constant pressure sensor, and consequent point of constant pressure, is located around two third along the index run. This is the strategy which has been specified for this building. However, by survey and from interview with the controls sub-contractor it was found that constant pressure is controlled at the pump location. From record drawings and maintenance documentation data was obtained so that a design exercise could examine the implications of this failure to comply with the specification. The result of this study was that the potential energy saving which compliance would have achieved was significant. The reasons for this non-compliance are not available. However, wherever the location of the constant pressure point is located has implications for the overall design of the pumped system but design information is not available from the consultant to indicate if this has been considered. More concerning, perhaps is that without the investigation instigated by this research this lack of compliance would have gone unnoticed. Whilst pumps are monitored by the campus BMS (electronic building management system), the sensing points and associated data did not reveal the problem. In fact, like many buildings services systems, although they are using more energy than is necessary, they still fulfil their function. In the case of the circulating pumps their function is to transfer heating and cooling in suitable proportions in response to load. Therefore, internal environmental conditions would not have been adversely affected and hard-pressed facilities managers would not have been alerted to this problem.

The addition of margins by designers is more clearly stated in the design consultant's specification for fans in ventilation equipment for the general hospital project. Margins, in this case have been considered to have a higher priority than efficiency. Fan energy use in the UK is limited under the Building Regulations which sets a limit in terms of a specific power allowance (W/L). Achieving this limit requires active involvement by the designer. Although much of the fan pressure available in a ventilation system is used to overcome the resistance of components with air handling units, designers must ensure that external ductwork pressure loss does not contribute to excessive fan duties. The practical effect of this requirement is that duct cross sectional areas cannot be too small and duct routes must be as non-tortuous as possible.

Pump energy use is also limited under the building regulations. In practical terms, this means that designers must specify pumps which comply with the required Energy Efficiency Index (EEI).

Given the significance of fan and pump energy use, this study has developed early stage energy assessment techniques for fans and pumps. It is proposed that these estimating are available for use as part of aTM54 type estimation. For both fans and pumps the energy required by the fluid is equal to the product of the volume flow rate and the systems resistance. At early design stage these values would be approximations, though the heating and cooling loads determined by the dynamic simulation model would provide some confidence. Recommended rates of pressure drop for straight lengths of pipes and ducts are available from CIBSE guidance. The greatest uncertainty relates to the pressure loss created by ducts and fittings. In order to develop the estimation techniques fan and pump pressures were compared with pipe and duct lengths. From this study a range of pressure drops in terms Pa/m were developed incorporated the additional losses from fittings were developed. These were tested against existing system in the hospital project and for systems in one the campus case studies. The results indicated a reliability suitable for application prior to detailed design.

The relationship between sizing of plant and efficiency was also explored for the boilers and chillers in the campus case study buildings. This indicated that this plant item is sized on a worst case basis. Whilst this strategy enables plant to meet all loads, for a great portion of the operating period plant was oversized with consequent implications for efficiency.

7.5 Major Outcome4: proposed energy management strategy

The process of delivering operational building engineering systems involves a sequence of stages which commence at feasibility and briefing stage, go through increasingly accurate steps in design, involves construction installation and handover, and finally achieves operational status. How each of these phases are managed influences the eventual level of performance of the operational systems. The relationship between design and operation has generated concern because, for many buildings, the gap between actual operational energy performance and the design estimates is unacceptably high. Several theories have been developed to explain why this occurs. Chapter 2 of this thesis has concluded that the transfer of design responsibility that can occur between consultant’s design information and contractor’s working drawings provides scope for varying interpretations of design intent. Energy estimates for the case study buildings (Chapter 4) demonstrates imperfections which can affect equipment selection and sizing. In Chapter 5 comparisons of specified performance and actual performance for pumps revealed excessive design margins for pumps. The specification data for the hospital project actually included margins for fans. Also in Chapter 5, investigations into speed control for pumps found that control systems had not conformed to specification. Each of these factors may negatively affect the performance level of the installed operational equipment. The concept of the performance gap indicates that project management of building services systems, in many cases less than ideal and therefore a significant part of the solution to the performance gap is to be found in the operational management of building services systems. The soft-landings procedure plays a part in this strategy. However, although a smooth and efficient handover from installer to client is important, the strategy set out in this study is much more comprehensive and is designed to be applied throughout all stages of a project life-cycle. Furthermore, the proposed strategy has been prepared so that the principles to be generalised from one project to another. Furthermore, the proposed strategy has been prepared so that the principles may be generalised from one project to another.

In Chapter 6, a proposed energy management strategy was established based on CIBSE TM54. This strategy should provide individual estimates for each of the building services systems. The accuracy of these estimates will depend on the project stage at which it is prepared and the availability of reliable data and may be described as approximate. The estimates then become an active management tool which acts as an accounting system for each individual energy stream. The accuracy of the estimates should be refined as projects progress and the reliability of data increases. At project handover, the estimating system becomes a facilities management tool where individual estimates are periodically compared with actual energy values. This system should become a routine facilities management duty.

The novelty of this energy management strategy lies in the ability to monitor individual building services equipment. Therefore it is vital that sensing and monitoring provides data which co-ordinates with this requirement. It is proposed that the sensing and monitoring would be part of an electronic building management system (BMS). The outputs from the BMS should be framed in a context which recognises the resources of the facilities management organisation. Simply reporting physical parameters, valuable though this is, requires the facilities management organisation to have trained building services engineers. It may be that the facilities management staff have a surveying or commercial background. Output data should be presented in terms such as boiler, fan and pump efficiencies, heat exchanger effectiveness, and heating and cooling duties in kW. Providing data in this manners will require close co-operation between building services designers and BMS specialists.

As part of the proposed strategy it also proposed that alongside energy monitoring, a regime of continuous commissioning be initiated. This would be arranged on a similar basis but would require the permanent installation of commissioning instrumentation. By this means facilities managers would have the capability of managing a continuous commissioning programme within a normal duty schedule. The data logged for this application would provide accurate performance parameters so that when plant replacement is necessary, facilities managers would be able to resolve original design/installation issues such as over-sized plant.

7.6 Limitations and future work

7.6.1 Limitations

Several limitations could still be found as follows:

1) Estimates prepared through the TM54 process produces operational energy values which are much closer to actual, conditions. This requires reliable historical data. Much this data for energy estimates is obtained from interviews with building occupants. The observations from non-technical building occupants of the case study buildings in this thesis tend to vary in reliability.
2) Consultants and facilities managers for projects are often reticent to provide information which indicates a less than successful project. The causes of this reticence may be reputational or because of liability issues. In this study, the data used has been therefore limited due to factors which have not made clear.
3) Metering of energy supplies to buildings is a critical factor in accounting for energy use. In this thesis, the metered energy figures were obtained directly from energy display certificates. The reliability of these depends on the competence of the source.

7.6.2 Future Work

As the design and control of building services engineering systems improve, the energy related to occupancy and occupant behaviour increases as a percentage of total building energy use. Presently, designers tend to predict occupancy factors in terms of fixed group patterns of behaviour. Further investigation of how the energy use design parameters associated with building occupancy should aim to reflect this area of energy use more realistically.

The resource available from specialist sub-contractors and suppliers is frequently only accessible to the design team after tender. Whilst there have been developments in contractual procedures to improve this situation, contract conditions should be explored and developed so that this resource is available at the design stage of projects.

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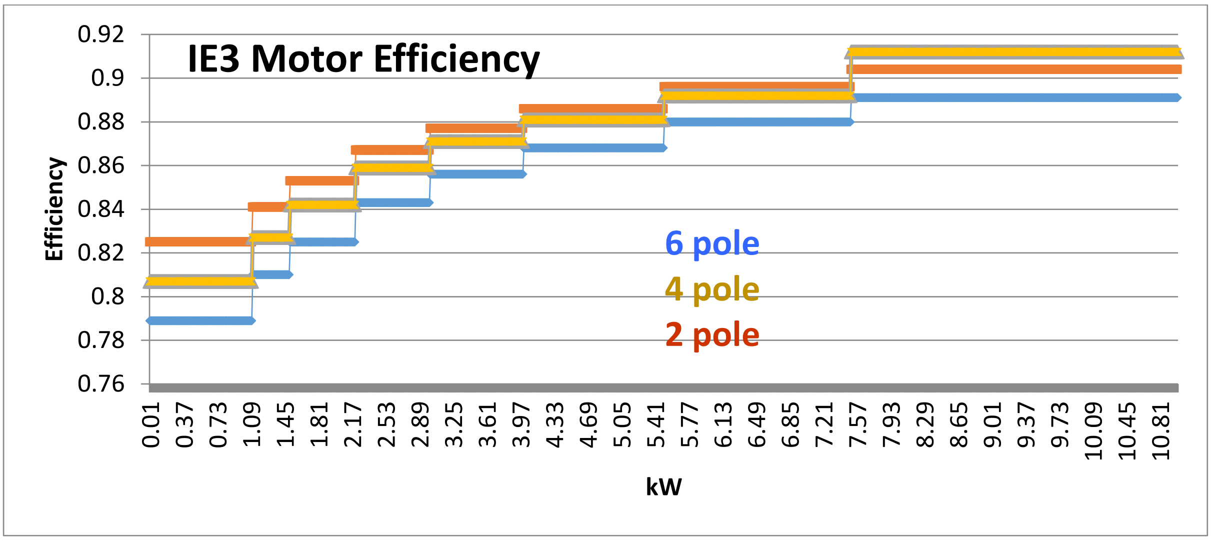
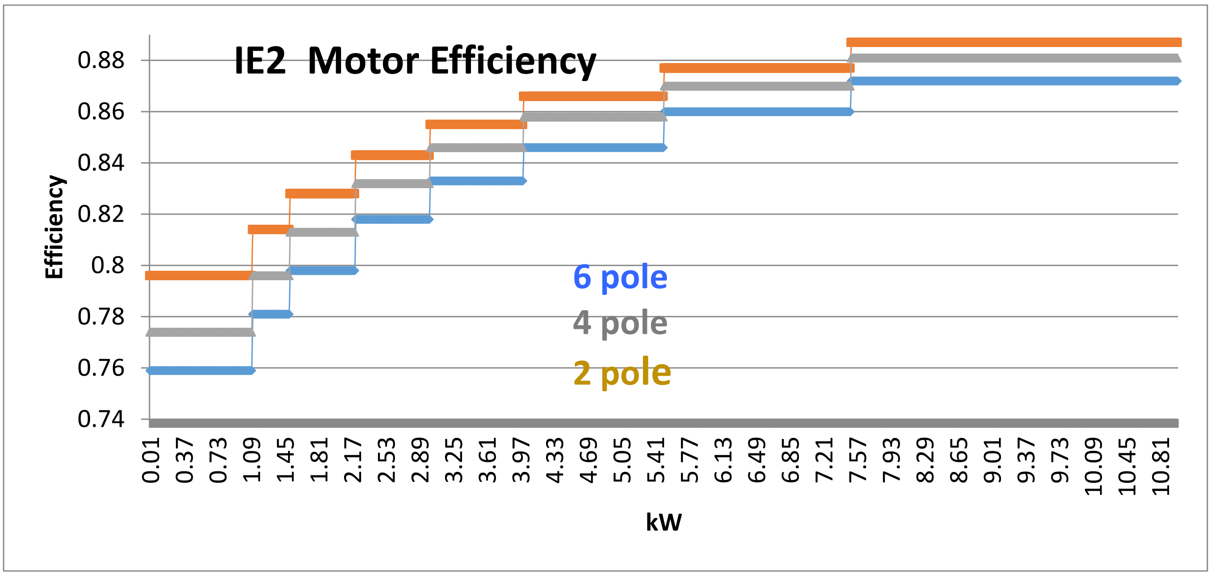
Appendices

Appendix CH2-1

Electric Motor Efficiencies





Commission Regulation (EU) No 4/2014 of 6 January 2014 amending Regulation (EC) No 640/2009 implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to eco-design requirements for electric motors.

Appendix CH3-1

Typical component pressure drops for air handling equipment in commercial buildings.

Face velocity	1.5 m/s	2 + m/s	m/s
Face velocity	50	50	Pa
Filter EU3 bag	50	50	Pa
Filter EU5 bag	75	75	Pa
Filter EU9 bag	110	110	Pa
Rotary heat exchanger	90-100	90-100	Pa
Heater battery	40	40	Pa
Cooler battery	60	60	Pa
Humidifier	20	20	Pa
Fan silencer	30	30	Pa

Sample commissioning report: hospital project

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Pressure drops and flow rates for AHU/03/ SW/01

Split system air conditioning - Cherie Booth lecture suite

Portable sensors were located at the indoor and outdoor units for the Cherie Booth lecture suite air conditioning system during July 2017. Based on manufacturer's specifications for air flow rates, heating/cooling outputs, and monitored air temperatures, evaporator and condenser temperatures were estimated. (The condenser unit is located on the building's North East face and is shaded by a perimeter wall .Effects of direct solar radiation have therefore, not been included). From temperatures monitored each minute, an average hourly temperatures was calculated and inserted into the Carnot formula to determine the hourly coefficient of performance (COP) for the system. This method for determining COP is theoretical and produces impractically high values. However, these values do indicate the variation in COP at different temperature conditions. This variation was applied to a manufacturer's quoted COP of 4. Figure CH3-1A demonstrates how the COP varies with temperature. This is a comparative value and does not account for the input energy required for powering fans and controls. However, it does indicate the likelihood of maximum operational COP's, and where additional BMS sensing could provide useful data for facilities managers.

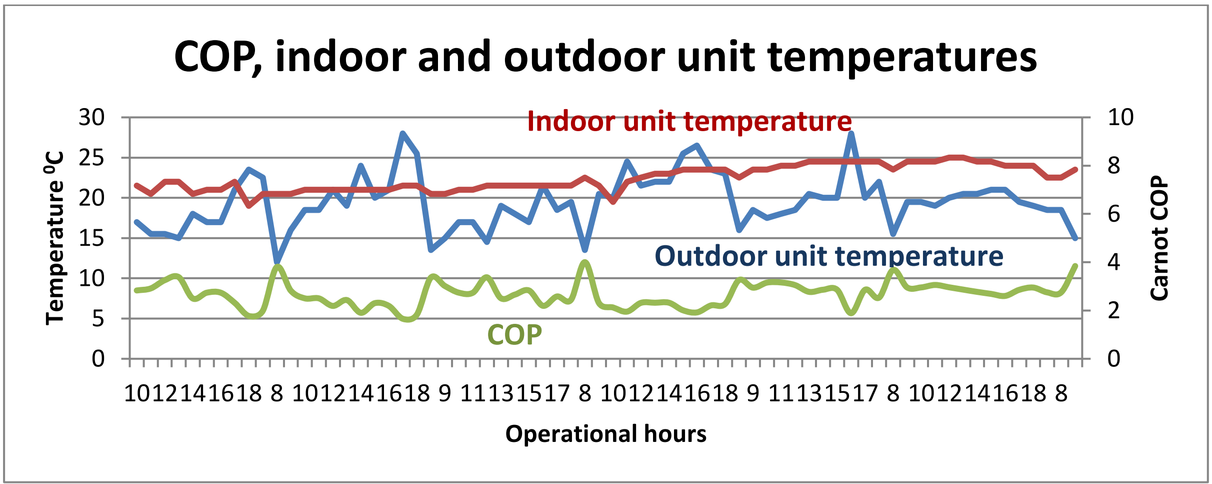


Figure CH3-1 A Operating air temperatures and COP for CB lecture theatre air conditioning system (Hitachi Utopia RC1-6HG 7E and RAS-6HG7E)

Appendix CH4-1

TM54 Spreadsheet Calculation Method

	Tom Reilly Building													
Lighting														
													Elec	**Gas**
Pn	Total installed power in room/zone				87399								kWh	kWh
Fc	Constant illuminance factor				0.9					(Pn * Fc)		78659.1		
Fo	Occupancy dependency factor				0.9					(td * Fo * Fd)		2563.2		
Fd	Daylight dependency factor				1					(tn * Fo)		714.825		
td	Daylight time usage				2848									
tn	Non-daylight time usage				794.25									
W1	Energy consumption for illumination				∑{(Pn * Fc) * [(td * Fo * Fd) + (tn * Fo)]}/1000					201619.7	kWh			
		Lighting load for constant and daylight control												
Wpc	Default parasitic load				5	kWh/m2								
Wem	Default emergency load				1	KWh/m2								
	Floor area				6855									
Wpc	Default load * floor area				41130									
	Total lighting energy				Wp = ∑ (Wpc +W1)					242749.7	kWh		242749.7	
Lift														
Operational days		311												
Operational hours		4354												
Motor		22	kW		4597.7	kWh							9195.4	
Starts/day		350												
Start/year		108850												
Time		0.004	Hours											
Distance		15	m				Energy use for 350 and 500 starts/day							
Standby		0.5	kW	2203										
Number		2												
Small Power				Small power for PC/screen use 7 and 6 hours/day										
		Number	Watts	Sleep Wat	Hours op	Hours sleep		Op kWh	Sleep kWh		kWh			
Work stations (PC's)		316	150	80	1866	6894		88448.4	174280.3		262728.7			
Screens		316	45	1	1866	6894		26534.52	2178.504		28713.02			
Lap tops		34	42	27	1866	311		2664.648	285.498		2950.146			
photocopiers		4	1100	300	1244	7516		5473.6	9019.2		14492.8			
printers		42	320	70	1244	7516		16719.36	22097.04		38816.4			
Microwave		2	800	100	622	8138		995.2	1627.6		2622.8			
Refrigerator		4	350		8760			140835.7	209488.2	350323.9	3066			
Kettle		4	1000		311						311			
Projectors lecture theatre											0			
Projectors conference											0			
									Annual kWh		353700.9		353700.9	
Servers														
Power of server		10							Annual kWh		58692		58692	
Ratio demand		0.67												
Hours		8760												
Domestic hot water														
				Domestic HW use for CIBSE Guidance of 7 or 15 L/person										
Daily hw consumption/person					L/person	7								
Number occupants						815								
Number occupants staff / summer students						400								
Days per year (semesters)						149								
Days per year staff/summer students					311-149	162								
Supply temp					^{0}C	65								
Return temp					^{0}C	55								
Δt					^{0}C	10								
Specific heat capacity					kJ/kg^{0}C	4.2								
Volume of water consumed /y			L/person * days			1303645								
Mass of water consumed / year						1303645								
Annual energy consumption						83650.55								83650.55
													664338	83650.55

		Peter Jost Building											
Lighting													
	Lighting energy for constant or daylight control												
Pn	Total installed power in room/zone				38310							**kWh E**	**kWg**
Fc	Constant illuminance factor				1				(Pn * Fc)		38310		
Fo	Occupancy dependency factor				1				(td * Fo * Fd)		3559.75		
Fd	Daylight dependency factor				1				(tn * Fo)		794.25		
td	Daylight time usage				3559.75								
tn	Non-daylight time usage				794.25								
W1	Energy consumption for illumination				∑{(Pn * Fc) * [(td * Fo * Fd) + (tn * Fo)]}/1(				136374.8	kWh			
Wpc	Default parasitic load				5	kWh/m2							
Wem	Default emergency load				1	KWh/m2							
	Floor area				2554								
Wpc	Default load * floor area				15324								
	Total lighting energy				Wp = ∑ (Wpc +W1)				151698.8	kWh		151698.8	
Lift													
Operational days		311											
Operational hours		4200											
Motor		8	kW		1026.8	kWh						1026.8	
Starts/day		300											
Start/year		93300											
Time		0.0055	Hours		Lift energy for 200 or 300 starts/day								
Distance		15	m										
Standby		0.5	kW										
Small Power													
		Number	Watts	Sleep Wat	Hours op	Hours slee	Op kWh	Sleep kWh		kWh			
Work stations (PC's)		60	150	80	2177	6583	19593	31598.4		51191.4			
Screens		60	45	1	2177	6583	5877.9	394.98		6272.88			
photocopiers		2	1100	300	1244	7516	2736.8	4509.6		7246.4			
printers		2	320	70	1244	7516	796.16	1052.24		1848.4			
Microwave		1	800	100	622	8138	497.6	813.8		1311.4			
Refrigerator		1	350		8760					3066			
Kettle		4	1000		311					311			
Projectors lecture th		2	1050		2488					2612.4			
Projectors conferenc		2	1050		1244					1306.2			
	Small power for PC/screen use 7 and 6 hours/day							Annual kWh		75166.08		75166.08	
Servers													
Power of server		1	kW					Annual kWh		5869.2		5869.2	
Ratio demand		0.67											
Hours		8760											
Domestic hot water													
Daily hw consumption/person					L/person	7							
Number occupants						246							
Number occupants staff / summer students						100							
Days per year (semesters)						149							
Days per year staff/summer students					311-149	162							
Supply temp					°C	65							
Return temp					°C	55							
Δt					°C	10							
Specific heat capacity					kJ/kg°C	4.2							
Volume of water consumed /y(			L/person * days			369978							
Mass of water consumed / year						369978							
Annual energy consumption						23740.26							23740.26
												233760.9	23740.26

		Henry Cotton Building												
Lighting														
	Energy used for constant illuminance and occupancy sensing													
Pn	Total installed power in room/zone				45162								**kWh E**	**kWg**
Fc	Constant illuminance factor				1					(Pn * Fc)		45162		
Fo	Occupancy dependency factor				0.9					(td * Fo * Fd)		3203.775		
Fd	Daylight dependency factor				1					(tn * Fo)		714.825		
td	Daylight time usage				3559.75									
tn	Non-daylight time usage				794.25									
W1	Energy consumption for illumination				?{(Pn * Fc) * [(td * Fo * Fd) + (tn * Fo)]}/1000					144689.6	kWh			
Wpc	Default parasitic load				5	kWh/m2								
Wem	Default emergency load				1	KWh/m2								
	Floor area				2554									
Wpc	Default load * floor area				15324									
	Total lighting energy				Wp = ? (Wpc +W1)					160013.6	kWh		160013.6	
Lift			150 or 300 starts/day											
Operational days		311												
Operational hours		4200												
Motor		18	kW		2573.895	kWh	5147.79						5147.79	
Starts/day		150												
Start/year		46650												
Time		0.0014	Hours											
Distance		12	m											
Standby		0.5	kW	2280										
Number of lifts		2												
Small Power														
		Number	Watts	Sleep Wat	Hours op	Hours sleep		Op kWh	Sleep kWh		kWh			
Work stations (PC's)		314	150	80	1866	6894		87888.6	173177.3		261065.9			
Screens		314	45	1	1866	6894		26366.58	2164.716		28531.3			
photocopiers		2	1100	300	1244	7516		2736.8	4509.6		7246.4			
printers		6	320	70	1244	7516		2388.48	3156.72		5545.2			
Microwave		2	800	100	622	8138		995.2	1627.6		2622.8			
Refrigerator		1	350		8760						3066			
Kettle		4	1000		311						311			
Projectors lecture th		4	1050		1244	7516		1306.2	7891.8		9198			
Projectors conferenc		2	1050		1244	7516		1306.2	7891.8		9198			
Vend		2	350	300	933	7827		326.55	2739.45		3066			
Lab equipment (ring		4	3450		1244						17167.2			
	Small power for PC/screen use 7 and 6 hours/day										347017.8		347017.8	
Servers														
Power of server		3							Annual kWh		17607.6		17607.6	
Ratio demand		0.67												
Hours		8760												

		Domestic HW use for CIBSE Guidance of 7 or 15 L/person												
Domestic hot water														
Daily hw consumption/person					L/person	7								
Number occupants						500								
Number occupants staff / summer students						100								
Days per year (semesters)						149								
Days per year staff/summer students					311-149	162								
Supply temp					^{0}C	65								
Return temp					^{0}C	55								
?t					^{0}C	10								
Specific heat capacity					kJ/kg^{0}C	4.2								
Volume of water consumed /y(			L/person * days			634900								
Mass of water consumed / year						634900								
Annual energy consumption						40739.42								40739.42
Other Equipment														
		Watts		Hours	Days									
Fume cupboards		1500	1	3	149			670.5					670.5	
													530457.3	40739.42

		Cherie Booth Building										
Lighting												
Pn				11101							**kWh E**	**kWg**
Fc				0.9				(Pn * Fc)		9990.9		
Fo				0.9				(td * Fo * Fd)		3204		
Fd				1				(tn * Fo)		714.825		
td				3560								
tn				794.25								
W1				?{(Pn * Fc) * [(td * Fo * Fd) + (tn * Fo)]}/1(				32011.56	kWh			
Wpc				5	kWh/m2		No daylight control at CB					
Wem				1	KWh/m2							
				1039								
Wpc				6234								
				Wp = ? (Wpc +W1)				38245.56	kWh		38245.56	
		Energy used at 300 and 500 starts/day										
Lift												
Operation	311											
Operation	4354											
Motor	8	kW		3695.8	kWh						3695.8	
Starts/day	300											
Start/year	93300											
Time	0.008	Hours										
Distance	12	m										
Standby	0.5	kW	2203									
Number	1											
Small Power												
	Number	Watts	Sleep Wat	Hours op	Hours slee	Op kWh	Sleep kWh		kWh			
Work stati	50	150	80	1244	7516	9330	30064		39394			
Screens	50	45	1	1244	7516	2799	375.8		3174.8			
Lap tops	50	42	27	1244	311	2612.4	419.85		3032.25			
photocopi	2	1100	300	1244	7516	2736.8	4509.6		7246.4			
printers	1	320	70	1244	7516	398.08	526.12		924.2			
Microwav	1	622	100	622	8138	386.884	813.8		1200.684			
Refrigerat	1	350		8760		18263.16	36709.17	54972.33	3066			
Plotter	1	1100		311					342.1			
Projector	1	1060		1354					1435.24			
	7 and 6 hours /day											
Accounting for teaching hours op hours becomes 4 hours/day							Annual kWh		59815.67		59815.67	
Servers												
Power of s	2						Annual kWh		11738.4		11738.4	
Ratio dem	0.67											
Hours	8760											

Domestic hot water	Domestic HW use for CIBSE Guidance of 7 or 15 L/person			
Daily hw consumption/person	L/person	15		
Number occupants		214		
Number occupants staff / summer students		107		
Days per year (semesters)		149		
Days per year staff/summer students	311-149	162		
Supply temp	^0C	65		
Return temp	^0C	55		
?t	^0C	10		
Specific heat capacity	kJ/kg^0C	4.2		
Volume of water cor	L/person * days	738300		
Mass of water consumed / year		738300		
Annual energy consumption		47374.25		47374.25
			113495.4	47374.25

Engineering Workshops

Lighting						
Pn	Total installed power in room/zone	7889				
Fc	Constant illuminance factor	0.9	(Pn * Fc)		(Pn * Fc)	7100.1
Fo	Occupancy dependency factor	1	(td * Fo * Fd)		(td * Fo * Fd)	3203.775
Fd	Daylight dependency factor	0.9	(tn * Fo)		(tn * Fo)	794.25
td	Daylight time usage	3559.75				
tn	Non-daylight time usage	794.25				
W1	Energy consumption for illumination	∑{(Pn * Fc) * [(td * Fo * Fd) + (tn * Fo)]}/1000			22747.92	kWh
Wpc	Default parasitic load	5	kWh/m2			
Wem	Default emergency load	1	KWh/m2			
	Floor area	1700				
Wpc	Default load * floor area	10200				
	Total lighting energy	Wp = ∑ (Wpc +W1)			32947.92	kWh

Lift rarely used

Lift						
Operational days	311					
Operational hours	4200					
Motor	11.7	kW		1140.351	kWh	1140.351
Starts/day	-60					
Start/year	60					
Time	0.002	Hours				
Distance	2	m				
Standby	0.25	kW	1140			
Number of lifts	1					

Small Power PC use 7, 6 and 5 hours/day

	Number	Watts	Sleep Wat	Hours op	Hours sleep	Op kWh	Sleep kWh	kWh
Work stations (PC's)	37	150	80	2177	6583	12082.35	19485.68	31568.03
Screens	37	45	1	2177	6583	3624.705	243.571	3868.276
photocopiers	1	1100	300	1244	7516	1368.4	2254.8	3623.2
printers	1	320	70	1244	7516	398.08	526.12	924.2
Microwave	2	800	100	622	8138	995.2	1627.6	2622.8
Refrigerator	2	350		8760				3066
Kettle	2	1000		311				311
Projectors conference	1	1050		1244	7516	1306.2	7891.8	9198
Vend	2	350	300	933	7827	326.55	2739.45	3066
								58247.51

Servers				
Power of server	kW	3	Annual kWh	17607.6
Ratio demand		0.67		
Hours		8760		

Domestic hot water

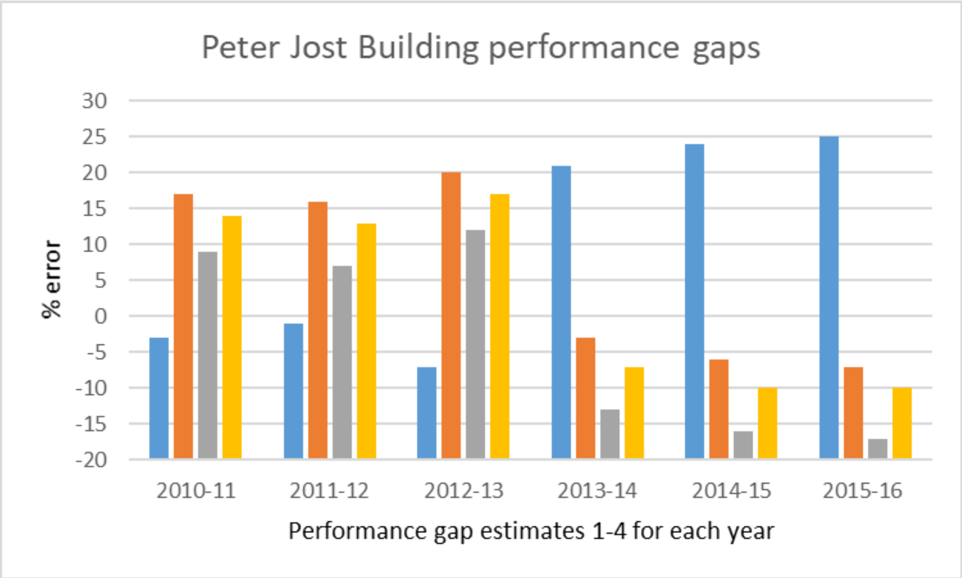
Domestic HW use for CIBSE Guidance of 7 or 15 L/person

Daily hw consumption/person	L/person	17
Number occupants (semesters)		63
Number occupants staff / summer students		20
Days per year (semesters)		149
Days per year staff/summer students	311-149	162
Supply temp	^{0}C	65
Return temp	^{0}C	55
Δt	^{0}C	10
Specific heat capacity	kJ/kg^{0}C	4.2
Volume of water consumed /year	L/person * days	214659
Mass of water consumed / year		214659
Annual energy consumption		13773.95

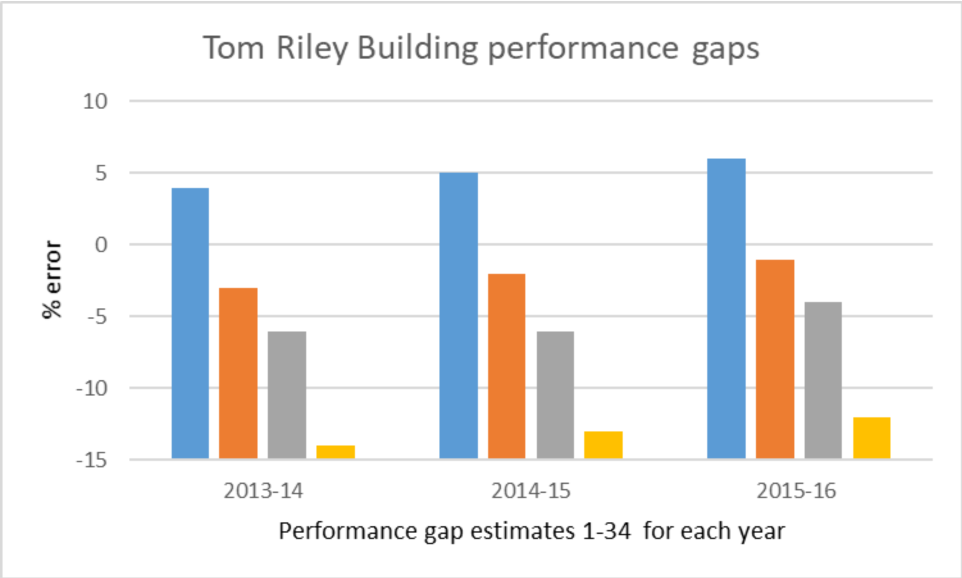
				Fume cupboard		4,3 or 2 hours/day									
				Workshops		6,5 or 4 hours/day									
				Labs		4,3 or 2 hours /day									
Other Equipment															
			Watts						1244						
Fume cupboard		2	1500	1244	3732		2488		1866						
Workshop 1		1	64325.56	1866	120031.5				1866						
Workshop 2		1	94927.04	1866	177133.9				1244						
Lab 1		1	49961.6	1244	62152.23				1244						
Lab 2		1	54957.76	1244	68367.45				1866						
Special Teaching		1	61827.48	1866	115370.1				311						
Toaster		1	1.5	311	0.4665				311						
Kettle		2	1.5	311	0.933				9952						
Hand drier		3	1.5	9952	44.784										
					546833.3									546833.3	
														656777	20558

Appendix CH4-2

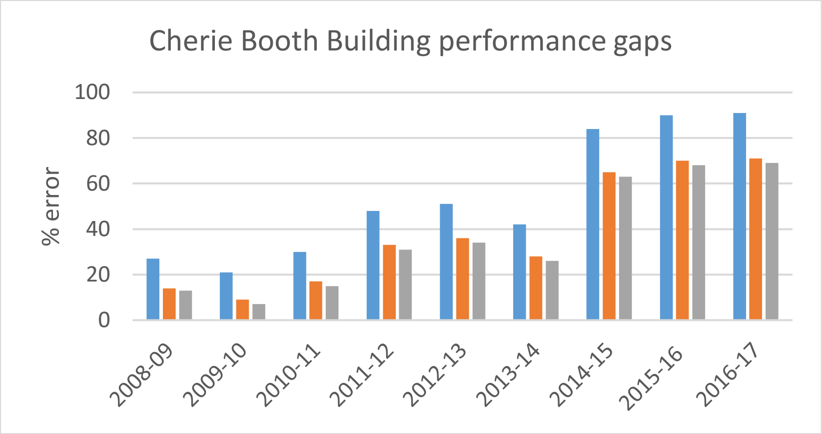
Graphical representation of percentage error between energy estimates and actual energy use.



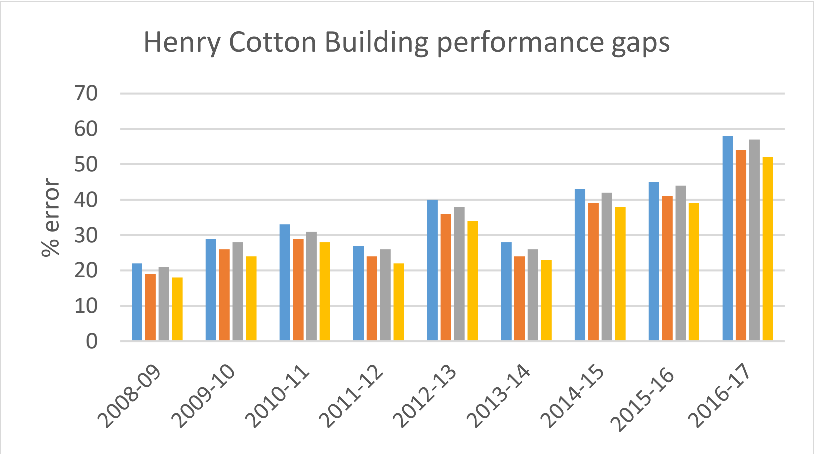
Estimates 1-4 Peter Jost Building (refer Table 4.18)



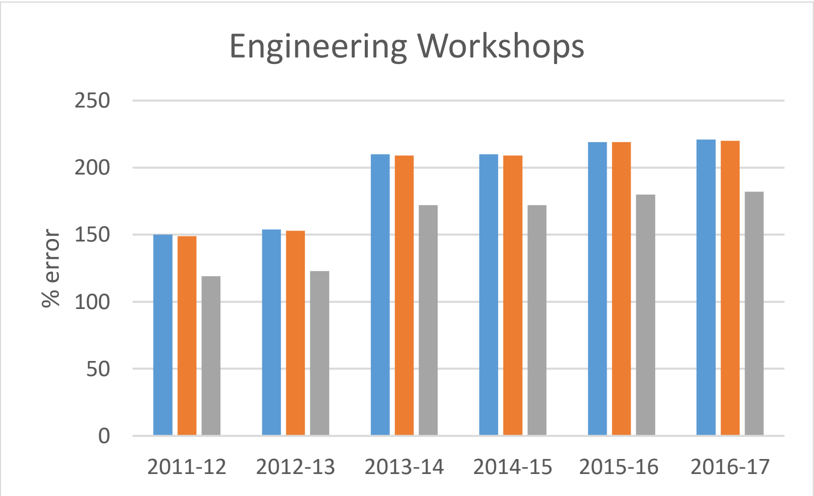
Estimates 1-4 Tom Reilly Building (refer Table 4.19)



Estimates 1-3 Cherie Booth Building (refer Table 4. 20)



Estimates 1-4 Henry Cotton Building (refer Table 4.21)



Estimates 1-4 Engineering Workshops (refer Table 4.22)

A breakdown of the various levels of the gaps between estimated and actual energy for the case study buildings reveals that this is a not a fixed value. Although the method applied in this study results in accuracies which are an improvement on typical values, absolute accuracy is unrealistic. Some correlation for weather related energy use (for example the degree day method) exists, but energy use related to occupant behaviour is much more difficult to estimate. This difficulty is clearly demonstrated by the performance gaps for the engineering workshops, where a greater proportion of overall energy use is related to occupant activities. For the Cherie Booth and Peter Jost buildings, the gap increases over the period under consideration. This may be related to improvements in control of weather related energy and therefore the occupant related energy becomes more significant

Appendix CH4-3

Cherie Booth Building Manual heat loss calculations

Ground floor					
Lecture Theatre			**m2**	**U**	**W**
		glass	5.224	2	287.32
		door 1	3	2.1994	32.991
		door 2	3	2.1994	32.991
		floor	156.25	0.25	976.5625
		Ceilng	156.25	2.2826	0
		Int wall N	29.25	1.9585	286.4306
		Int wall S	16.6	1.9585	162.5555
		Ex wall W	56.12	0.35	491.05
		Ex wall S	7.66	0.35	67.025
		Ex wall N	8.56	0.35	74.9
		Ex wall E	56.36	0.35	493.15
		Volume	625.017		30938.34
Fire escape		door 1	3	2.1994	32.991
		floor	25.45	0.25	159.0625
		Ex wall W	57.22	0.35	500.675
		Volume	70		288.75
		Floor	13.4	0.25	83.75
Lobby		Ex wall W	56	0.35	490
		glass E	16	2	880
		glass S	12	2	660
		glass W	52	2	2860
		Floor	12	0.25	75
		Volume	50		206.25
WC 1		Ex wall	21.6	0.35	189
		Int wall	19.8	1.9585	193.8915
		Door	1.8	2.1994	19.7946
		Floor	6.78	0.25	42.375
		Volume	27.12		1342.44
WC 2		Ex wall	6.88	0.35	60.2
		Int wall	5	1.9585	48.9625
		Door	1.8	2.1994	19.7946
		Floor	4.66	0.25	29.125
		Volume	18.64		922.68
WC lobby		Int wall	14.8	1.9585	144.929
		Floor	1.64	0.25	10.25
		Volume	6.56		27.06
Entrance		Ex wall	15.8	0.35	138.25
		Int wall	19.36	1.9585	189.5828
		Floor	9.6	0.25	60

		Volume	38.3		1895.85
					45413.98

First floor			m2	U	W
IT suite		glass E	21.5	2	1182.5
		glass S	1.753	2	96.415
		glass N	1.753	2	96.415
		door 1	3	2.1994	32.991
		door 2	3	2.1994	32.991
		floor	102.21	2.2826	0
		Ceilng	102.21	2.2826	0
		Int wall N	20.3	1.9585	198.7878
		Int wall S	25	1.9585	244.8125
		Ex wall W	28	0.35	245
		Ex wall E	14.65	0.35	128.1875
		Volume	286.18		1180.493
Fire escape		floor	28.45	0.2882	0
		Ex wall W	60.22	0.35	526.925
		Volume	120		495
offices	* 4	glass E	72	2	3960
		door	8	2.1994	87.976
		floor	54	2.2826	0
		Ceilng	54	2.2826	0
		Int wall W	38	1.9585	372.115
		Ex wall E	29.2	0.35	255.5
		Volume	151.4		624.525
Corridor		Ex wall W	157.14	0.35	1374.975
		Door	2	2.1994	21.994
		Floor	19.9	2.2826	0
		Ceiling	19.9	2.2826	0
		Volume	55.75		229.9688
Landing		Ex wall	38	0.35	332.5
		glass S	11.8	2	649
		Floor	24	2.2826	0
		Ceiling	24	2.2826	0
		Volume	88.57		365.3513
WC		Ex wall	24	0.35	210
		Floor	18.2	2.2826	0
		Ceiling	18.2	2.2826	0
		Door	2	2.1994	21.994
		Int wall	8	1.9585	78.34
		Volume	50.9		2519.55
					15564.31

2nd Floor			m2	U	W
offices	* 9	glass E	162	2	8910
		door	18	2.1994	197.946
		floor	121.5	2.2826	0
		Ceilng	121.5	2.2826	0
		Int wall W	85.5	2.1994	940.2435
		Ex wall E	65.7	0.35	574.875
		Volume	340.65		1405.181
Fire escape		floor	28.45	0.2882	0
		Ex wall W	60.22	0.35	526.925
		Volume	120		495
Landing		Ex wall	49.8	0.35	435.75
		Floor	24	2.2826	0
		Ceiling	24	2.2826	0
		Volume	88.57		182.6756
Tea Room		Ex wall	24	0.35	210
		Floor	18.2	2.2826	0
		Ceiling	18.2	2.2826	0
		Door	2	2.1994	21.994
		Int wall	8	2.1994	87.976
		Volume	50.9		251.955
Corridor		Ex Wall	69.57	0.35	608.7375
		Floor	48	2.2826	0
		Ceiling	48	2.2826	0
		Door 1	2	2.1994	21.994
		Door 2	2	2.1994	21.994
		Volume	134.47		554.6888
		Glass S	0.43	2	21.6
		Glass N	0.43	2	21.6
					15491.14

3rd Floor			m2	U	W
offices	*** 9**	glass E	162	2.2	8910
		door	18	2.1994	989.73
		floor	121.5	2.2826	0
		Ceilng	121.5	0.25	759.375
		Int wall W	85.5	1.9585	837.2588
		Ex wall E	65.7	0.35	574.875
		Volume	340.65		1405.181
Fire escape		floor	28.45	2.2826	0
		Ex wall W	60.22	0.35	526.925
		Volume	120		495
		roof	28.45	0.25	177.8125
Landing		Ex wall	49.8	0.35	435.75
		Floor	24	2.2826	0
		Ceiling	24	0.25	150
		Volume	88.57		365.3513
WC		Ex wall	24	0.35	210
		Floor	18.2	2.2826	0
		Ceiling	18.2	0.25	113.75
		Door	2	2.1994	21.994
		Int wall	8	1.9585	0
		Volume	50.9		2519.55
Corridor		Ext wall	79	0.35	691.25
		glass	59.4	2.2	3267
		Door 1	2	2.1994	21.994
		Door 2	2	2.1994	21.994
		Volume	139		573.375
		roof	29.73	0.25	185.8125
		Floor		2.2826	0
					23253.98

Henry Cotton Building: manual heat loss calculations

Ground floor		m2	U	W
Labs Civil	Ext wall	296.00	0.7	5177.55
	Floor	383.97	0.7	6719.4
	Volume	2057.98		67913.34
Lobby	Ext wall	11.30	0.7	198
	Floor	9.28	0.7	162.3375
	Volume	54.83		2714.085
	Door Glass	1.60	0.33	13.2
Stairs	Ext wall	13.40	0.7	233.7
	Floor	17.42	0.7	304.875
	Volume	103.00		849.75
Lobby	Floor	1.86	0.7	32.625
	Volume	10.87		89.6775
Office	Floor	32.79	0.7	573.75
	Int wall	61.00	1.95	594.75
	Volume	200.00		1650
Stairs	Ext wall	10.80	0.7	189
	Floor	17.42	0.7	304.875
	Volume	103.00		849.75
Store	Floor	7.79	0.7	136.35
	Volume	46.10		380.325
Corridor	Floor	97.71	0.7	1710
	Volume	578.00		4768.5
G19	Ext wall	27.00	0.7	472.5
	Floor	17.86	0.7	312.525
	Int wall	35.00	1.95	341.25
	Volume	105.56		3483.48
P Resear	Ext wall	48.50	0.7	849.6
	Glass	16.80	0.33	138.6
	Floor	284.09	0.7	4971.6
	Int wall	124.00	1.95	1209
	Volume	1332.70		10994.78
Inrt spaces	Floor	123.67	0.7	2164.275
	Volume	674.00		5560.5
	Int wall	74.80	1.95	729.3
Int Space	Ext wall	49.60	0.7	868.05
	Glass	8.93	0.33	73.6725
	Floor	176.92	0.7	3096.113
	Volume	1030.35		8500.388
WC	Ext wall	8.14	0.7	142.5

	Floor	32.53	0.7	569.25
	Volume	192.35		9521.325
Reception	Ext glass	15.80	0.33	130.35
	Floor	70.86	0.7	1239.975
	Volume	653.92		21579.36
Labs E	Ext wall	94.00	0.7	1643.4
	Glass	9.00	0.33	74.25
	Floor	139.17	0.7	2435.4
	Volume	616.96		20359.68
				197027

First floor		**m2**	**U**	**W**
Env Sc Lab	Ext wall	102	0.7	1777.245
	Glass	14.9348	3.3	1232.121
	Floor	110.6		0
	Int wall	21.6	1.95	210.6
	Volume	431.21		2845.986
	Door	2	2.2	110
1 teach	Ext wall	203	0.7	3555
	Glass	52.33	3.3	4317.225
	Floor	501.33		0
	Int wall	203.6	1.95	1985.1
	Door	16	2.2	176
	Volume	1915.46		15802.55
Lobby/sta	Volume	133		1097.25
1 Lecture	Ext wall	86	0.7	1500
	Glass	28	3.3	2310
	Floor	240.3		0
	Int wall	51.6	1.95	503.1
	Door	8	2.2	88
	Volume	913.12		7533.24
Teach 3	Ext wall	84	0.7	1467.6
	Glass	19.6	3.3	1617
	Floor	274.054		0
	Int wall	84	1.95	819
	Door	6	2.2	66
	Volume	1041.41		8591.633
Teach 4	Ext wall	88	0.7	1532.4
	Glass	30	3.3	2475
	Floor	123.14		0
	Int wall	58.18	1.95	567.255

	Door	10	2.2	110
	Volume	467.91		3860.258
Corridor	Volume	1117.017		9215.39
Lecture Theatre	Volume	354.76		17560.62
	Int wall	42.86	1.95	417.885
	Door	2	2.2	22
Lecture room	Volume	403.34		13310.22
	Int wall	32.06	1.95	312.585
	Door	2	2.2	22
Lobby/store	Volume	238.174		1964.936
Stairs	Volume	106.626		879.6645
Photocopier	Volume	52.28		431.31
Counselling	Int wall	20.28	1.95	197.73
	Volume	39.68		327.36
WC	Volume	208.003		10296.15
				121107.4

Second floor		**m2**	**U**	**W**
St Office	Ext wall	288.46	0.7	5047.98
	Glass	70.60	3.3	5824.5
	Int wall	163.54	1.95	1594.515
	Volume	2359.14		19462.91
	Door	12.00	2.2	132
	Roof	161.27	0.7	2822.175
Lobby/sta	Volume	266.00		2194.5
offices	Ext wall	65.50	0.7	1146
	Glass	39.60	3.3	3267
	Int wall	64.59	1.95	629.7525
	Volume	798.76		6589.77
	Door	2.00	2.2	22
	Roof	105.43	0.7	1845
Ark Room	int wall	52.58	1.95	512.655
	Door	2.00	2.2	22
	Volume	184.68		1523.61
Admin	Ext wall	13.40	0.7	234
	Glass	6.20	3.3	511.5
	Int Wall	26.20	1.95	255.45
	Volume	430.08		3548.193
	Roof	0.00	0.7	2385
WC	Ext wall	9.50	0.6	142.5
	Volume	198.06		9803.97

	Roof	0.00	0.7	825
Lecture theatre	Int wall	78.00	1.95	760.5
	Volume	846.98		6987.585
	Roof	0.00	0.7	1350
Meeting room	Int wall	53.10	1.95	517.725
	Volume	369.13		3045.323
Post roomInt wall		42.42	1.95	413.595
	Volume	109.70		905.025
Stair	Volume	146.68		1210.11
Corridor	Volume	1067.11		8803.658
				94335.5

Third floor		**m2**	**U**	**W**
Offices	Ext wall	122.40	0.7	2141.55
	Glass	12.90	3.3	1061.438
	Int wall	93.80	1.95	914.55
	Door	42.00	2.2	462
	Roof	379.12	0.7	6634.65
	Volume	1152.60		9508.95
Stairs	Ext wall	3.24	0.7	56.7
	Glass	0.45	3.3	37.125
	Roof	12.09	0.7	211.5
	Volume	54.91		453.0075
Stairs	Ext wall	3.24	0.7	56.7
	Glass	0.45	3.3	37.125
	Roof	12.09	0.7	211.5
	Volume	54.91		453.0075
Office	Ext wall	20.80	0.7	364.5
	Glass	2.40	0.45	199.125
	Int wall	20.98	1.95	204.555
	Door	6.00	2.2	66
	Roof	51.03	0.7	893.1
	Volume	173.06		1427.745
Office	Ext wall	9.50	0.7	165.45
	Glass	0.45	3.3	357.1875
	Int wall	43.70	1.95	426.075
	Door	16.00	2.2	176
	Roof	268.58	0.7	4700.1
	Volume	299.88		2474.043
Lobby	Ext wall	25.00	0.6	375

	Glass	21.00	0.45	236.25
	Roof	56.90	0.7	995.7
	Volume	211.25		1742.813
Offices	Ext wall	13.40	0.7	235.05
	Glass	5.10	3.3	414
	Int wall	55.50	1.95	541.125
	Door	14.00	2.2	154
	Roof	329.83	0.7	5772
	Volume	390.00		3217.5
Corridor	Roof	208.13	0.7	3642.3
	Volume	630.64		5202.78
WC	Roof	42.70	0.7	747.3
	Volume	129.79		6424.605
Office	Roof	18.86	0.7	330
	Volume	57.10		471.075
Post	Roof	49.71	0.7	870
	Volume	208.15		1717.238
				66782.42

Peter Jost Building: manual heat loss calculations

Ground floor			**m2**	**U**	**W**
Corridor		ExtGlazing	220	3.3	18150
		Ex door G	4.3	3.3	354.75
		Floor	92	0.45	1035
		Int wall	80.9	1.95	788.775
		Volume	363.43		5996.595
Stair		ExtGlazing	220	3.3	18150
		Ext wall	26.1	0.45	293.625
		Floor	126	0.45	1417.5
		Volume	330.8		2729.1
WC		Floor	8.19	0.45	92.1375
		Volume	34.4		1702.8
WC		Floor	11	0.45	123.75
		Volume	34.4		1702.8
Clean		Floor	5	0.45	56.25
		Volume	62		511.5
Lecture		ExtGlazing	28	3.3	2310
		Ext wall	120	0.45	1350
		Floor	1575	0.45	17718.75
		Int wall	105	1.95	1023.75
		Volume	6300		207900
					283407.1

First floor		m2	U	W
Stair 1	Ext wall	53.7	0.45	604.125
	Floor (int)	31.04		0
	Volume	125		1031.25
Conf	Ext wall	85.5	0.45	961.875
	Floor (int)	74.7		0
	Int wall	54	1.95	526.5
	Glass	12	3.3	990
	Vol	257		2120.25
WC	Ext wall	30.4	0.45	342
	Floor (int)	24.5		0
	Vol	85.8		4247.1
Offices	Ext wall	78.92	0.45	887.85
	glass	25	3.3	2062.5
	Floor (int)	80		0
	Vol	220		1815
Stair 3	Ext wall	53.7	0.45	604.125
	Floor	31.04	0.45	349.2
	Volume	118		973.5
Clean	Floor (int)	2.1		
	volume	6.6		54.45
Corridor	Floor	128.43	0.45	604.125
	Ext wall	7.22	0.45	604.125
	volume	488.02		4026.165
Offices	Floor	57.27	0.45	644.2875
	volume	198.63	0.45	1638.698
	Ext wall	44	0.45	495
	Int wall	36	1.95	351
	Glass	22	3.3	1815
	Roof	31.82	0.45	357.9375
Store	Ext wall	15.9	0.45	178.875
	Floor	31.7	0.45	356.625
	Glass	12	3.3	990
	Roof	18	0.45	200
	Volume	120.5		994.125
Lect	Ext wall	32.6	0.45	366.75
	Glass	16	3.3	1320
	Int wall	34	1.95	331.5
	Floor	288	0.45	3240
	Volume	885		29205
Kitchen	Floor	11.65	0.45	131.0625
	Volume	44.25		365.0625
Offices	Ext wall	68	0.45	765

	Glass	26	3.3	2145
	roof	72	0.25	806.25
	Floor	118	0.25	737.5
	Volume	355.42		2932.215
				73171.03

Second floor		**m2**	**U**	**W**
Stair 1	Ext wall	50.69	0.45	570.2625
	Roof	25	0.45	281.25
	Volume	77.56		639.87
Corridor	Roof	94	0.45	1062.5
	Volume	213.9		1764.675
Stair 1	Ext wall	50.69	0.45	570.2625
	Roof	25	0.45	281.25
	Volume	77.56		639.87
Offices	Ext wall	221	0.45	2486.25
	Roof	169.4	0.45	1906.25
	Glass	179	3.3	14767.5
	Wall int	85.4	1.95	832.65
	Volume	923		7614.75
				33417.34

Tom Reilly Building: manual heat loss calculations

Low Ground floor		**m2**	**U**	**W**
P Room	Ex Wall	55.6	0.35	486.5
	Floor	68.83	0.25	430.1875
	Ceiling	68.83		0
	Volume	275.3		7267.92
Lobby P	Ex Wall	18.4	0.35	161
	Floor	17.48	0.25	109.25
	Ceiling	17.48		0
	Volume	69.92		115.368
Gas Boiler	Ex Wall	35.2	0.35	308
	Floor	19	0.25	118.75
	Ceiling	19		0
	Volume	76		125.4
Stair 1	Ex Wall	2.4	0.35	21
	Floor	29.65	0.25	185.3125
	Volume	118.65		195.7725
Lobby 8	Floor	22.17	0.25	138.5625

	Ceiling	22.17		0
	Volume	88.6		146.19
Switch	Ex Wall	55.6	0.35	486.5
	Floor	68.3	0.25	426.875
	Ceiling	68.3		0
	volume	275.32		454.278
Lobby 6	Ex Wall	14	0.35	122.5
	Floor	9.1	0.25	56.875
	Ceiling	9.1		0
	volume	36.4		60.06
Move R	Floor	129	0.25	806.25
	Ceiling	129		0
	volume	129.8		5140.08
	Int wall	45.43	0.7	795.025
BM R	Floor	112	0.25	700
	Ceiling	112		0
	volume	448		17740.8
	Int wall	181	0.7	380.1
Store	Floor	20.6	0.25	128.75
	Ceiling	20.6		0
	volume	82.6		545.16
Store	Floor	7.7	0.25	48.125
	Ceiling	7.7		0
	volume	31		51.15
BM2	Floor	170	0.25	1062.5
	Ceiling	170		0
	volume	679		26888.4
	Int wall	104.2305	0.7	218.8841
Motor	Floor	144	0.25	900
	Ceiling	144		0
	volume	576		22809.6
	Int wall	96	0.7	201.6
Store	Floor	7.7	0.25	50.05
	Ceiling	7.7		0
	volume	31		51.15
Q Lab 1	Floor	12.4	0.25	50.05
	Ceiling	12.4		0
	volume	48		1900.8
Q Lab 2	Floor	12.4	0.25	77.5
	Ceiling	12.4		0
	volume	48		316.8
LG Ent	Ex Wall	26	0.35	227.5
	Floor	44	0.22	242
	Ceiling	44		0

	volume	177		7009.2
	glass	6	2.2	330
LG corr	Ex Wall	230	0.35	2012.5
	Floor	109	0.25	681.25
	Ceiling	109		0
	volume	871		1437.15
	glass	84	2.2	4620
LG lab	Floor	14	0.25	87.5
	Ceiling	14		0
	volume	55		2178
wc's	Floor	57	0.25	356.25
	Ceiling	57		0
	volume	228		9028.8
Bio R	Floor	189	0.25	1181.25
	Ceiling	189		0
	volume	750		29700
	Ex wall	48	0.35	420
Lobby.S	Floor	54	0.25	337.5
	Ceiling	54		0
	volume	215		354.75
Run T	Floor	245	0.25	1531.25
	Ceiling	245		0
	volume	979		1615.35
	Ex wall	336	0.35	2940
Lift Lobby	Floor	92	0.25	575
	Ceiling	92		0
	volume	366		603.9
WC	Floor	57	0.25	356.25
	Ceiling	57		0
	volume	228		9028.8
UG Lab	Floor	190	0.25	1187.5
	Ceiling	190		0
	volume	190		7524
	Ex wall	48	0.35	420
Stair 3	Floor	54	0.25	337.5
	Ceiling	54		0
	volume	217		358.05
	Ex wall	67	0.35	586.25
Corrridor	Floor	170	0.25	1062.5
	Ceiling	170		0
	volume	678		1118.7
UG shower	Floor			0
	Ceiling	47.6		0
	Floor	47.6	0.25	297.5

	volume	191		7563.6
	Ex wall	47.6	0.35	416.5
File Srve	Ceiling	23		0
	Floor	23	0.25	143.75
	volume	94		620.4
	Ex wall	25	0.35	218.75
LG Corr 1	Ceiling	263		0
	Floor	263	0.25	1643.75
	volume	1569		2588.85
	Ex wall	382	0.35	3342.5
	Ex Glass	172.5	2.2	9487.5
LG Corr 1	Ceiling	109		0
	Floor	109	0.25	681.25
	volume	871		1437.15
	Ex wall	230	0.35	2012.5
	Ex Glass	120	2.2	9487.5
				221669.3
Upper ground floor		m2	U	**W**
Lab 4	Ex wall	36	0.35	**63**
	Int wall	38	0.7	**133**
	Volume	59		**2920.5**
Stair	Ex Wall	2.4	0.35	**15.354**
	Volume	118.65		**195.7725**
Tech Supp	Ex wall	23	0.35	**201.25**
	Int wall	21	0.7	**73.5**
	Volume	87		**179.4375**
Tech Supp	Ex wall	23	0.35	**201.25**
	Int wall	21	0.7	**73.5**
	Volume	87		**179.4375**
Tech Supp	Ex wall	23	0.35	**201.25**
	Int wall	21	0.7	**73.5**
	Volume	87		**179.4375**
Tech Supp	Ex wall	23	0.35	**201.25**
	Int wall	21	0.7	**73.5**
	Volume	87		**179.4375**
Tech Supp	Ex wall	23	0.35	**201.25**
	Int wall	21	0.7	**73.5**
	Volume	87		**179.4375**
Tech Supp	Ex wall	23	0.35	**201.25**
	Int wall	21	0.7	**73.5**
	Volume	87		**179.4375**
Tech Supp	Ex wall	23	0.35	**201.25**
	Int wall	21	0.7	**73.5**
	Volume	87		**179.4375**

Shower	Ex wall	24	0.35	**210**
	Int wall	20	0.7	**70**
	Volume			**0**
Tech Supp	Ex wall	23	0.35	**201.25**
	Int wall	21	0.7	**73.5**
	Volume	87		**179.4375**
Stair	Ex Wall	2.4	0.35	**15.354**
	Volume	118.65		**195.7725**
Tech Store	Ex Wall	36.8	0.35	**322**
	Int	30	0.7	**105**
	Volume	63		**129.9375**
Corridor	Volume	679		**1400.438**
	Ex Wall	12.4	0.35	**108.5**
Lab FSCS	Ex wall	47.6	0.35	**2356.2**
	Int wall	49	0.7	**171.5**
WC	Volume	173		**8563.5**
Staff	Ex Wall	16	0.35	**140**
	Int	6	0.7	**21**
	Volume	55		**113.4375**
Corridor	Ex Wall	382	0.35	**3342.5**
	Ex glass	173		**0**
	Volume	1568		**3234**
Lift lobby	Volume	135		**278.4375**
Lab 5 *6	Int wall	120	0.7	**420**
	Volume	232		**7656**
UG Lobby	Volume	118		**1947**
Lab 7	Int wall	160	0.7	**560**
	Volume	588		**29106**
Lab 8	Int wall	70	0.7	**245**
	Volume	59		**2920.5**
Lab 9*10	Int wall	70	0.7	**245**
	Volume	59		**2920.5**
Lab 11*12	Int wall	70		**0**
	Volume	59		**2920.5**
Corridor	Volume	78		**160.875**
	Glass	25	2.2	**1375**
Lab 14	Ext wall	62	0.35	**542.5**
	Volume	48		**792**
Shower	Ext wall	7.6	0.35	**13.3**
	Volume	32		**1584**
LG cor voidGlass		280	2.2	11704
	Ex wall	16	0.35	106.4
	Volume	1120		1755.6
				94712.88

First floor			m2	U	W
mtg R2		Ex wall	24.1	0.35	210.875
In wall		In wall	6	0.7	21
Volume		Volume	96.4		4771.8
stair		ex wall	32	0.35	280
		volume	122		251.625
office 19		Ex wall	11	0.35	96.25
		In wall	5	0.7	17.5
		Volume	41		84.5625
		glass	5.3	2.2	291.5
office 20		Ex wall	12	0.35	105
		In wall	5	0.7	17.5
		Volume	46		94.875
		glass	5.3	2.2	291.5
office 21		Ex wall	12	0.35	105
		In wall	5	0.7	17.5
		Volume	46		94.875
		glass	5.3	2.2	291.5
office 22		Ex wall	12	0.35	105
		In wall	5	0.7	17.5
		Volume	46		94.875
		glass	5.3	2.2	291.5
office 23		Ex wall	12	0.35	105
		In wall	5	0.7	17.5
		Volume	46		94.875
		glass	5.3	2.2	291.5
office 24		Ex wall	12	0.35	105
		In wall	5	0.7	17.5
		Volume	46		94.875
		glass	5.3	2.2	291.5
office 25		Ex wall	12	0.35	105
		In wall	5	0.7	17.5
		Volume	46		94.875
		glass	5.3	2.2	291.5
office 26		Ex wall	12	0.35	105
		In wall	5	0.7	17.5
		Volume	46		94.875
		glass	5.3	2.2	291.5
office 27		Ex wall	12	0.35	105
		In wall	5	0.7	17.5
		Volume	46		94.875
		glass	5.3	2.2	291.5
office 28		Ex wall	12	0.35	105

		In wall	5	0.7	17.5
		Volume	46		94.875
		glass	5.3	2.2	291.5
office 29		Ex wall	12	0.35	105
		In wall	5	0.7	17.5
		Volume	46		94.875
		glass	5.3	2.2	291.5
office 30		Ex wall	12	0.35	105
		In wall	5	0.7	17.5
		Volume	46		94.875
		glass	5.3	2.2	291.5
office 31		Ex wall	24.4	0.35	42.7
		In wall	24	0.7	420
		Volume	95		195.9375
		glass	10.25	2.2	563.75
office 31		Ex wall	12	0.35	105
		In wall	5	0.7	17.5
		Volume	46		94.875
		glass	5.3	2.2	291.5
office 32		Ex wall	12	0.35	105
		In wall	5	0.7	17.5
		Volume	46		94.875
		glass	5.3	2.2	291.5
office 33		Ex wall	12	0.35	105
		In wall	5	0.7	17.5
		Volume	46		94.875
		glass	5.3	2.2	291.5
office 340		Ex wall	12	0.35	105
		In wall	10	0.7	20.625
		Volume	46		94.875
		glass	5.3	2.2	291.5
stair		ex wall	32	0.35	280
		volume	122		251.625
office 36		Ex wall	11	0.35	96.25
		In wall	5	0.7	17.5
		Volume	41		84.5625
		glass	5.3	2.2	291.5
office 36		Ex wall	12.4	0.35	108.5
		In wall	12	0.7	42
		Volume	55		113.4375
		glass	5.3	2.2	291.5
office 36		Ex wall	11	0.35	96.25
		In wall	11	0.7	38.5
		Volume	56		115.5

		glass	10.75	2.2	591.25
Corridor		Ex wall	81.4	0.35	712.25
		Volume	1557.68		3212.715
		Glass	25	2.2	1375
PG Room		Ex wall	29.2	0.35	255.5
		In wall	40	0.7	140
		Volume	181		373.3125
		glass	11	2.2	605
Read R		In wall	34	0.7	119
		Volume	152		5016
Office 12		In wall	9	0.7	31.5
		Volume	40.3		83.11875
Office 13		In wall	9	0.7	31.5
		Volume	40.3		1329.9
Office 14		In wall	9	0.7	31.5
		Volume	40.3		1329.9
Office 15		In wall	9	0.7	31.5
		Volume	40.3		1329.9
Office 16		In wall	9	0.7	31.5
		Volume	40.3		1329.9
Office 17		In wall	9	0.7	31.5
		Volume	40.3		1329.9
Office 18		In wall	9	0.7	31.5
		Volume	40.3		1329.9
Office 19		In wall	9	0.7	31.5
		Volume	40.3		1329.9
Shower		Volume	114		5643
Admin		Ex wall	12	0.35	21
		In wall	10	0.7	175
		Volume	53		109.3125
		glass	10	2.2	550
Staff		Ex wall	24	0.35	210
		In wall	22	0.7	77
		Volume	106		218.625
		glass	21.2	2.2	1166
Staff		Ex wall	12	0.35	105
		In wall	10	0.7	35
		Volume	53		109.3125
		glass	10	2.2	550
It Suite		Ex wall	24	0.35	210
		In wall	22	0.7	77
		Volume	341		16879.5
		glass	20	2.2	1100
IT Suite 2		Ex wall	24	0.35	210

		In wall	22	0.7	77
		Volume	341		16879.5
		glass	20	2.2	1100
Teach		Ex wall	24	0.35	210
		In wall	22	0.7	77
		Volume	341		16879.5
		glass	20	2.2	1100
Teach		Ex wall	24	0.35	210
		In wall	22	0.7	77
		Volume	341		16879.5
		glass	20	2.2	1100
Teach		Ex wall	90	0.35	787.5
		In wall	24	0.7	84
		Volume	471		23314.5
		glass	28	2.2	1540
					146516.6

Second floor		**m2**	**U**	**W**
Reception	Ex wall	52	0.35	455
	In wall	12	0.7	42
	Volume	115.2		237.6
	glass	16.5	2.2	907.5
Kitchen	Ex wall	14.4	0.35	126
	In wall	12	0.7	42
	Volume	67.7		2234.1
	glass	8	2.2	440
F lab 1	Ex wall	8	0.35	70
	In wall	6	0.7	21
	Volume	37.6		1240.8
	glass	1	2.2	55
F lab 2	Ex wall	8	0.35	70
	In wall	6	0.7	21
	Volume	37.6		1240.8
	glass	1	2.2	55
F lab 3	Ex wall	8	0.35	70
	In wall	6	0.7	21
	Volume	37.6		1240.8
	glass	1	2.2	55
F lab 4	Ex wall	8	0.35	70
	In wall	6	0.7	21
	Volume	37.6		1240.8
	glass	1	2.2	55
F lab 5	Ex wall	12	0.35	105

	In wall	7	0.7	24.5
	Volume	54.6		1801.8
	glass	5.25	2.2	288.75
F lab 6	Ex wall	12	0.35	105
	In wall	7	0.7	24.5
	Volume	54.6		1801.8
	glass	5.25	2.2	288.75
F lab 7	Ex wall	12	0.35	105
	In wall	7	0.7	24.5
	Volume	54.6		1801.8
	glass	5.25	2.2	288.75
Prep room	Ex wall	12	0.35	105
	In wall	7	0.7	24.5
	Volume	54.6		1801.8
	glass	5.25	2.2	288.75
F lab 8	Ex wall	52.8	0.35	462
	In wall	16	0.7	56
	Volume	150.6		4969.8
	glass	19.5	2.2	1072.5
F lab 9	Ex wall	29.1	0.35	254.625
	In wall	14	0.7	49
	Volume	181.4		5986.2
	glass	11	2.2	605
F lab 16	Ex wall	41.6	0.35	364
	In wall	12	0.7	42
	Volume	104.6		3451.8
	glass	16	2.2	880
Office 6	Ex wall	17.6	0.35	154
	In wall	8	0.7	28
	Volume	53.4		1762.2
	glass	5.25	2.2	288.75
stair	ex wall	32	0.35	280
	volume	122		251.625
office 5	Ex wall	12	0.35	105
	In wall	5	0.7	17.5
	Volume	46		1518
	glass	5.3	2.2	291.5
office 4	Ex wall	12	0.35	105
	In wall	5	0.7	17.5
	Volume	46		1518
	glass	5.3	2.2	291.5
office 3	Ex wall	12	0.35	105
	In wall	5	0.7	17.5
	Volume	46		1518

	glass	5.3	2.2	291.5
office 2	Ex wall	12	0.35	105
	In wall	5	0.7	17.5
	Volume	46		1518
	glass	5.3	2.2	291.5
Office 6	Ex wall	17.6	0.35	154
	In wall	8	0.7	28
	Volume	53.4		1762.2
	glass	5.25	2.2	288.75
Lift lobby	Volume	154.8		319.275
	Glass	25	2.2	1375
Corridor	Ex wall	11.5	0.35	100.625
	Volume	691.14		1425.476
WC	Volume	107.64		3552.12
Interview	Volume	35.2		1742.4
Interview	Volume	35.2		1742.4
Interview	Volume	35.2		1742.4
Interview	Volume	35.2		1742.4
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Interview	Volume	35.2		1742.4
Interview	Volume	35.2		1742.4
Interview	Volume	35.2		1742.4
Interview	Volume	35.2		1742.4
				74026.55

Third floor		**m2**	**U**	**W**
office 14	Ex wall	38	0.35	332.5
	In wall	10	0.7	42
	roof	22.6	0.25	141.25
	Volume	90.7		2993.1
	glass	5.25	2.2	288.75
office 15	Ex wall	12.4	0.35	108.5
	In wall	10	0.7	42
	roof	11.64	0.25	72.75
	Volume	45.56		1503.48
	glass	5.25	2.2	288.75
office 15	Ex wall	12.4	0.35	108.5
	In wall	10	0.7	42
	roof	11.64	0.25	72.75
	Volume	45.56		1503.48
	glass	5.25	2.2	288.75
office 15	Ex wall	12.4	0.35	108.5

	In wall	10	0.7	42
	roof	11.64	0.25	72.75
	Volume	45.56		1503.48
	glass	5.25	2.2	288.75
office 15	Ex wall	12.4	0.35	108.5
	In wall	14	0.7	58.8
	roof	11.64	0.25	72.75
	Volume	45.56		1503.48
	glass	5.25	2.2	288.75
stair	ex wall	32	0.35	280
	volume	122	0.7	4026
	Roof	29.7	6	4455
office 15	Ex wall	17.6	0.35	154
	In wall	14	0.7	58.8
	roof	14	0.25	87.5
	Volume	55.92		1845.36
	glass	5.25	2.2	288.75
office 15	Ex wall	12.4	0.35	108.5
	In wall	10	0.7	42
	roof	11.64	0.25	72.75
	Volume	45.56		1503.48
	glass	5.25	2.2	288.75
office 15	Ex wall	12.4	0.35	108.5
	In wall	10	0.7	42
	roof	11.64	0.25	72.75
	Volume	45.56		1503.48
	glass	10.7	2.2	588.5
office 15	Ex wall	12.4	0.35	108.5
	In wall	10	0.7	42
	roof	11.64	0.25	72.75
	Volume	45.56		1503.48
	glass	10.7	2.2	588.5
office 15	Ex wall	12.4	0.35	108.5
	In wall	14	0.7	58.8
	roof	11.64	0.25	72.75
	Volume	45.56		1503.48
	glass	5.25	2.2	288.75
office 15	Ex wall	12.4	0.35	108.5
	In wall	14	0.7	58.8
	roof	11.64	0.25	72.75
	Volume	45.56		1503.48
	glass	5.25	2.2	288.75
office 15	Ex wall	12.4	0.36	111.6
	In wall	14	0.7	58.8

	roof	11.64	0.25	72.75
	Volume	45.56		1503.48
	glass	5.25	2.2	288.75
office 15	Ex wall	12.4	0.2559	79.329
	In wall	14	0.7	58.8
	roof	11.64	0.25	72.75
	Volume	45.56		1503.48
	glass	5.25	2.2	288.75
office 15	Ex wall	12.4	0.2559	79.329
	In wall	14	0.7	58.8
	roof	11.64	0.25	72.75
	Volume	45.56		1503.48
	glass	5.25	2.2	288.75
office 15	Ex wall	12.4	0.2559	79.329
	In wall	14	0.7	58.8
	roof	11.64	0.25	72.75
	Volume	45.56		1503.48
	glass	5.25	2.2	288.75
office 15	Ex wall	12.4	0.2559	79.329
	In wall	14	0.35	29.4
	roof	11.64	0.25	72.75
	Volume	45.56		1503.48
	glass	5.25	2.2	288.75
office 15	Ex wall	12.4	0.2559	79.329
	In wall	14	0.35	29.4
	roof	11.64	0.25	72.75
	Volume	45.56		1503.48
	glass	5.25	2.2	288.75
office 15	Ex wall	12.4	0.35	108.5
	In wall	14	0.7	58.8
	roof	11.64	0.25	72.75
	Volume	45.56		1503.48
	glass	5.25	2.2	288.75
P Grad	Ex wall	29.2	0.35	255.5
	In wall	64	0.7	268.8
	roof	86.87	0.25	542.9375
	Volume	347.48		11466.84
	glass	11	2.2	605
office 15	roof	16.9	0.25	105.625
	Volume	67.68		3350.16
Tech Support	roof	43.8	0.25	273.75
	Volume	175.2		8672.4
Lab	roof	17.4	0.25	108.75
	Volume	69.56		3443.22

WC	roof	38.47	0.25	240.4375
	Volume	114		5643
Lockers	roof	16.1	0.25	100.625
	Volume	64.24		3179.88
Lift L +Cor	roof	88.4	0.25	552.5
	Volume	353.8		729.7125
	Glass	24	2.2	1320
Corridor	roof	146	0.25	912.5
	Ex wall	17.6	0.35	154
	volume	620.2		1279.163
				91011.44

Appendix CH4-4

Annual heating energy use: average temperature method

Algorithm:

$$Daily\ building\ heat\ load = \ design\ day\ heat\ loss * \frac{actual\ \Delta t}{design\ \Delta t} * operational\ time$$

Annual heating energy use: Bin method

Algorithm:

$$Q = \frac{H_T\ t_b\ \Sigma f\mathrm{b}\ (\ \Theta_{base} - \ \Theta_{bin})}{\eta * 100}$$

Where

$Q = heating\ energy$ (kWh)

$H_T = total\ heat\ loss\ coefficient\ (W.K^{-1})$

$t_b = total\ time\ in\ calculation\ period\ (hours)$

$f_b = \ \ frequency\ of\ occurrance\ of\ temperature\ in\ each\ bin$ (%)

Θ_{base} = baseline temperature of the building ($^0\ C$)

Θ_{base} = mean temperature of bin ($^0\ C$)

$\eta = boiler\ efficiency$

Results:

Cherie Booth									
		Min	Max	Av	Design Δt	Actual Δt	Design Los	Actual los	KWh/day
Nov	1	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
	2	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
	5	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
	6	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
	7	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
	8	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
	9	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
	12	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
	13	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
	14	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
	15	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
	16	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
	19	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
	20	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
	21	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
	22	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
	23	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
	26	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
	27	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
	28	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
	29	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
	30	10.5	15.1	12.8	25	8.2	109.6957	35.98019	431.7623
Dec	3	9.4	13.8	11.6	25	9.4	109.6957	41.24558	494.947
	4	9.4	13.8	11.6	25	9.4	109.6957	41.24558	494.947
	5	9.4	13.8	11.6	25	9.4	109.6957	41.24558	494.947
	6	9.4	13.8	11.6	25	9.4	109.6957	41.24558	494.947
Jan	7	9.4	13.8	11.6	25	9.4	109.6957	41.24558	494.947
Jan	10	9.4	13.8	11.6	25	9.4	109.6957	41.24558	494.947
	11	9.4	13.8	11.6	25	9.4	109.6957	41.24558	494.947
	12	9.4	13.8	11.6	25	9.4	109.6957	41.24558	494.947
	13	9.4	13.8	11.6	25	9.4	109.6957	41.24558	494.947
	14	9.4	13.8	11.6	25	9.4	109.6957	41.24558	494.947

	8	8.6	13.1	10.85	25	10.15	109.6957	44.53645	534.4375
	9	8.6	13.1	10.85	25	10.15	109.6957	44.53645	534.4375
	10	8.6	13.1	10.85	25	10.15	109.6957	44.53645	534.4375
	11	8.6	13.1	10.85	25	10.15	109.6957	44.53645	534.4375
	14	8.6	13.1	10.85	25	10.15	109.6957	44.53645	534.4375
	1	8.6	13.1	10.85	25	10.15	109.6957	44.53645	534.4375
	5	8.6	13.1	10.85	25	10.15	109.6957	44.53645	534.4375
	16	8.6	13.1	10.85	25	10.15	109.6957	44.53645	534.4375
	17	8.6	13.1	10.85	25	10.15	109.6957	44.53645	534.4375
	21	8.6	13.1	10.85	25	10.15	109.6957	44.53645	534.4375
	22	8.6	13.1	10.85	25	10.15	109.6957	44.53645	534.4375
	23	8.6	13.1	10.85	25	10.15	109.6957	44.53645	534.4375
	24	8.6	13.1	10.85	25	10.15	109.6957	44.53645	534.4375
	25	8.6	13.1	10.85	25	10.15	109.6957	44.53645	534.4375
	28	8.6	13.1	10.85	25	10.15	109.6957	44.53645	534.4375
	29	8.6	13.1	10.85	25	10.15	109.6957	44.53645	534.4375
	20	8.6	13.1	10.85	25	10.15	109.6957	44.53645	534.4375
	31	8.6	13.1	10.85	25	10.15	109.6957	44.53645	534.4375
Feb	1	8.1	13.2	10.65	25	10.35	109.6957	45.41402	544.9682
	4	8.1	13.2	10.65	25	10.35	109.6957	45.41402	544.9682
	5	8.1	13.2	10.65	25	10.35	109.6957	45.41402	544.9682
	6	8.1	13.2	10.65	25	10.35	109.6957	45.41402	544.9682
	7	8.1	13.2	10.65	25	10.35	109.6957	45.41402	544.9682
	8	8.1	13.2	10.65	25	10.35	109.6957	45.41402	544.9682
	11	8.1	13.2	10.65	25	10.35	109.6957	45.41402	544.9682
	12	8.1	13.2	10.65	25	10.35	109.6957	45.41402	544.9682
	13	8.1	13.2	10.65	25	10.35	109.6957	45.41402	544.9682
	14	8.1	13.2	10.65	25	10.35	109.6957	45.41402	544.9682
	15	8.1	13.2	10.65	25	10.35	109.6957	45.41402	544.9682
	18	8.1	13.2	10.65	25	10.35	109.6957	45.41402	544.9682
	19	8.1	13.2	10.65	25	10.35	109.6957	45.41402	544.9682
	20	8.1	13.2	10.65	25	10.35	109.6957	45.41402	544.9682
	21	8.1	13.2	10.65	25	10.35	109.6957	45.41402	544.9682
	22	8.1	13.2	10.65	25	10.35	109.6957	45.41402	544.9682
	25	8.1	13.2	10.65	25	10.35	109.6957	45.41402	544.9682
	26	8.1	13.2	10.65	25	10.35	109.6957	45.41402	544.9682
	27	8.1	13.2	10.65	25	10.35	109.6957	45.41402	544.9682
	28	8.1	13.2	10.65	25	10.35	109.6957	45.41402	544.9682

March	1	9.4	15.2	12.3	25	8.7	109.6957	38.1741	458.0892
	4	9.4	15.2	12.3	25	8.7	109.6957	38.1741	458.0892
	5	9.4	15.2	12.3	25	8.7	109.6957	38.1741	458.0892
	6	9.4	15.2	12.3	25	8.7	109.6957	38.1741	458.0892
	7	9.4	15.2	12.3	25	8.7	109.6957	38.1741	458.0892
	8	9.4	15.2	12.3	25	8.7	109.6957	38.1741	458.0892
	11	9.4	15.2	12.3	25	8.7	109.6957	38.1741	458.0892
	12	9.4	15.2	12.3	25	8.7	109.6957	38.1741	458.0892
	13	9.4	15.2	12.3	25	8.7	109.6957	38.1741	458.0892
	14	9.4	15.2	12.3	25	8.7	109.6957	38.1741	458.0892
	15	9.4	15.2	12.3	25	8.7	109.6957	38.1741	458.0892
	18	9.4	15.2	12.3	25	8.7	109.6957	38.1741	458.0892
	19	9.4	15.2	12.3	25	8.7	109.6957	38.1741	458.0892
	20	9.4	15.2	12.3	25	8.7	109.6957	38.1741	458.0892
	21	9.4	15.2	12.3	25	8.7	109.6957	38.1741	458.0892
	22	9.4	15.2	12.3	25	8.7	109.6957	38.1741	458.0892
	25	9.4	15.2	12.3	25	8.7	109.6957	38.1741	458.0892
	26	9.4	15.2	12.3	25	8.7	109.6957	38.1741	458.0892
	27	9.4	15.2	12.3	25	8.7	109.6957	38.1741	458.0892
	28	9.4	15.2	12.3	25	8.7	109.6957	38.1741	458.0892
	29	9.4	15.2	12.3	25	8.7	109.6957	38.1741	458.0892
									45121.79

	Henry Cotton								
		Min	Max	Av	Design Δt	Actual Δt	Design Lo:	Actual los	KWh/day
Nov	1	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
	2	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
	5	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
	6	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
	7	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
	8	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
	9	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
	12	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
	13	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
	14	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
	15	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
	16	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
	19	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
	20	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
	21	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
	22	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
	23	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
	26	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
	27	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
	28	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
	29	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
	30	10.5	15.1	12.8	25	8.2	527.178	172.9144	2074.973
Dec	3	9.4	13.8	11.6	25	9.4	527.178	198.2189	2378.627
	4	9.4	13.8	11.6	25	9.4	527.178	198.2189	2378.627
	5	9.4	13.8	11.6	25	9.4	527.178	198.2189	2378.627
	6	9.4	13.8	11.6	25	9.4	527.178	198.2189	2378.627
	7	9.4	13.8	11.6	25	9.4	527.178	198.2189	2378.627
	10	9.4	13.8	11.6	25	9.4	527.178	198.2189	2378.627
	11	9.4	13.8	11.6	25	9.4	527.178	198.2189	2378.627
	12	9.4	13.8	11.6	25	9.4	527.178	198.2189	2378.627
	13	9.4	13.8	11.6	25	9.4	527.178	198.2189	2378.627
	14	9.4	13.8	11.6	25	9.4	527.178	198.2189	2378.627

Jan	7	8.6	13.1	10.85	25	10.15	527.178	214.0343	2568.411
	8	8.6	13.1	10.85	25	10.15	527.178	214.0343	2568.411
	9	8.6	13.1	10.85	25	10.15	527.178	214.0343	2568.411
	10	8.6	13.1	10.85	25	10.15	527.178	214.0343	2568.411
	11	8.6	13.1	10.85	25	10.15	527.178	214.0343	2568.411
	14	8.6	13.1	10.85	25	10.15	527.178	214.0343	2568.411
	1	8.6	13.1	10.85	25	10.15	527.178	214.0343	2568.411
	5	8.6	13.1	10.85	25	10.15	527.178	214.0343	2568.411
	16	8.6	13.1	10.85	25	10.15	527.178	214.0343	2568.411
	17	8.6	13.1	10.85	25	10.15	527.178	214.0343	2568.411
	21	8.6	13.1	10.85	25	10.15	527.178	214.0343	2568.411
	22	8.6	13.1	10.85	25	10.15	527.178	214.0343	2568.411
	23	8.6	13.1	10.85	25	10.15	527.178	214.0343	2568.411
	24	8.6	13.1	10.85	25	10.15	527.178	214.0343	2568.411
	25	8.6	13.1	10.85	25	10.15	527.178	214.0343	2568.411
	28	8.6	13.1	10.85	25	10.15	527.178	214.0343	2568.411
	29	8.6	13.1	10.85	25	10.15	527.178	214.0343	2568.411
	20	8.6	13.1	10.85	25	10.15	527.178	214.0343	2568.411
	31	8.6	13.1	10.85	25	10.15	527.178	214.0343	2568.411
Feb	1	8.1	13.2	10.65	25	10.35	527.178	218.2517	2619.02
	4	8.1	13.2	10.65	25	10.35	527.178	218.2517	2619.02
	5	8.1	13.2	10.65	25	10.35	527.178	218.2517	2619.02
	6	8.1	13.2	10.65	25	10.35	527.178	218.2517	2619.02
	7	8.1	13.2	10.65	25	10.35	527.178	218.2517	2619.02
	8	8.1	13.2	10.65	25	10.35	527.178	218.2517	2619.02
	11	8.1	13.2	10.65	25	10.35	527.178	218.2517	2619.02
	12	8.1	13.2	10.65	25	10.35	527.178	218.2517	2619.02
	13	8.1	13.2	10.65	25	10.35	527.178	218.2517	2619.02
	14	8.1	13.2	10.65	25	10.35	527.178	218.2517	2619.02
	15	8.1	13.2	10.65	25	10.35	527.178	218.2517	2619.02
	18	8.1	13.2	10.65	25	10.35	527.178	218.2517	2619.02
	19	8.1	13.2	10.65	25	10.35	527.178	218.2517	2619.02
	20	8.1	13.2	10.65	25	10.35	527.178	218.2517	2619.02
	21	8.1	13.2	10.65	25	10.35	527.178	218.2517	2619.02
	22	8.1	13.2	10.65	25	10.35	527.178	218.2517	2619.02
	25	8.1	13.2	10.65	25	10.35	527.178	218.2517	2619.02
	26	8.1	13.2	10.65	25	10.35	527.178	218.2517	2619.02
	27	8.1	13.2	10.65	25	10.35	527.178	218.2517	2619.02
	28	8.1	13.2	10.65	25	10.35	527.178	218.2517	2619.02

March	1	9.4	15.2	12.3	25	8.7	527.178	183.4579	2201.495
	4	9.4	15.2	12.3	25	8.7	527.178	183.4579	2201.495
	5	9.4	15.2	12.3	25	8.7	527.178	183.4579	2201.495
	6	9.4	15.2	12.3	25	8.7	527.178	183.4579	2201.495
	7	9.4	15.2	12.3	25	8.7	527.178	183.4579	2201.495
	8	9.4	15.2	12.3	25	8.7	527.178	183.4579	2201.495
	11	9.4	15.2	12.3	25	8.7	527.178	183.4579	2201.495
	12	9.4	15.2	12.3	25	8.7	527.178	183.4579	2201.495
	13	9.4	15.2	12.3	25	8.7	527.178	183.4579	2201.495
	14	9.4	15.2	12.3	25	8.7	527.178	183.4579	2201.495
	15	9.4	15.2	12.3	25	8.7	527.178	183.4579	2201.495
	18	9.4	15.2	12.3	25	8.7	527.178	183.4579	2201.495
	19	9.4	15.2	12.3	25	8.7	527.178	183.4579	2201.495
	20	9.4	15.2	12.3	25	8.7	527.178	183.4579	2201.495
	21	9.4	15.2	12.3	25	8.7	527.178	183.4579	2201.495
	22	9.4	15.2	12.3	25	8.7	527.178	183.4579	2201.495
	25	9.4	15.2	12.3	25	8.7	527.178	183.4579	2201.495
	26	9.4	15.2	12.3	25	8.7	527.178	183.4579	2201.495
	27	9.4	15.2	12.3	25	8.7	527.178	183.4579	2201.495
	28	9.4	15.2	12.3	25	8.7	527.178	183.4579	2201.495
	29	9.4	15.2	12.3	25	8.7	527.178	183.4579	2201.495
									216847.3

					Peter Jost				
		Min	Max	Av	Design Δt	Actual Δt	Design Los	Actual los	KWh/day
Nov	1	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
	2	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
	5	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
	6	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
	7	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
	8	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
	9	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
	12	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
	13	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
	14	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
	15	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
	16	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
	19	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
	20	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
	21	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
	22	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
	23	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
	26	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
	27	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
	28	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
	29	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
	30	10.5	15.1	12.8	25	8.2	429	140.712	1688.544
Dec	3	9.4	13.8	11.6	25	9.4	429	161.304	1935.648
	4	9.4	13.8	11.6	25	9.4	429	161.304	1935.648
	5	9.4	13.8	11.6	25	9.4	429	161.304	1935.648
	6	9.4	13.8	11.6	25	9.4	429	161.304	1935.648
	7	9.4	13.8	11.6	25	9.4	429	161.304	1935.648
	10	9.4	13.8	11.6	25	9.4	429	161.304	1935.648
	11	9.4	13.8	11.6	25	9.4	429	161.304	1935.648
	12	9.4	13.8	11.6	25	9.4	429	161.304	1935.648
	13	9.4	13.8	11.6	25	9.4	429	161.304	1935.648
	14	9.4	13.8	11.6	25	9.4	429	161.304	1935.648

Jan	7	8.6	13.1	10.9	25	10.15	429	174.174	2090.088
	8	8.6	13.1	10.9	25	10.15	429	174.174	2090.088
	9	8.6	13.1	10.9	25	10.15	429	174.174	2090.088
	10	8.6	13.1	10.9	25	10.15	429	174.174	2090.088
	11	8.6	13.1	10.9	25	10.15	429	174.174	2090.088
	14	8.6	13.1	10.9	25	10.15	429	174.174	2090.088
	1	8.6	13.1	10.9	25	10.15	429	174.174	2090.088
	5	8.6	13.1	10.9	25	10.15	429	174.174	2090.088
	16	8.6	13.1	10.9	25	10.15	429	174.174	2090.088
	17	8.6	13.1	10.9	25	10.15	429	174.174	2090.088
	21	8.6	13.1	10.9	25	10.15	429	174.174	2090.088
	22	8.6	13.1	10.9	25	10.15	429	174.174	2090.088
	23	8.6	13.1	10.9	25	10.15	429	174.174	2090.088
	24	8.6	13.1	10.9	25	10.15	429	174.174	2090.088
	25	8.6	13.1	10.9	25	10.15	429	174.174	2090.088
	28	8.6	13.1	10.9	25	10.15	429	174.174	2090.088
	29	8.6	13.1	10.9	25	10.15	429	174.174	2090.088
	20	8.6	13.1	10.9	25	10.15	429	174.174	2090.088
	31	8.6	13.1	10.9	25	10.15	429	174.174	2090.088
Feb	1	8.1	13.2	10.7	25	10.35	429	177.606	2131.272
	4	8.1	13.2	10.7	25	10.35	429	177.606	2131.272
	5	8.1	13.2	10.7	25	10.35	429	177.606	2131.272
	6	8.1	13.2	10.7	25	10.35	429	177.606	2131.272
	7	8.1	13.2	10.7	25	10.35	429	177.606	2131.272
	8	8.1	13.2	10.7	25	10.35	429	177.606	2131.272
	11	8.1	13.2	10.7	25	10.35	429	177.606	2131.272
	12	8.1	13.2	10.7	25	10.35	429	177.606	2131.272
	13	8.1	13.2	10.7	25	10.35	429	177.606	2131.272
	14	8.1	13.2	10.7	25	10.35	429	177.606	2131.272
	15	8.1	13.2	10.7	25	10.35	429	177.606	2131.272
	18	8.1	13.2	10.7	25	10.35	429	177.606	2131.272
	19	8.1	13.2	10.7	25	10.35	429	177.606	2131.272
	20	8.1	13.2	10.7	25	10.35	429	177.606	2131.272
	21	8.1	13.2	10.7	25	10.35	429	177.606	2131.272
	22	8.1	13.2	10.7	25	10.35	429	177.606	2131.272
	25	8.1	13.2	10.7	25	10.35	429	177.606	2131.272
	26	8.1	13.2	10.7	25	10.35	429	177.606	2131.272
	27	8.1	13.2	10.7	25	10.35	429	177.606	2131.272
	28	8.1	13.2	10.7	25	10.35	429	177.606	2131.272

March	1	9.4	15.2	12.3	25	8.7	429	149.292	1791.504
	4	9.4	15.2	12.3	25	8.7	429	149.292	1791.504
	5	9.4	15.2	12.3	25	8.7	429	149.292	1791.504
	6	9.4	15.2	12.3	25	8.7	429	149.292	1791.504
	7	9.4	15.2	12.3	25	8.7	429	149.292	1791.504
	8	9.4	15.2	12.3	25	8.7	429	149.292	1791.504
	11	9.4	15.2	12.3	25	8.7	429	149.292	1791.504
	12	9.4	15.2	12.3	25	8.7	429	149.292	1791.504
	13	9.4	15.2	12.3	25	8.7	429	149.292	1791.504
	14	9.4	15.2	12.3	25	8.7	429	149.292	1791.504
	15	9.4	15.2	12.3	25	8.7	429	149.292	1791.504
	18	9.4	15.2	12.3	25	8.7	429	149.292	1791.504
	19	9.4	15.2	12.3	25	8.7	429	149.292	1791.504
	20	9.4	15.2	12.3	25	8.7	429	149.292	1791.504
	21	9.4	15.2	12.3	25	8.7	429	149.292	1791.504
	22	9.4	15.2	12.3	25	8.7	429	149.292	1791.504
	25	9.4	15.2	12.3	25	8.7	429	149.292	1791.504
	26	9.4	15.2	12.3	25	8.7	429	149.292	1791.504
	27	9.4	15.2	12.3	25	8.7	429	149.292	1791.504
	28	9.4	15.2	12.3	25	8.7	429	149.292	1791.504
	29	9.4	15.2	12.3	25	8.7	429	149.292	1791.504
									176463.1

					Tom Riley				
		Min	Max	Av	Design Δt	Actual Δt	Design Los	Actual los	KWh/day
Nov	1	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	2	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	3	Sat			25	8.2	690.73	323.736	1942.416
	5	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	6	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	7	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	8	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	9	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	10	Sat			25	8.2	690.73	323.736	1942.416
	12	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	13	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	14	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	15	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	16	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	17	Sat			25		690.73	323.736	1942.416
	19	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	20	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	21	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	22	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	23	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	24	Sat			25		690.73	323.736	1942.416
	26	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	27	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	28	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	29	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	30	10.5	15.1	12.8	25	8.2	690.73	226.5594	2718.713
	1	Sat			25		690.73	371.112	2226.672
Dec	3	9.4	13.8	11.6	25	9.4	690.73	259.7145	3116.574
	4	9.4	13.8	11.6	25	9.4	690.73	259.7145	3116.574
	5	9.4	13.8	11.6	25	9.4	690.73	259.7145	3116.574
	6	9.4	13.8	11.6	25	9.4	690.73	259.7145	3116.574
	7	9.4	13.8	11.6	25	9.4	690.73	259.7145	3116.574
	8	Sat			25		690.73	371.112	2226.672
	10	9.4	13.8	11.6	25	9.4	690.73	259.7145	3116.574
	11	9.4	13.8	11.6	25	9.4	690.73	259.7145	3116.574
	12	9.4	13.8	11.6	25	9.4	690.73	259.7145	3116.574
	13	9.4	13.8	11.6	25	9.4	690.73	259.7145	3116.574
	14	9.4	13.8	11.6	25	9.4	690.73	259.7145	3116.574
	15	Sat			25		690.73	371.112	2226.672

Jan	7	8.6	13.1	10.9	25	10.15	690.73	280.4364	3365.237
	8	8.6	13.1	10.9	25	10.15	690.73	280.4364	3365.237
	9	8.6	13.1	10.9	25	10.15	690.73	280.4364	3365.237
	10	8.6	13.1	10.9	25	10.15	690.73	280.4364	3365.237
	11	8.6	13.1	10.9	25	10.15	690.73	280.4364	3365.237
	12	Sat			25		690.73	400.722	2404.332
	14	8.6	13.1	10.9	25	10.15	690.73	280.4364	3365.237
	15	8.6	13.1	10.9	25	10.15	690.73	280.4364	3365.237
	16	8.6	13.1	10.9	25	10.15	690.73	280.4364	3365.237
	17	8.6	13.1	10.9	25	10.15	690.73	280.4364	3365.237
	18	8.6	13.1	10.9	25	10.15	690.73	280.4364	3365.237
	19	Sat			25		690.73	400.722	2404.332
	21	8.6	13.1	10.9	25	10.15	690.73	280.4364	3365.237
	22	8.6	13.1	10.9	25	10.15	690.73	280.4364	3365.237
	23	8.6	13.1	10.9	25	10.15	690.73	280.4364	3365.237
	24	8.6	13.1	10.9	25	10.15	690.73	280.4364	3365.237
	25	8.6	13.1	10.9	25	10.15	690.73	280.4364	3365.237
	26	Sat			25		690.73	400.722	2404.332
	28	8.6	13.1	10.9	25	10.15	690.73	280.4364	3365.237
	29	8.6	13.1	10.9	25	10.15	690.73	280.4364	3365.237
	20	8.6	13.1	10.9	25	10.15	690.73	280.4364	3365.237
	31	8.6	13.1	10.9	25	10.15	690.73	280.4364	3365.237
Feb	1	8.1	13.2	10.7	25	10.35	690.73	285.9622	3431.547
	2	Sat			25		690.73	408.618	2451.708
	4	8.1	13.2	10.7	25	10.35	690.73	285.9622	3431.547
	5	8.1	13.2	10.7	25	10.35	690.73	285.9622	3431.547
	6	8.1	13.2	10.7	25	10.35	690.73	285.9622	3431.547
	7	8.1	13.2	10.7	25	10.35	690.73	285.9622	3431.547
	8	8.1	13.2	10.7	25	10.35	690.73	285.9622	3431.547
		Sat			25		690.73	408.618	2451.708
	11	8.1	13.2	10.7	25	10.35	690.73	285.9622	3431.547
	12	8.1	13.2	10.7	25	10.35	690.73	285.9622	3431.547
	13	8.1	13.2	10.7	25	10.35	690.73	285.9622	3431.547
	14	8.1	13.2	10.7	25	10.35	690.73	285.9622	3431.547
	15	8.1	13.2	10.7	25	10.35	690.73	285.9622	3431.547
	16	Sat			25		690.73	408.618	2451.708
	18	8.1	13.2	10.7	25	10.35	690.73	285.9622	3431.547
	19	8.1	13.2	10.7	25	10.35	690.73	285.9622	3431.547
	20	8.1	13.2	10.7	25	10.35	690.73	285.9622	3431.547
	21	8.1	13.2	10.7	25	10.35	690.73	285.9622	3431.547
	22	8.1	13.2	10.7	25	10.35	690.73	285.9622	3431.547
	23	Sat			25		690.73	408.618	2451.708
	25	8.1	13.2	10.7	25	10.35	690.73	285.9622	3431.547
	26	8.1	13.2	10.7	25	10.35	690.73	285.9622	3431.547
	27	8.1	13.2	10.7	25	10.35	690.73	285.9622	3431.547
Jan	28	8.1	13.2	10.7	25	10.35	690.73	285.9622	3431.547

March	1	9.4	15.2	12.3	25	8.7	690.73	240.374	2884.488
	2	Sat			25		690.73	343.476	2060.856
	4	9.4	15.2	12.3	25	8.7	690.73	240.374	2884.488
	5	9.4	15.2	12.3	25	8.7	690.73	240.374	2884.488
	6	9.4	15.2	12.3	25	8.7	690.73	240.374	2884.488
	7	9.4	15.2	12.3	25	8.7	690.73	240.374	2884.488
	8	9.4	15.2	12.3	25	8.7	690.73	240.374	2884.488
	9	Sat			25		690.73	343.476	2060.856
	11	9.4	15.2	12.3	25	8.7	690.73	240.374	2884.488
	12	9.4	15.2	12.3	25	8.7	690.73	240.374	2884.488
	13	9.4	15.2	12.3	25	8.7	690.73	240.374	2884.488
	14	9.4	15.2	12.3	25	8.7	690.73	240.374	2884.488
	15	9.4	15.2	12.3	25	8.7	690.73	240.374	2884.488
	16	Sat			25		690.73	343.476	2060.856
	18	9.4	15.2	12.3	25	8.7	690.73	240.374	2884.488
	19	9.4	15.2	12.3	25	8.7	690.73	240.374	2884.488
	20	9.4	15.2	12.3	25	8.7	690.73	240.374	2884.488
	21	9.4	15.2	12.3	25	8.7	690.73	240.374	2884.488
	22	9.4	15.2	12.3	25	8.7	690.73	240.374	2884.488
	23	Sat			25		690.73	343.476	2060.856
	25	9.4	15.2	12.3	25	8.7	690.73	240.374	2884.488
	26	9.4	15.2	12.3	25	8.7	690.73	240.374	2884.488
	27	9.4	15.2	12.3	25	8.7	690.73	240.374	2884.488
	28	9.4	15.2	12.3	25	8.7	690.73	240.374	2884.488
	29	9.4	15.2	12.3	25	8.7	690.73	240.374	2884.488
	30	Sat					690.73	240.374	1442.244
									325277.3

Appendix CH5-1

Consultant and contractor schedules for AHU flow rate and pressure drop

	Flow rate (m^3/s)	Margin (%)	Pressure drop (Pa)	Margin (%)
HB-AHU-03-NE-01	4.421	8%	460	10%
HB-AHU-03-NE-02	2.825	8%	460	10%
HB-AHU-03-NE-11	5.062	5%	460	10%
HB-AHU-03-NE-15	1.082	10%	460	21%
HB-AHU-03-SE-13	3.662	8%	460	10%
HB-AHU-03-SE-18	3.006	8%	460	10%
HB-AHU-03-SW-01	4.211	8%	462	10%
HB-AHU-03-SW-02	4.347	8%	497	10%
HB-AHU-03-SW-03	1.035	10%	460	21%
HB-AHU-10-NW-03	5.216	5%	460	10%
HB-AHU-10-NW-04	3.798	8%	460	10%
HB-AHU-10-SW-05	4.446	8%	460	10%
HB-AHU-10-SW-06	4.273	8%	460	10%

Consultant schedule

	Flow rate (m^3/s)	ΔP (Pa)
HB-AHU-03-NE-01	4.75	506
HB-AHU-03-NE-02	3.04	506
HB-AHU-03-NE-11	5.32	5.6
HB-AHU-03-NE-15	1.19	557
HB-AHU-03-SE-13	3.94	506
HB-AHU-03-SE-18	3.23	506
HB-AHU-10-NW-03	5.48	506
HB-AHU-10-NW-04	4.08	506
HB-AHU-10-SW-05	4.78	506
HB-AHU-10-SW-06	4.59	506

Contractor schedule

Appendix CH5-2

Heating and chilled water flow rates (kg/s) for flow and return temperature differences of 10^0C, 20^0C and 6^0C.

$$mass\ flow\ rate\ \ kg/s = \frac{Heating/cooling\ load\ (kW)}{Specific\ heat\ capacity\ (kJ/kg^0C) * temp\ difference\ (^0C)}$$

kW	Δt = 10^0C	Δt = 20^0C	Δt = 6^0C
1	0.02	0.01	0.04
2	0.05	0.02	0.08
3	0.07	0.04	0.12
4	0.10	0.05	0.16
5	0.12	0.06	0.20
6	0.14	0.07	0.24
7	0.17	0.08	0.28
8	0.19	0.10	0.32
9	0.21	0.11	0.36
10	0.24	0.12	0.40
15	0.36	0.18	0.60
20	0.48	0.24	0.80
25	0.60	0.30	1.00
30	0.72	0.36	1.19
35	0.84	0.42	1.39
40	0.96	0.48	1.59
45	1.07	0.54	1.79
50	1.19	0.60	1.99
55	1.31	0.66	2.19
60	1.43	0.72	2.39
65	1.55	0.78	2.59
70	1.67	0.84	2.79
75	1.79	0.90	2.99
80	1.91	0.96	3.18
85	2.03	1.02	3.38
90	2.15	1.07	3.58
95	2.27	1.13	3.78
100	2.39	1.19	3.98

Appendix CH5-3

Peter Jost LectureTheatre

Comfort survey (based on ANSI/ASHRAE Standard 55-2010**)**

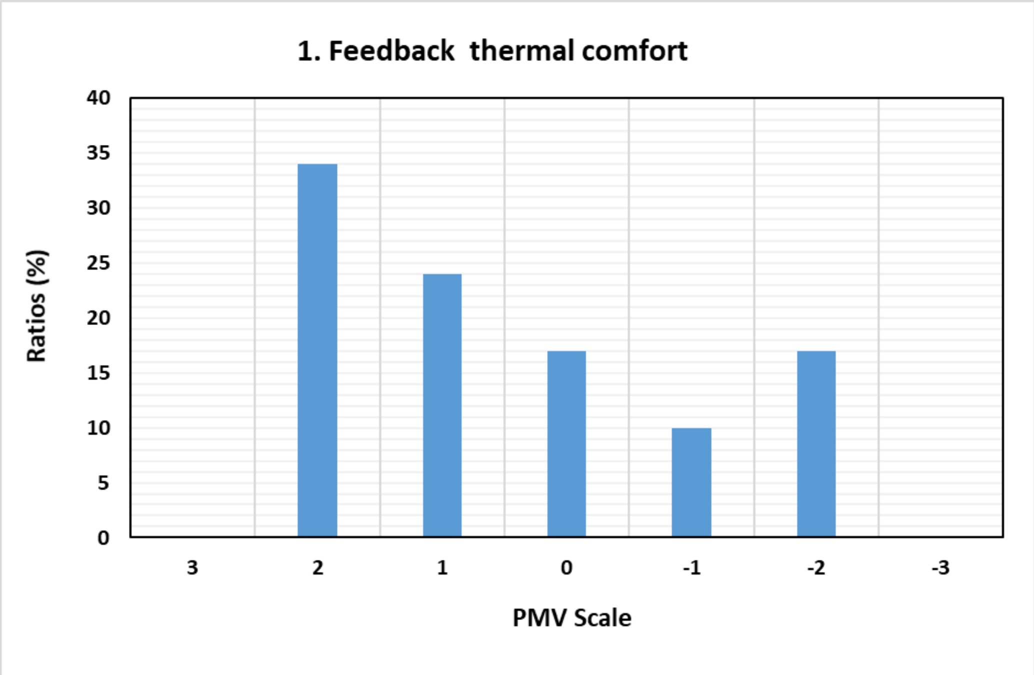


Figure CH5-3 A Thermal comfort PMV scale Peter Jost lecture theatre

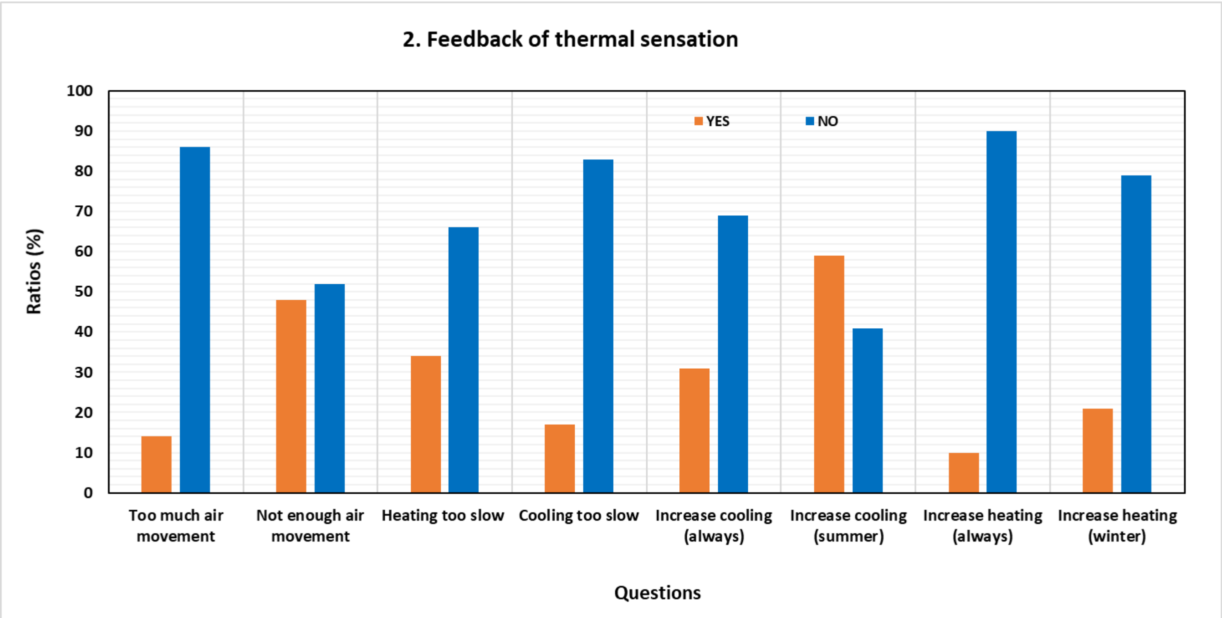
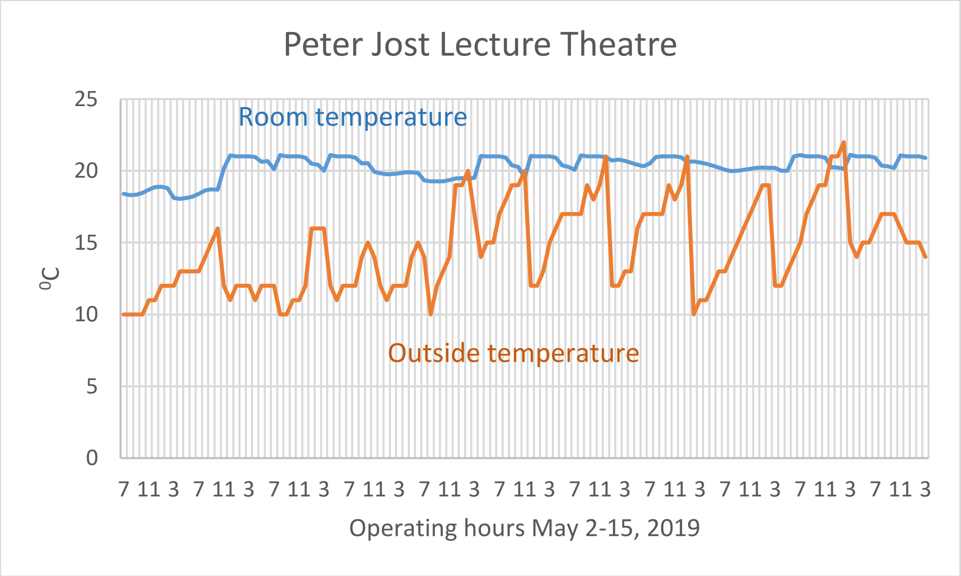


Figure CH5-3 B Occupancy comfort % vote Peter Jost lecture theatre



CH5-3C Monitored (BMS) temperatures for Peter Jost lecture theatre

Clearly student occupant opinion was not unanimously satisfied with comfort conditions. However, the occupant votes did tend to indicate that air movement did not create discomfort. There was a strong trend to favour cooling against heating and this would appear to be appropriate for the occupant age range (young). The monitored temperatures indicate that the upgraded cooling capacity can maintain design temperatures.

Publication list

(Research output relevant to this PhD Thesis)

Journal Article

L Brady & M Abdellatif, "*Assessment of energy consumption in existing buildings*" Energy and Buildings. 2017, 149: 142-150. (Impact Factor: 4.067).

https://doi.org/10.1016/j.enbuild.2017.05.051

Abstract: There has been general recognition within the construction industry that there is a discrepancy between the amount of energy that buildings actually use and what designers considered that they should use. This phenomenon is termed "The Performance Gap" and is normally associated with new buildings. However, existing and older buildings contribute a greater amount of operational carbon. In response to the Performance Gap, CIBSE have developed the TM54 process which is aimed at improving energy estimates at design stage. This paper considers how the TM54 process can also be used to develop energy management procedures for existing buildings. The paper describes an exercise carried out for a university workshop building in which design energy use has been compared with the actual building energy use and standard benchmarks. Moreover, a sensitivity assessment has been carried out using different scenarios based on operation hours of building/equipment, boiler efficiency and impact of climate change. The analysis of these results showed high uncertainty in estimates of energy consumption. If carbon challenges are to be met then improved energy management techniques will require a more systematic approach so that facilities managers can identify energy streams and pinpoint problems, particularly where they have assumed responsibility for existing buildings which often have a legacy of poorly metered fuel consumption.

Conference Article

L Brady & R Hanmer-Dwight, "*The management and control of energy at the design stage of buildings*", Proceedings of Associations of Research in Construction Management, 2017, Manchester, UK. (http://www.arcom.ac.uk/-docs/proceedings/5863670380c300fe766c968b1c6f8293.pdf)

Abstract: An essential element of a sustainable building is the amount of operational energy that will be needed to power the engineering services which provide buildings with safe, healthy, comfortable and secure environments. The environmental impact and financial costs associated with energy running costs are factors which are increasingly recognised for their importance. The paper considers the accuracy and usefulness of energy bench-marking and discusses its application in the management of the design of sustainable buildings. Within this context, the design of building services plant is an iterative process in which design decisions become progressively more accurate. At the stage when project objectives and sustainability aspirations are not fully defined designers may use benchmarks data for preliminary energy target setting. There are several types of bench-marking systems available for predicting building energy use. Typically, benchmarks are provided in which annual energy use is allocated in terms of annual KWh/square metre of building floor area for various building types. CIBSE has developed a Technical Manual which provides more sophisticated guidance on evaluating energy performance. This investigation used TM54 and TM46 to compare predictive energy consumption against actual energy bills for an existing large educational building in Liverpool. The research consisted of seven individual applied studies, which together produced a comparative range of estimates. Subsequent review of the work indicated some imperfections; however, the TM54 method was found to produce greater accuracy for energy consumption prediction which remains an important and necessary component of sustainable design.

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