Energy Efficiency in Laboratory Buildings

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“As a building type, the laboratory demands our attention: what the cathedral was to the 14th century, the train station was to the 19th century, and the office building was to the 20th century the laboratory is to the 21st Century. That is, it is the building type that embodies, in both program and technology, the spirit and culture of our age and attracts some of the greatest intellectual and economic resources of our time”. (1)

Abstract

The objective of this work is to investigate the energy efficient strategies that can be employed within laboratories and demonstrate the role of modelling and simulation in the designing of low energy laboratories.

The Building Regulations, British Standards, health and safety regulations and voluntary rating schemes all combine to determine the minimum ventilation rates and air conditioning loads within laboratories and as such the energy consumption. It is suggested that within the framework set out by the regulations, relevant standards and health and safety guidelines there is opportunity for innovative environmental strategies that can reduce energy consumption beyond conventional practice.

Case studies are presented demonstrating current industry best practice in laboratory design. The purpose of evaluating these case studies is to demonstrate that energy reduction can be achieved in laboratory buildings and to outline the approach taken by these facilities to achieve this outcome.

Energy benchmarking data has been collated for a range of laboratories, considered energy conscious, and is tabled to demonstrate the energy consumption range for these building types. This forms a method of benchmarking future buildings of similar size and function.

Design approach, building envelope, planning and building services are all considered with respect to energy efficiency. The key factors associated with the successful achievement of low energy laboratory design have been identified and formulated into a methodology to provide a guide for designers.

Finally, an energy analysis case study was carried out to evaluate selected energy efficiency measures for a generic laboratory building. Demonstrating application of the methodology and computer modelling and simulation as a powerful evaluation tool.

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1 Introduction

Laboratories are high-energy users, consuming up to 10 times more energy per metre squared than commercial office buildings. [2] Therefore a reduction in energy consumption in such building types would relate to a significant relative reduction in carbon dioxide emissions. The objective of this work is to investigate the energy efficient strategies that can be employed highlight how these can be selected and demonstrate the role of modelling and simulation in the designing of low energy laboratories.

1.1 Laboratory Definition

The laboratory is a unique building type. Human comfort is not the only objective as in domestic housing and the majority of commercial buildings. Health and safety requirements and environmental conditions for experimental work are equally important. Laboratory buildings are expected to be highly achieving architecturally without limiting functionality. Stakeholders are typically sophisticated with high environmental performance expectations as they depend on the building fabric and services to maintain their environment. In an increasingly competitive industry institutions rely on their buildings to attract and retain scientists and staff. The laboratories represent long-term investments, which gives an opportunity to invest in energy saving strategies with paybacks not considered under normal commercial constraints. Laboratories have complex operations with multiple service requirements. They are high-energy users because of this complex operation and the requirement to maintain functionality, health and safety and aesthetics.

Laboratories as referred to within this work can be categorised into three main groups, as defined in the ASHRAE (American Society of Heating and Refrigeration and Air-Conditioning Engineers) Laboratory Design Guide [3]: Biological, Research and Instrumentation.

- Biological

  These laboratories employ a mix of fume cupboards and safety cabinets; they typically operate with a range of thermal environments (e.g. cold rooms and hot rooms) and varying levels of containment to contain toxic and infectious biological materials. These laboratories are often defined by bio-safety levels and may require decontamination procedures.

- Research

  These laboratories are fume cupboard intensive and are devoted to organic, inorganic and analytical chemistry. Ventilation rates are often the highest in this type of facility to remove solvents and gaseous fumes.

- Instrumentation

  These laboratories are less focused on ventilation rates for containment and safety. Experimental work is more instrumental than practical, involving materials testing or electronics, and as such there are high-connected power loads with a variety of electrically powered instruments leading to relatively high air conditioning loads and process water cooling requirements. Close control of temperature and humidity is often required along with low levels of airborne pollutants.

1.2 Energy Consumption Factors

The key reason for the high-energy consumption, in laboratory facilities, is the high ventilation rates and the associated air conditioning loads. The ventilation rates are typically required to maintain safety and containment levels and meet the relevant authority and risk management guidelines. This supply or make-up air is normally conditioned to meet user comfort expectations and deal with internal heat gains. Air change rates can be between a minimum of 8 ACH up to 30 ACH (4) in fume cupboard intensive labs, clean rooms or cryogen usage areas, where inert oxygen depleting gases are present. An office building with a conventional VAV air conditioning system is between 4-6 ACH (5). The air in laboratory buildings is often 100% outside air with little opportunity to re-circulate due to risk of cross contamination especially when air is extracted via fume cupboards and safety cabinets. Further to the high ventilation rates in laboratory buildings the internal load can be dominate regardless of external climate conditions. Ventilation rates and the associated air conditioning loads, lead by internal heat loads generated by equipment and close environmental control bands, dominate in relation to energy usage in laboratories.

Due to the high air change rates, multiple mechanical and electrical services requirements and the levels of heat gain generated from equipment energy efficiency strategies commonly utilised in commercial buildings can often not be readily or easily applied in laboratories. Natural ventilation, passive cooling and heat recovery may not be acceptable in strict environmentally controlled spaces where the risk of cross contamination is prevalent.

1.3 Design Team Approach

To achieve the goal of an energy efficient laboratory building an integrated design approach is essential. The building professionals involved must understand that all building systems are interdependent and have the ability to be part of an interactive design process. Involving not only the design team and client, but also multiple building users with varying requirements and levels of understanding. Each discipline must be considered in relation to others and any design decisions assessed in terms of the impact on the whole building design. This should be an iterative process carried out throughout the building design from design development through to construction. To be successful energy efficiency should be considered as part of the fundamental project brief and 'bought into' by design team members and the client. Benchmark figures should be targeted and assessed at each stage of the design as it develops and as other parties, such as contractors, start to become involved. The use of modelling and simulation is an essential tool in quantifying and measuring targets to determine if they are consistently meet as the project evolves. Third party expert commissioning is also considered essential in the realisation of energy efficient laboratories and should be built into the brief from onset. It is widely acknowledged that this final part of the process if not carried out properly limits the building from achieving its optimised performance.

Building services engineers will be largely responsible for the overall energy performance of the laboratory in conjunction with the architects. Hence laboratory design must integrate the mechanical and electrical services with the architectural philosophy form project conception to ensure opportunities are not missed.

1.4 Engineering Principles

Equipment and plant that is generally oversized in engineering practices, to allow for a margin of error and future flexibility, should be carefully considered as this can lead to higher capital costs and energy consumption. The diversities that are likely to occur in the laboratories should be studied and applied to allow selection of the correct plant capacity. It should be understood that plant will not be continuously operating at peak or simultaneous demand and plant should be designed with this in mind. For example fans and pumps should be selected with variable speed drives and the part load efficiency of generation plant should be assessed during equipment selection. The number and size of fume cupboards and safety cabinets will directly influence the buildings energy performance. Options to supply these directly with outside air or air re-circulated from other spaces should be considered where possible to minimise energy usage. Variable volume supply and exhaust fans should be employed in any energy conscience facility over traditional constant volume systems. The air volume extracted is continuously varied depending on use as well as the conditioned supply air, through pressure controls, while maintaining the velocities required to achieve containment levels.

Further energy saving design measures that should be considered specifically within laboratories are; low pressure drop design, high efficiency motors, free cooling via low ambient air temperatures, energy recovery from air systems or waste hot water systems e.g. chiller condensers and open loop process cooling systems.

1.4.1 Building Energy Management System

A Building Energy Management System (BEMS) should be incorporated into the laboratory for automatic controlling and measuring of all mechanical plant and equipment. It is fundamental to the success of the buildings operation and should be commissioned by a third party expert. It allows the plant to be controlled so that it only operates as required within predetermined parameters or dynamic measurements taken via field sensors. A BEMS also allows the building plant to be interrogated and monitored throughout its seasonal use. Set points and operating parameters can then be optimised based on season or operational profiles. Operational profiles may change; particularly in laboratory facilities where user groups rotate regularly with the type of research or if predictions made initially for occupancy and usage are found to be inaccurate. It also allows areas of high-energy consumption to be exposed and then targeted. Capital investment could be directed to target and optimise the highest energy users and allow stakeholders to see a quicker return. The BEMS outputs can also be used to educate and make users more aware of what their practices, in terms of energy usage, are costing environmentally and financially. This can encourage good housekeeping for example switching off plug in items or closing fume cupboard sashes when not required. For a laboratory building to achieve optimum design performance it must be carefully commissioned. During the buildings life cycle it must also be operated effectively under the management of an automated control system as described above and all plant and equipment should be maintained to ensure maximum mechanical operating efficiency.

1.5 Energy Supply

As well as reducing energy consumption within laboratories energy efficient power sources should also be considered. Laboratories are often located on large university or commercial green field campuses. These are ideal for onsite combined heat and power generation for electrical supply and load levelling. This can be coupled with a hot water and chilled water, if an absorption chiller is employed, district distribution system. This could further involve a thermal storage facility to store energy for use at peak times.

Renewable technologies should also be considered such as solar hot water heating, localised wind power or photovoltaic systems. These would however have to be carefully analysed, as laboratories require reliable on demand energy not intermittent and diffuse as is often associated with these technologies. A back up power source would have to be present to meet the laboratories functional requirements. Passive energy harnessing by virtue of the built form can be employed to supplement and reduce the peak demand imposed on the mechanical plant during periods of availability such as natural day lighting and ventilation.

1.6 Summary

Laboratory facilities are high consumers of energy therefore a reduction in energy consumption allows relative reductions in carbon dioxide emissions. Carbon dioxide emissions are linked to the effects of global warming and climate change. Whilst there is potential to save energy in these premises, it is critical to remember that whilst energy efficiency is a major consideration, it will take second place to the functional demands of the building and the need to control air movement to avoid spread of contamination. This work aims to outline relevant strategies to achieve energy efficiency through the built form and efficient servicing strategies while maintaining the primary demands of function and health and safety.

The measures described will be considered and how these can be incorporated into a laboratory building type to achieve energy efficiency. The approach to be taken by the project design time and client will also be investigated and a general approach methodology developed as an aid to designers. Existing best practice facilities will be considered to allow assessment of industry standards and for benchmarking purposes. The Building Regulations, British Standards and health and safety guidelines will also be considered specifically in relation to energy use in laboratory type buildings. Finally modelling and simulation will be demonstrated as an essential tool for the building designer in assessing and developing engineered solutions to the complex building energy systems within laboratories.

2 Regulations, Standards and Voluntary Ratings

Building Regulations, British Standards, health and safety regulations and voluntary rating schemes all combine to determine the minimum ventilation rates and air conditioning loads within laboratories and as such the energy consumption. The Scottish Building Regulations outline the minimum standards for new buildings, taking into account minimum ventilation requirements and fuel conservation. The British Standards relevant to laboratories dictate the design and performance criteria that the installed systems must meet. British Standard BS 7258 Laboratory Fume Cupboards Part 1 and 2 (1994) is considered the most relevant to this work and is discussed below. Health and safety regulations and guidance must be followed to ensure occupants are not put at risk. This can determine the ventilation principles to generate safety barriers and provide containment. Voluntary environmental rating schemes are also being increasingly adopted to promote sustainable and low energy design. Those considered are BREEAM (Building Research Establishment Environmental Assessment Method) and the EPC (Environmental Performance Criteria) assessments.

2.1 Building Regulations

The minimum standards for new buildings are established through the Building Regulations. On the 1st of May 2005 a new building standards system came into operation in Scotland. Within the new Scottish Building Regulations laboratories are categorised under non-domestic buildings. Section 3 and 6, of the Scottish Building Standards Agency Non-Domestic Handbook, ‘Environment’ and ‘Energy’ respectively are relevant to the issue of energy efficiency.

2.1.1 Environment

Section 3.14 of the Technical Handbook for non-domestic buildings outlines the requirements to satisfy regulations with regard to ventilation. The building must have provision for ventilation by natural means, mechanical means or a combination of both i.e. mixed mode. The air provision relates to requirements for human respiration and is in addition to air supply needed for smoke control purposes or operation of combustion appliances.

Mechanical ventilation and air conditioning must be designed with no detrimental impact to the health of occupants and should be accessible for regular maintenance. Minimum outside airflow rates for human respiration are set at 8 litres/second per occupant. Mechanical ventilation must be in accordance with “BS 5720:1979 Code of practice for mechanical ventilation and air conditioning in buildings” and “CIBSE Guide B: 2001 Installation and Equipment Data: Ventilation and air conditioning”. The latter is the most explicit in its description of ventilation and air conditioning with particular regard to laboratories and makes the following recommendations that affect energy usage:

- 6-15 Air Changes/Hour (allowance to be made for fume cupboards). Minimum air change rates are dependent on the type of work and the need to remove contaminants.

- Low face velocity fume cupboards, to reduce exhausted air volumes.

- Variable air volume systems and suitable controls, with diversity of use accounted for, to reduce quantities of air delivered and extracted based on demand.

2.1.2 Energy

Section 6 of the Technical Handbook for non-domestic buildings outlines the requirements to satisfy regulations with regard to energy conservation. These can be summarised as follows:

The building must be designed, installed, controlled and constructed in such a way that:

- the insulation envelope resists thermal transfer. This translates to a minimum prescribed thermal performance for the envelope that can be demonstrated via three methods available; the elemental, heat loss or carbon emissions calculation.

- the heating and hot water service systems achieve optimum energy efficiency. Maximum carbon intensity limits must be adhered to.

- temperature loss/gain from vessels, piped and ducted services is resisted. Insulation and lagging must applied as nominated in BS 5422: 2001.

- the artificial lighting systems achieve optimum energy efficiency. Minimum efficacy limits must be adhered to.

- the form and fabric minimises the use of mechanical ventilating or cooling systems, however those systems installed must achieve optimum energy efficiency. Total specific fan power to be not greater than 1.5 W/litres/second.

- energy consuming services to be commissioned to achieve optimum energy efficiency.

2.1.3 Sustainable Development Policy into Practice – New Buildings

There is work in progress by the Scottish Executive to further the sustainable development of new buildings, both domestic and non-domestic. It is the policy of the Scottish Executive to continue to embed the principles of sustainable development in building regulations, planning policy and procurement guidance, rather than expecting developers to adopt voluntary codes of practice. Further improvement on the current regulations with regard to the sustainability of new buildings is expected through forthcoming changes. Amendments to the Building Regulations have been issued for consultation and are likely to come into force in May 2007. The topics that will impact on building energy efficiency are most notably; energy performance, low and zero carbon technologies including renewable sources and energy metering. It is also expected that a consultation will be issued on the implementation of the Energy Performance of Buildings Directive 2002/91/EU.

2.1.4 Energy Performance of Buildings Directive 2002/91/EU

The Energy Performance of Buildings Directive of the European Parliament and Council came into force in January 2003. The purpose of the Directive is to increase awareness of energy use in buildings and force building owners to invest in energy efficiency measures. It is approximated that there are “160 million buildings in the European Union consuming over 40% of Europe’s energy.” [7] Europe is committed globally to reducing carbon emissions under the Kyoto Protocol and this measure is intended to contribute towards the proposed reduction.

A standard UK method of calculating integrated energy performance of buildings is to be used to compare against minimum energy targets for new and existing buildings. The method takes into account the thermal characteristics of the building fabric, position, orientation, local climate, design parameters and all mechanical and electrical building services. Buildings will therefore be classified with laboratories potentially falling into any of the following categories: education, hospital or "other energy consuming building". As discussed previously laboratories are a specialised building type with typically more complex high-energy usage and may have to be considered in an independent category particularly where energy targets come into consideration. As part of the legislation formal consideration must be given to alternative systems for heating including; combined heat and power (CHP), district heating systems, heat pumps and renewable technologies based on technical, environmental and financial feasibility.

The implications of the Directive are currently being realised within the UK as the construction industry and building operators have to adapt to the changes. The eventual outcome of the Directive will be reduced energy consumption within the building sector and a greater awareness of energy reducing strategies and the environmental benefits.

2.2 BS 7258 Laboratory Fume Cupboards Parts 1 & 2 1994

The primary function of a fume cupboard system is to safely contain and exhaust potentially dangerous fumes from the fume cupboard to an outside discharge point from which they can be dispersed at an acceptably low concentration. Fume cupboards often dictate airflow quantities, particularly within research laboratories, due to the required exhaust rates. Airflow quantities are derived based on the face velocity across the fume cupboard. A typical 2m wide fume cupboard with a 0.5m/s face velocity and the sash set at maximum working height requires an exhaust rate of approximately $0.5m^3/s$. The sash provides a barrier between the internal fume cupboard and user. This is likely to be conditioned air drawn from adjacent spaces or supplied directly. It is not uncommon for laboratories to accommodate over 100 fume cupboards particularly within education facilities. The following clauses identified within BS 7258 Laboratory Fume Cupboards Part 1 and 2 directly influence the energy consumption of fume cupboard systems and should be considered in any energy conscious laboratory facilities:

BS 7258-1 Laboratory Fume Cupboards Part 1: [(8)]

- *Clause 7.1.1* – It is unlikely that face velocities below 0.3m/s will give satisfactory containment. In some cases, face velocities of 0.5m/s or above may be necessary.

BS 7258-2 Laboratory Fume Cupboards Part 2: [(9)]

- *Clause 3.2.1.2* - Heat recovery systems may form part of the exhaust system.
- *Clause 3.2.1.4* - Fans should be mounted at roof level with extract systems within the building under negative pressure.
- *Clause 3.2.1.5* - Fan capacities should exceed the operating requirements by at least 10%.
- *Clause 3.2.1.7* - Fume cupboards are often not all used at any one time. Economics in running costs can be achieved by providing independent extract systems for groups of fume cupboards (manifolding). To prevent mixing of fumes that could give rise to unacceptable hazards fume cupboards should be grouped according to the processes to be undertaken. A collection/dilution system may be used for the dispersal of fumes from a number of individual extract systems or from common extract systems. The collection/dilution duct, discharge fan and common discharge flue should have a capacity (after allowing for the frequency of fume cupboard use) in excess of the total capacity of the extract fans connected to the duct.
- *Clause 3.2.3.1* - Fans should be selected so that their performance is near to the point of the maximum efficiency on the fan characteristic curve.
- *Clause 3.2.4.2* - Discharge velocities to be not less than 7m/s and a design figure of 10m/s is desirable.
- *Clause 3.3.4* - The opening of the windows should not be relied upon for the supply of laboratory make-up air because staff may omit to open them, particularly in cold weather, and draughts from windows in the vicinity of a fume cupboard may prevent the attainment of the level of performance.
- *Clause 3.3.5* - Sufficient openings, louvers or transfer grilles should be provided in walls and doors for laboratory make-up air to be infiltrated into the

room from its surroundings, preferably from adjacent heated corridors. The drawing in of contaminated air e.g. from adjacent laboratories should be avoided.

- *Clause 3.3.7* - A fan-assisted source of laboratory makeup air should be filtered, heated and otherwise rated as necessary, to maintain the environmental conditions required for the laboratory. Prevent pressurisation by supplying less fan assisted make up air than the total extract rate. When in such an installation there is for any reason a significant reduction in the rate of (or complete loss of) air extraction from the room by the fume cupboard installation, the fan assisted lab make-up air rate should be correspondingly reduced, or discounted either automatically or manually following an automatic alarm.
- *Clause 3.3.9* - Air extracted from a room in which a fume cupboard is situated should not be recirculated.

In summary the main consequences for energy usage that can be drawn from this standard are that heat recovery is possible from exhaust streams however cross contamination must be considered and recirculation is not possible. Fume cupboards should be located on the upper levels of the building where possible to minimise ductwork routes and as such pressure drops, as fans must be mounted at roof level. Diversity of use should be taken into account when designing exhaust systems and it is possible to manifold fume cupboards with similar applications into one system, this will have the benefit of reducing exhaust air quantities and fan energy. Make up air should not be introduced through natural ventilation unless automatically controlled and must either be passively transferred from adjacent spaces or directly into the laboratory and must maintain environmental conditions. Fume cupboard laboratories should be under negative pressure and as the extraction demand is reduced the make-up air supply should be correspondingly reduced.

2.3 Health and Safety

2.3.1 Control of Substances Hazardous to Health (COSHH)

Using chemicals or other hazardous substances in laboratories can put occupants health at risk. The Control of Substances Hazardous to Health (COSHH) Regulations control the exposure to hazardous substances to prevent ill health. The Health and

Safety Executive publishes annual guidance with regard to the COSHH Regulations. It outlines limits to which exposure to hazardous airborne substances should be controlled; this is in the form of an Occupational Exposure Limit (OEL) metric. OEL limits are available for a large number of substances and are given for long-term exposure (8 hours) and short-term exposure (10 minutes). These must be adhered to ensure compliance with the COSHH Regulations and will directly influence ventilation rates.

2.3.2 Advisory Committee on Dangerous Pathogens

Guidance from the Advisory Committee on Dangerous Pathogens defines hazard groups and provides recommendations for containment levels for laboratories. This guidance is relevant to Biological type labs as defined in the introduction. Hazardous work involving biological agents is usually carried out in safety cabinets, which provide protection to the user and the process. The containment levels prescribed will directly influence ventilation rates can be summarised as follows:

- Level 1 – Suitable for substances in hazard group 1, which are unlikely to cause disease by infection but can be hazardous in other ways. Negative room pressure (inward air flow) is preferable.
- Level 2 - Suitable for substances in hazard group 2, biological agents. Restricted access to the space is required and a negative room pressure (inward air flow) with closed door while work is being carried out.
- Level 3 - Suitable for substances in hazard group 3, biological agents. These laboratories must be isolated from the main building activities and accessed by authorised occupants only. Negative room pressure (inward air flow) with closed door while work is being carried out. Ventilation should be designed to prevent reverse airflow at anytime. Extract must be filtered. Labs must have the ability to be fully sealed for fumigation to decontaminate the space.
- Level 4 - Suitable for substances in hazard group 4, biological agents. Negative room pressure (inward air flow) with closed door, while work is being carried out. Supply and air to be filtered. Extract air to be double filtered.

As the level of containment increases so does the associated energy consumption of the mechanical ventilation and air conditioning system. Passive solutions are discounted, as they do not offer the required level of airflow control. Increased volumes of air-conditioned supply are required to maintain pressure differentials and meet comfort levels. Additional system components such as pressure stabilisers (to allow air flow when doors are closed) and filters increase fan energy due to the pressure drop.

2.4 Voluntary Schemes

There are multiple voluntary ‘green design’ rating systems currently in use within industry. Many large estates such as universities have a pledge to receive high ratings under these schemes for new buildings as a commitment to sustainability. The most universally used system in the U.K is the BREEAM [10] (Building Research Establishment Environmental Assessment Method). The equivalent American system is the LEED [11] assessment (Leadership in Energy and Environmental Design). These rating systems are intended to assess the key criteria pertaining to all areas of sustainable building design inclusive of energy efficiency, during the design stage and then post construction.

2.4.1 BREEAM

BREEAM is an auditing tool used to assess the environmental performance of buildings and is designed to promote best practice in the construction industry. It rewards building owners and developers for improved environmental performance standards above regulatory requirements. Lower running costs can be achieved, through greater energy and water efficiency, and greater health and comfort, which improve both occupant satisfaction and productivity. Building labelling has been proven as an effective method of raising public awareness and relating to customers the credentials and benefits of a building and occupant for marketing purposes.

There are eight categories within the BREEAM, which represent a variety of sustainable building concerns. Each category is not considered of equal importance and a weighting system is applied (developed with industry representatives) to take into account the relative importance of each. The categories and environmental weightings applied are listed below. Within each category is a range of environmental criteria and each is allocated a specific number of credits. The credits awarded for each category are summed and the category weighting applied. The weighted score is then summed to give a single environmental rating expressed on a scale of Pass (25%) to Excellent (>70%).

- Management (15%)
- Health and Well Being (15%)
- Energy and Transport (25%)
- Water (5%)
- Materials (10%)
- Land Use & Ecology (15%)
- Pollution (15%)

A bespoke BREEAM is used where a project cannot be assessed under a standard BREEAM for Offices assessment procedure. The bespoke scheme is tailored to suit the building under consideration following the same methodology as a traditional assessment. The standard categories are maintained but the criteria within each category may differ slightly. Some criteria may only apply to particular functional areas. A laboratory building would require a bespoke BREAAM and the functional areas may be classified as: laboratories, support space, instrumentation space, technical write up, ancillary, cold or warm rooms.

From personal project experience a bespoke laboratory BREEAM assessment focuses on the additional criteria within the Management, Health and Well Being and Energy categories. The main emphasis is placed upon the efficient operation of the fume cupboards. Credits are awarded within the Management and Health and Well Being categories for design and commissioning carried out in line with the British Standards. This would have to be carried as a matter of course within a project and is typically the responsibility of the fume cupboard manufacturer.

The Energy category aims to reduce operational energy consumption through low energy lights and equipment, increased performance of the building fabric, renewable energy technologies, metering, controls, heat recovery and variable speed drives. All of which are applicable to office buildings and laboratories alike. In addition reward is given for utilising low face velocity fume cupboard technology and energy efficient strategies for the provision of fume cupboard make-up air. Automated door closing on cold and hot rooms is also recognised.

Within the existing basic structure the BREEAM assessment can be tailored for application to different laboratory types. The bespoke assessment will vary depending on the type and complexity of the laboratory. The additional criteria described above may be sufficient for a University research laboratory but would have to increase in scale and depth if put in context of a complex biological or industrial facility.

2.4.2 EPC

Laboratories for the 21st Century group have developed a green rating system specifically for laboratories, known as the EPC [(12)] (Environmental Performance Criteria). It is based on the U.S. LEED system with additional and modified credits pertaining to laboratory function. It is again a voluntary scheme developed by industry building professionals but has no certification attached to it. The US Green Building Council is currently developing a LEED Application Guide for Laboratories (LEED-AGL) based on the Labs 21 Group EPC rating.

The EPC is a rating scheme for use by laboratory building owners to assess the facilities environmental performance. It attempts to incorporate the inherent complexity of systems, health and safety needs, flexibility and energy efficiency issues in the context of laboratory buildings. The EPC follows the format of LEED version 2.1 but includes additional and modified existing credits. The standard credits affected that influence energy consumption are summarised as follows:

Energy and Atmosphere

- *Prerequisite 2 - Minimum Energy Use (Replaces LEED Prerequisite 2).* Establish the minimum level of energy efficiency for the base building and systems. Design to meet building energy efficiency and performance as required by the local energy code or ASHRAE/IESNA Standard 90.1-1999, which is even more stringent. In addition comply with Labs21 Lab Modelling Guidelines for all systems serving lab areas.

- *Prerequisite 4 - Assess Minimum Ventilation Requirements (New credit).* Determine minimum ventilation requirements in labs based on user needs, health and safety protection and energy consumption. At a minimum the following shall be done:

-determine the necessary fresh air ventilation rate and number of fume cupboards and other exhaust devices based on applicable codes and the planned use of the lab over the next 5 years.
-consider exhaust alternatives to fume cupboards – such as instrument exhaust, ventilated storage cabinets with very low flow and good ergonomic accessibility.
-develop a workable fume hood sash management plan – alarms etc

- *Credit 1 - Optimise Energy Performance (Replaces LEED Credit 1).* Reduce design energy cost compared to the energy cost budget for regulated energy components as described in the requirements of ASHRAE/IESNA Standard 90.1-1999 as demonstrated by a whole building simulation. Regulated energy systems include the following: HVAC, fans, pumps, domestic hot water, lighting, lab ventilation and exhaust.

- *Credit 2 - Renewable Energy (Replaces LEED Credit 2).* Supply a net fraction of the buildings total energy use with on site renewable energy systems. Assess the project for renewable energy potential.

- *Credit 7 Energy Supply Efficiency (New credit).* Reduce the total non-renewable source energy required for the facility through increased energy supply efficiency e.g. CHP.

- *Credit 8 Improve Lab Equipment Efficiency (New credit).* Save energy with efficient lab equipment. Use energy star compliant equipment or equipment in the top 25% of models. Consider all models and work with users to identify functional equipment alternatives.

- *Credit 9 Right Size Lab Equipment Load (New credit).* Right size mechanical equipment by improving estimates of heat gain from lab and process equipment, this can lead to wasted capital cost and ongoing inefficient operation. Measure base usage of equipment electrical loads in a comparable lab for each functional type of lab space and design electrical and cooling systems based on these. Design for future capacity through modular HVAC design to avoid inefficient operation.

Indoor Environment Quality (IAQ)

- *Prerequisite 3 Lab Ventilation (New credit).* Ensure that minimum requirements for IAQ and safety are met. Provide monitoring and control of fume cupboards and room pressure.

- *Credit 6 Controllability of Systems (Replaces LEED Credit 6)*. Provide a high level of individual occupant control of thermal, ventilation and lighting systems to support optimum health, productivity and comfort conditions. Provide operable windows, lighting controls for defined % of areas. Pressure controlled spaces are exempted from operable window requirements.

The majority of the modifications to the LEED system were focused on energy because it has a more significant environmental impact in laboratories compared to other commercial buildings. There are typically two approaches that can be taken to address energy usage in rating schemes; prescriptive, where points are awarded for implementing certain energy efficiency strategies and performance, where an energy target is given and points awarded based on reductions below this target. A performance-based system has been adopted for the LEED and subsequently the EPC system with modifications to allow for laboratory system parameters including fume hoods, ventilation rates and lighting power density. This allows more flexibility to meet the intent of the credit. The changes for the EPC also focus on minimising ventilation rates recognising this can significantly reduce energy consumption. This is to be achieved through a team based decision-making process. Notably the EPC system also rewards source energy reduction form on-site co-generation systems, unlike LEED. This recognises the suitability of laboratories for co/tri -generation due to frequent 24 hour operation and a year round demand for heating and cooling.

2.5 Summary

Current legislation and industry practice combine to make laboratories a safe workplace for users and reduce energy consumption within reasonable limits. It is the duty of the building designers to ensure the minimum levels of energy efficiency set by legislation are achieved while maintaining health and safety requirements and functionality. Where building owners, stakeholders and design teams are focused and committed to achieving best practice minimum requirements can be exceeded.

One possible framework for this is ‘green rating’ voluntary schemes. There is typically an increased capital cost incurred in such projects through premiums for: equipment, plant, consulting fees and analysis fees, to prove non-conventional design solutions. Energy savings through increased efficiency however can justify the capital expenditure through attractive paybacks.

It is suggested that within the framework set out by the regulations, relevant standards and health and safety guidelines there is opportunity for innovative environmental strategies that can reduce energy consumption beyond conventional practice. The proceeding chapter provides examples, through case study analysis, of developments that have achieved such an outcome.

3 Industry Case Studies and Benchmark Metrics

The University of Glasgow's Cardiovascular and Biomedical Research Centre and the University of California Santa Barbara's Donald Bren Hall School of Environmental Science & Management are presented as case studies demonstrating current industry best practice in laboratory design. Both facilities exceeded regulatory energy parameters, sought a voluntary green scheme rating, BREEAM and LEED respectively, and incorporated energy efficiency as a core design principle at the early stages of briefing. The laboratories are reviewed with reference to their architectural and services design and how this impacted on the overall energy consumption of the buildings. The purpose of evaluating these case studies is to demonstrate that energy reduction can be achieved in laboratory buildings and to outline the approach taken by each of these facilities to achieve this outcome.

Total annual energy consumption was predicted for these facilities and is included for use as a benchmark for similar laboratory buildings. Influencing parameters such as local climate, percentage lab ratio and gross floor area are provided to allow a relative comparison to be made. Further to the two detailed case studies additional data has been collated for a range of laboratories, considered energy conscious, and is tabled to demonstrate the energy consumption range for these building types. This forms a method of benchmarking future buildings of similar size and function.

3.1 Cardiovascular & Biomedical Research Centres, Glasgow

The Cardiovascular & Biomedical Research Centres are flagship developments in the biomedical field. They comprise of two concrete frame linked buildings of 12,000m^2. The building and services systems were designed for 24-hour use with 365-day access requirements. It was commented by the University of Glasgow Energy Officer "biomedical research by its nature is very energy intensive". [13]

3.1.1 Approach & Lessons Learned

In an industry presentation [14], for The Higher Education – Environmental Performance Improvement (HEEPI) Council, Boswell, Mitchell and Johnston (BMJ) the architects of the Cardiovascular & Biomedical Research Centres highlighted the approach that was adopted to achieve a high performance building and the key lessons learned. It was noted that a whole building approach must be adopted from the onset with appropriately experienced designers and contractors working closely as an integrated design team. Sustainability targets should be established early on; for this facility a whole building BREEAM rating was committed to at the onset of the project driven by the University of Glasgow's energy policy.

Architectural and thermal models were developed to provide a 'conversation tool' between the design team and the building stakeholders and to support design decisions throughout the process. It allowed options to be analysed on a whole life basis and provided a powerful demonstration tool. Regular consultations with staff and engaging with stakeholders throughout the project lead to the development of the best possible work environment for researchers while allowing the design team to fully understand the requirements for the labs.

It was stated that provision for active building control measures must be incorporated into early budget costs to avoid issues further into the design process. For this facility it included solar shading, a Building Energy Management System (BEMS) and site wide automated control actuators. Finally it was noted that independently managed 'whole building' commissioning should be planned and budgeted for early on and operational performance should be monitored continually against agreed benchmarks.

3.1.2 Architectural Planning

The concept architectural design and planning maximised exploitation of passive measures. The building orientation, natural daylight penetration, natural ventilation potential and the zoning of facilities were considered and influenced the preliminary building form. Narrow floor plates were adopted with main work areas (labs and offices) located along the perimeter to maximise natural daylight to the interior. Office areas were located on the Northern façade to minimise solar impact and allow satisfactory internal comfort conditions through natural ventilation, solar gains were minimised through external fixed solar shading. Individual offices were located on the perimeter with operable windows to allow natural ventilation. This is shown in the typical architectural floor plate below.

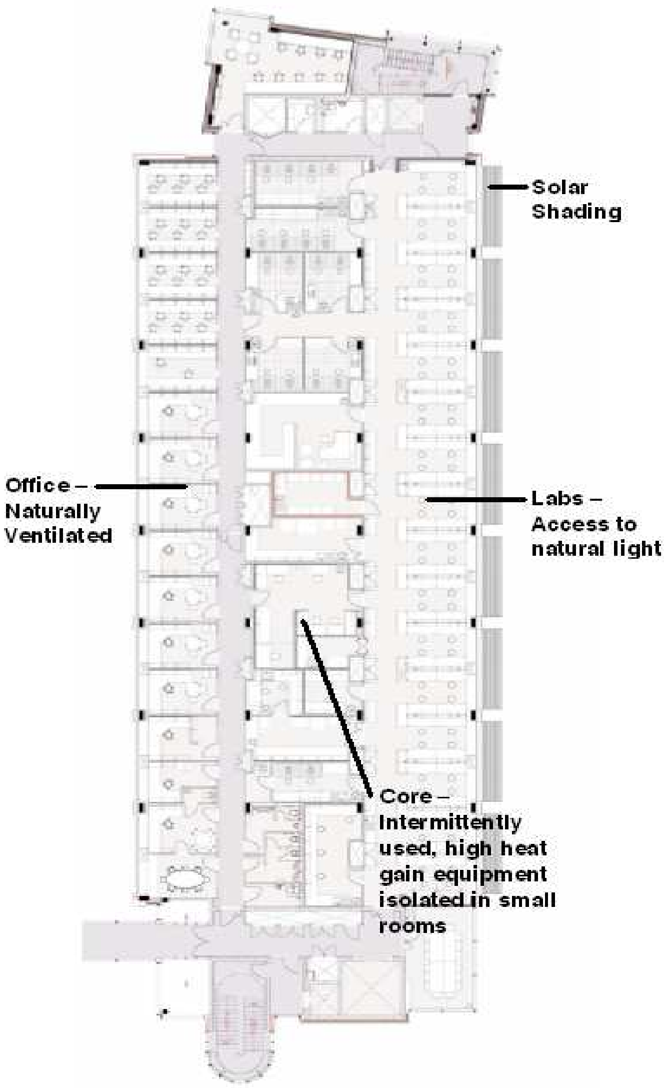


Figure 1: Cardiovascular & Biomedical Research Centre typical floor plate.

Areas with similar environmental requirements were zoned together to minimise local reheat or humidifiers. Intermittently occupied specialist rooms were located in core areas with activity controlled HVAC. High heat producing items of equipment were grouped in separate rooms to minimise the air-conditioned volume. Specialised biological resource units, Level 3 or greater (as defined by the Advisory Committee on Dangerous Pathogens) were located at high level next to the roof plant. This allowed practical isolation and minimised fan energy by reducing the supply and exhaust index run pressure drop which were already high due to the ventilation rates and extensive filtering required.

3.1.3 Building Services

Energy efficiency formed part of the briefing statement and design procurement. The brief stated that renewable and technical energy efficiency options must be identified and investigated through feasibility studies. Sustainable energy technology assessments were undertaken using thermal and electrical modelling using the specialist services of the University of Strathclyde Energy Systems Research Unit (ESRU). Photovoltaic, lighting control with daylight dimming and optimisation of fabric and façade thermal performance were assessed through computer modelling and simulation. These initiatives with the exception of the photovoltaics were included within the development.

Further to this high efficiency equipment was selected and combined with control strategies to reduce the total energy consumption of the facility by a predicted 25% per annum. These are outlined below:

- Condensing boilers,
- Free cooling chillers,
- Ventilation heat recovery plant,
- Occupancy detectors to control HVAC plant,
- Variable speed drives on fans,
- Variable speed drives on LTHW and CHW pumps,
- High efficiency luminaires

3.2 Donald Bren Hall, California

The Donald Bren Hall was completed in October 2003. The building has 2 components comprising of a 4 storey classroom, office and laboratory building and a 7 storey teaching laboratories, research laboratories and office building. 45% of the NLA is labs and 55% is offices, classrooms and conference facilities. It was designed to exceed the local California’s Title 24 requirements for energy efficiency by more than 30%. Computer modelling was utilised to analyse and predict the potential energy usage and evaluate options.

3.2.1 Architectural Planning

The saw tooth form of the roof was designed to maximise natural light. Photo sensors detect the amount of natural light in the space and dim the artificial lighting accordingly. The building was also designed to take advantage of the site's sea air. As it faces the ocean the office wings are naturally ventilated with operable windows, no air conditioning is provided. The windows have sensors built into the frame so when the windows are opened the hot water convectors automatically turn off.

3.2.2 Building Services

The laboratory encompasses a number of energy efficiency and renewable energy features. Including the following:

- Premium efficiency motors on all equipment,
- Variable speed drives on LTHW and CHW pumps,
- Lighting control with daylight dimming,
- 47kW Photovoltaic system (7 to 10% of the buildings total electricity),
- Maximised chiller and cooling tower efficiencies,
- Variable air volume laboratory exhaust and supply

The maximised chiller and cooling tower efficiencies are achieved through a multi building chilled water loop. The loop connects Don Bren Hall's (DBHs) chiller to all other chiller plants on campus. This allows other chillers to become fully loaded and thus operate at optimum efficiency before DBHs chiller comes on. Alternatively DBHs chiller can be running and take on a portion of the whole campus load as needed; the chiller has a runtime of approximately 15%.

The laboratory contains 17 variable air volume (VAV) fume cupboards and make up air is provided at an approximate rate of 8 ACH when occupied and 4 or 5 ACH when unoccupied (night and weekends). The design includes three fume exhaust stacks of varying sizes with different sized exhaust fans, 7.6, 10.9 and 14.2 m^3/s, located on the roof. The system is controlled to ensure that only one or a combination of fans run at a given time to maintain the minimum static pressure in the exhaust duct. If the static pressure cannot be maintained the next larger fan or combination of fans turns on as the fan that was previously running turns off. The exhaust fans use variable frequency drives and a bypass damper to maintain the discharge (exhaust stack) velocity. The fans therefore operate nearest to the point of maximum efficiency possible with respect to the varying fume cupboard demand.

Independent commissioning agents conducted a review of the design and construction documents at multiple stages of the project and the building was fully commissioned by a third party. Staff continually obtain real time building performance data and implement a structured monitoring and management system.

3.3 Energy Benchmarking

Energy benchmarking allows users to compare laboratories using a standard set of building and system level energy metrics. It is understood by laboratory operators that the buildings are high energy consumers but it is often difficult to ascertain whether the performance is within reasonable limits relative to function. The variety of laboratories types and differences in function and operational scheduling makes benchmarking of their energy performance a challenging task. The Cardiovascular & Biomedical Research Centres described previously was not benchmarked against any other facilities due to a lack of available data. Instead the approach taken was to calculate the base case energy consumption, based on industry standards and then improve upon this through the introduction of energy efficiency measures. Consequently the process would have benefited from relative energy benchmark targeting during the design and subsequently commissioning and operation.

Building energy benchmarking involves selecting an appropriate metric and comparing buildings using this metric, after normalizing for variable parameters. In this example whole building energy consumption (kWh/m^2/yr) has been focused on and is documented in Table 1 below for a number of U.S. based facilities. This data was extracted from a series of case studies published by the Laboratories for the 21st Century group highlighting sustainable features in engineering, architecture and facilities management.

Normalising parameters included within Table 1 include; gross area of the facility, percentage lab area ratio to other, weather in the form of descriptive climate zones and lab type description. Other key normalising parameters that would ideally be included are occupancy schedules, ventilation rates and equipment loads. These parameters can be used to modify the value of the whole building energy consumption metric for a specific facility in order to obtain a meaningful comparison. This provides a series of benchmark data that could be used to set energy consumption targets for buildings and allow the performance of facilities to be ranked.

Normalisation can be most readily achieved through a simulation model based approach. The simulation model can be used to calculate a benchmark against which the energy use can be compared. The model would account for the relevant normalising factors and be representative of an ideal case against which the actual energy use can be compared. A standard protocol with specified scheduling, equipment and lighting densities would have to be followed.

The data in Table 1 provides a limited data set that could provide assessment of energy targets for facilities with a series of assumptions. Overall there is a lack of data available currently in the U.K. regarding energy usage in laboratories, which makes benchmarking a difficult process. The majority of facilities are not sub metered and monitored at the level desirable for benchmarking.

Facility Name	Location	Climate Zone***	Type	Total Gross Floor Area m^2	Measured (M) / Predicted (P)	Total Annual Thermal Energy $kWh/m^2/yr$	Total Annual Electrical Energy $kWh/m^2/yr$	Total Annual Ventilation Energy $kWh/m^2/yr$	Total Annual Cooling Plant Energy $kWh/m^2/yr$	Total Annual Lighting Energy $kWh/m^2/yr$	Total Annual Small Power Energy $kWh/m^2/yr$
Donald Bren Hall	California	Warm, Marine	Research	7,866	M	148	188	31	12	93	47
Cardiovascular and Biomedical Research Centre	Glasgow	Cool, Dry/Marine	Research	12,000	P**	360	455	not available	not available	not available	not available
Fred Hutchinson Cancer Research Centre	Washington	Mixed, Humid	Research	49,480	M	590	524	not available	not available	not available	not available
Marian E Koshland Integrated Natural Science Centre	Pennsylvania	Cool, Humid	Research	17,226	P	102	239	57	24	23	136
Pharmacia Building Q	Illinois	Cool, Humid	Research	16,351	M	not available	473	307	57	33	75
Whitehead Biomedical Research Building	Georgia	Warm, Humid	Research	30,194	M	682	681	not available	not available	not available	not available
Louis Stokes Laboratories	Maryland	Mixed, Humid	Biological	27,363	P	not available	726	323	161	78	164
Nidus Centre	Missouri	Mixed, Humid	Biological	3,831	M	463	476	173	161	40	117
Georgia Public Health Laboratories	Georgia	Warm, Humid	Instrumentation	6,134	M	631	497	not available	not available	not available	not available
Process and Environmental Technology Laboratory	New Mexico	Warm, Dry	Instrumentation	14,069	M	385	463	not available	71	not available	60
The U.S EPA'S National Vehicle and Fuel Emissions Lab	Michigan	Cool, Humid	Instrumentation	12,542	M	746	311	not available	not available	not available	not available

* Energy data extracted from a series of case studies published on the Labs 21 website, www.labs21century.gov ,highlighting sustainable features in both engineering, architecture and facilities management.

** Energy data predicted by project consulting engineers, Hulley and Kirkwood.

*** Climate zones based on Briggs, Lucas, and Taylor 2002 " Climate Classification for Building Energy Codes and Standards". http://www.energycodes.gov/implement/pdfs/climate_paper_review_draft_rev.pdf.

**** 24 Hour operation is assumed for labs where energy data is predicted.

Table 1: Benchmark whole building energy consumption data with normalising parameters.

4 Design Approach, Building Envelope and Planning

Issues concerning environmental design in laboratories, in the context of this work, are satisfying functional requirements with minimum energy demand and utilising energy from low impact sources. This is dependent on the design approach adopted from concept stage forward, which is reliant on a well-informed brief. To achieve an energy efficient solution an integrated interdisciplinary approach must be adopted. The interactions between the built form, environmental control systems and occupants are intricately linked thus it is appropriate that all design team members contribute to the decision making process. In the first instance this will allow the design of a low energy building envelope, which will form a passive element of the laboratory climate control system reducing the level of services required and ultimately the optimised balance between functional brief and operational efficiency. A first principles approach is most appropriate for laboratory design; rules of thumb should not be relied on. The consideration of these factors can reduce the size and complexity of the HVAC (Heating, Ventilation and Air Conditioning) system and lighting requirements and as such energy consumption.

4.1 Design Brief

Low energy design principles should be committed to at the inception of the project by the client and whole design team and incorporated into the brief. The design brief guides the overall design and construction process and influences the approach adopted and outcomes. The building envelope should be briefed as part of the environmental control strategy and optimised from project onset as a method of harnessing natural daylight, ventilation and temperature control through passive design.

The service requirements outlined within the design brief should be challenged. Building user requests and rules of thumb should be questioned and broken down to get a true understanding of the building needs and the laboratory-operating brief that is required. This will reduce energy usage and subsequently capital and operational costs.

User assumptions, regarding internal environment conditions and the need for full air conditioning, should be challenged to avoid over provision of services and to maximise flexibility. Inflexible design can become prematurely redundant whereas designing for flexibility can influence future energy efficiency. Future adaptation should be built into the brief and should consider services and space planning strategies, rather than creating all-purpose spaces. User assumptions could be based on previous experience from different facilities or operating information for equipment that is to be upgraded. Design parameters such a temperature bands of 1 or 2 degrees and humidity bands within 5 to 10% are common in laboratory facilities and should be questioned. These are often not required for functionality but automatically determine the space has to be mechanically ventilated and air-conditioned. If only one process requires such conditions it can be moved to a smaller dedicated room reducing energy consumption in the larger space.

4.2 Integrated Design

Integrated interdisciplinary design is required to achieve the essential balance between functionality, health and safety and operational efficiency. It is particularly important in lab design due to the level and complexity of services that can influence each other. The integrated design team approach, particularly between architects and engineers of specialised disciplines, will involve working through a design development and optimisation process. Issues regarding the interaction between fabric and services should be considered as outlined in Figure 2 below.

As an example there is an optimisation to be made with regard to the level of daylight entering the space, for this to be maximised large amounts of glazing would be integrated into the facade design. However laboratories are typically trying to reduce air conditioning needs, as internal gains are dominant, and this will consequently increase the solar radiation penetrating the space causing the air conditioning dependence to increase. Therefore to minimise the need for air conditioning solar heat gains should be reduced through minimising excessive window area, over that required for daylighting and occupant views. The glazing should form part of the solar control system through performance film with low emissivity or reflective properties to reduce solar heat gain. External shading should also be considered to reduce solar gain while allowing daylight penetration. Light shelf fins do this by shading the glass but allowing daylight to bounce off a reflective surface and into the space.

4.3 Building Form & Fabric

The primary goal regarding low energy laboratory design is to minimise energy consumption and thus environmental impact. Reducing energy consumption through efficient design of the building services is often the first focus, however before efficient servicing is considered the building form and fabric should be addressed as a method of reducing initial demand. Good planning and passive design measures allow the built form to perform as part of the environmental control system. Daylighting, passive heating, passive cooling and natural ventilation should be considered to reduce demand on HVAC loads and lighting. The building services can then be optimised based on the reduced loads.

Sustainable building design considers the building form and fabric as the primary method of environmental control. There are several planning and fabric considerations that can potentially reduce the reliance on mechanical and electrical building services. Site location and the building functional brief should be considered in the early stages of design development to identify any constraints on the building envelope. For laboratories this may include issues such as no direct sunlight, high levels of privacy or strict temperature/humidity control. Once identified these areas can be prioritised and the remaining floor area rationalised and planned to take advantage of the benefits to be derived from good envelope design.

The performance of the building envelope and the influence it has on the building energy consumption and indoor environment quality can be assessed through consideration of the following issues:

Fabric	Services
Building construction	-Storage of heat in thermal mass and control of response time. -Storage of heat in the fabric during the day then removal at night through night purge cooling. -Utilise effect of thermal mass on response time of air conditioning. -Ensure an airtight construction to minimise infiltration loads for heating/cooling.
Depth of floor plate	-Deep plan leads to a greater need for mechanical ventilation and, depending on the climate, air conditioning. -Heat loss through the fabric is reduced.

	-Shallow plan gives access to daylight and natural or mixed mode ventilation.
Orientation	-Location of air-conditioned zones on the Northern façade (Northern hemisphere) to minimise solar gains. -Use of north light or external shading to limit solar gains. -Intake air from the northern façade to give cooler air.
Glazing	-Design to optimise solar gain, heat loss and daylighting. -Use of solar shading to optimise performance. -Use of natural ventilation.
Light wells and atria	- Design to optimise solar gain, heat loss and daylighting. -Use of passive air circulation strategies. -Use of natural ventilation or mixed mode ventilation. -Use to provide natural daylight to secure spaces.

Figure 2 – Fabric vs. Services Issues [15]

The building construction could be utilised as a passive thermal store. A heavy weight construction could be used to store internal heat gains, predominant in a laboratory environment, throughout the day and then emit then outside of occupied hours. The thermal capacity of the building construction and response has to be matched to the occupancy patterns and HVAC system operation. This is effectively achieved through night purge cooling where air at a lower ambient temperature is passed over the surfaces internally or through enclosed ducts in the structure. For security reasons façade openings are usually not possible therefore night purge cooling systems require a mechanical supply with atria or roof lights providing a passive exhaust path at high level. This would be most effective in physical science laboratories with high equipment plug in loads. It would not be as effective in biological or chemical laboratories where heat gains are removed by virtue of high air change rates or where 24-hour air conditioning is required.

Glare should be analysed and minimised, through the building form, to avoid the use of internal blinds that will reduce daylight availability. Dark interior fit outs that absorb useful daylight should be avoided. Light shelves can be used to maximise light penetration or ceiling service voids pulled back at the perimeter as illustrated in Figure 3 below. Atria should also be made use of to provide daylight to internal areas without perimeter facade access.

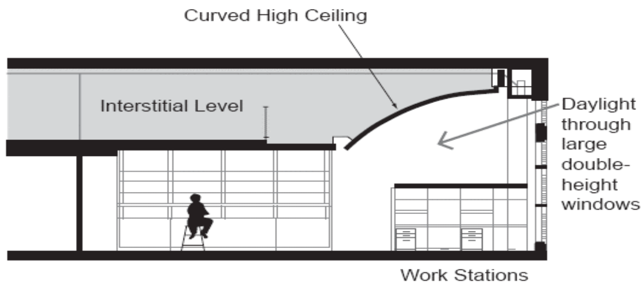


Figure 3 – Increase daylight levels. [16]

4.3.1 Example of Passive Design Measures Implemented

The University College Cork's (UCC) Environmental Research Institute, completed in August 2005, includes a number of passive design features. It is part of an ongoing research project run by the Informatics Research Unit in Sustainable Engineering at UCC and serves as a full-scale test bed for sustainable building technology.

The building brings together four research centres and the work carried out requires both laboratories and office space, for uses ranging from analysing soil samples to assessing marine pollution. Laboratories occupy the entire ground floor and northern side of the first and second floors and include 23 fume cupboards. Open plan offices are housed on the southern side of the building. Areas that don't require natural daylight, such as the cold stores, have been located together centrally. The narrow shape of the building lends itself to a natural ventilation strategy, with a maximum floor plate depth of 7.5m and floor-to-ceiling heights in the range of 3 to 4m.

A single-sided ventilation strategy is used in the offices as the primary natural ventilation strategy. In addition to the tilting windows, there are a series of manually operated ventilation doors with an external louver and fine mesh screen to provide draught- free ventilation throughout the year. Ventilation in the laboratories is again achieved using louvered ventilation doors, as well as a second door where the louvers and screen have been omitted. When fully open, these provide an almost 100% free area to meet summertime cooling loads. The doors rely on manual and automatic control, with fine control achieved through the degree of door opening. The only mechanically ventilated areas are the clean room, internal stores, and toilet areas.

The south-facing side of the building has a higher area of glazing than the other facades and the internal airflow is encouraged to distribute the passive solar gain collected here. During summer conditions, the stairwells act as thermal stacks to draw warm air out of the building. To complement the passive thermal approach, the building uses a concrete frame construction with cast in situ walls, floors and roof to give it a high thermal mass.

An overall daylight factor of 5% was briefed and the amount of glass required and the position was optimized to achieve this. Full height glazing was avoided as it was thought that this would throw the daylight below the working plane and reduce the heat loss to daylight benefit balance. The glazing was co-ordinated with the internal planning with desks set back from the wall and aligned with the higher-level windows. Full height windows were positioned between groups of desks to improve indoor environment quality by providing access to external views. Occupant level windows were fitted with solar control glass to limit glare and avoid the need for blinds, to avoid a blinds-down lights-on scenario.

The energy target for the building based on these passive solutions was set at an ambitious 100 kWh/m^2/yr. For the type of laboratory and function a good practice figure of 240 kWh/m^2/yr was used as the benchmark. In addition to the passive solutions a number of active systems were also included to reduce energy consumption; heat pumps utilizing the local river with the supply water preheated from heat scavenging within the building e.g. from cold rooms, a solar array comprised of both flat and vacuum collector panels (part of an additional research project), an energy efficient lighting system, under floor heating system with reduced LTHW temperatures and condensing boilers. Active systems for energy reduction are considered further in Chapter 5.

4.4 Space Planning

The introduction of low energy building design means that architectural space planning, based on relationships between spaces and internal communication, must also consider access to the façade and natural daylighting. Typically the premium locations on a floor plate are considered to be around the perimeter with access to daylight and external views. The internal core areas are often considered secondary. Laboratories however often require protection form direct solar heat gain and a level of isolation.

Space planning should take into account the different use of spaces and the relative position of spaces. Often in laboratory buildings, lab areas are located central to the floor plate with administrative offices and write up spaces around the perimeter. The core laboratory spaces often require air conditioning to deal with equipment and occupancy heat gain. The perimeter will experience less heat gain, excluding solar, and greater heat loss through the fabric thus requiring heating. Heated air from the offices will typically be drawn into the laboratory, under negative pressure, only to be cooled back down again. All functional requirements should therefore be considered. Correctly grouping equivalent areas and zoning services to match the actual requirements of each area is an important factor in achieving energy efficiency. Improved zoning can lead to the separation of areas of high heat gain. The interaction between the building services should be considered to avoid conflict. Controls should be designed into the system to avoid basic issues such as simultaneous heating and cooling between spaces.

Laboratories central to the floor plate could be formed around a central courtyard. The solar heat gain can be controlled at roof level and through the courtyard while natural daylight can be introduced to internal areas. Spaces on the perimeter have the benefit of access to views and natural ventilation and daylight potential by being on the façade.

Internal planning should also consider the services distribution in terms ceiling void and riser allowances to ensure adequate space is provided to facilitate low pressure drop design. Plantroom locations should also be considered in this respect preferably allowing for decentralised air handling units for effective zoning as discussed in the proceeding chapter. Energy recovery in terms of adjacency of supply and exhaust systems should also be considered.

5 Energy Efficient Servicing Strategies

Once the building envelope has been established the building services are to be developed and selected. The building services should be designed to take advantage of the benefits provided by the structure through passive design. For example if natural day lighting has been incorporated into the passive function of the envelope suitable lighting controls must be provided to allow the artificial lighting only to operate when required to avoid unnecessary usage. This can be controlled using photoelectric daylight sensing controls. The building services must be developed to suit the operational brief of the laboratory while providing flexibility for future operations and change of use. The function of a laboratory, particularly research types, is continually evolving. Distributed modular plant as opposed to central air handling units often provides the most flexible solution to a changing brief. Close control air conditioning systems should only serve areas occupied or requiring critical control. It should be limited to areas identified during the briefing process with wider environmental conditions to all others. The opportunity to maximise the energy efficiency of laboratory environmental control systems is discussed below including recommendations for practical energy saving strategies that could potentially be employed.

5.1 Central Plant

5.1.1 Chillers and Boilers

Well-designed chillier operational strategies should take advantage of 'free cooling' when the external ambient allows, typically below 10^{o}C (dry bulb) in the U.K. This can be achieved in a conventional air-cooled system with dry coolers, the chiller is by-passed and only fan energy, passing outside air over a bed of coils, is required to reject heat. Alternatively in a water based heat rejection system, the wet bulb temperature becomes more significant in the free cooling cycle. The chiller is by-passed and the condenser water circulates through the cooling tower and a heat exchanger coupled with the chilled water circuit. Both options provide opportunity to save compressor energy within the chiller when satisfying internal space cooling loads.

If close control (temperature and humidity) is not required outside air, of low ambient temperature, could also be introduced directly into the space with no chiller operation required, the effectiveness of this strategy will depend on the quantity of air delivery compared to the space cooling load. The peak building cooling loads usually coincides with the maximum (summer) ambient temperatures. However laboratories often have continuous all year round internal gains from equipment and processes, which can take advantage of free cooling throughout the year. Enthalpy controls can be used in the return air system to increase the fresh air supply when the outside air can be used for useful cooling and/or dehumidification purposes. This can also be achieved using a mixed mode ventilation system, natural ventilation via trickle vents or openable windows can introduce outside air in winter. Free cooling may not provide opportunity to reduce the peak-cooling load and as such the chiller size, however operating time is reduced and as such energy consumption.

Chilled water should be provided at the highest temperature possible. Raising the maximum space and humidity limits should be considered as this often drives chilled water supply temperatures.

Condensing boilers should be used to maximize efficiency by recovering latent and sensible heat from combustion gases. Operating water temperatures should be reduced to obtain maximum benefits e.g. 60°C to 40°C flow and 50°C to 30°C return. The return water temperature should reduce with falling load using a 2-port valve arrangement and variable speed pumping, 3-port terminal control will increase the return water temperature. The boiler selection and circuitry should ensure that the lead condensing boiler units operate at the lowest water return temperatures and carry the annual base heating loads for the facility. Lower capital cost non-condensing boilers could be used to deal with the peak load.

Centralised chiller and boiler systems offer better efficiencies and should be modular where budget and space allow. This will permit a smaller number of units to operate at near maximum capacity to meet the current demand, each modular unit will be brought online as required, leading to higher efficiency part load cycles. The part load efficiency should be analysed and selections should consider these figures, as due to the high diversity of laboratory usage the plant will regularly be operating below maximum capacity. Modules of differing size should be considered to best match the loads more accurately.

The length of air and water distribution circuits should be minimised to reduce fan and pump energy respectively. System pressure drop should also be minimised through correct sizing of pipework and ductwork using the minimum number of bends and fittings. In particular the index run to the furthest point in the system should be detailed in the simplest route possible as this determines the pressure drop for the whole system. Decentralised air handling plant should be located as close to the treatment zone as possible. To achieve this plantroom locations, air intakes/exhausts positions and reticulation routes have to be included in the space planning at an early stage.

Variable speed drives should be considered on all relevant central plant items, this includes chilled water, hot water and condenser water pumps, chillers, air coolers and cooling tower fans. These will allow systems to respond to changes in load, reducing speed and as such energy consumption while maintaining operation at high part load efficiencies.

Centralised heating and cooling plants for laboratories provide an ideal application for Combined Heat and Power (CHP) systems. CHP needs to maximize the use of thermal output and the waste heat can be used in the laboratory for space heating, process heating, dehumidification and reheat. High-grade heat from the exhaust gas may also be used to power absorption chillers to provide a chilled water source. Typically labs have an all year round cooling load, due to equipment loads, which makes CHP coupled with absorption cooling a feasible option.

5.1.2 Central Plant Sizing

The central energy plant should be selected based on accurate sizing methodology to ensure optimum efficiency under operation. Internal heat gains along with realistic heat outputs from equipment, as provided by the manufacturer should be taken into account when sizing the central energy plant and heat rejection systems. Rules of thumb applied over floor areas are common and should be avoided. This could be achieved using dynamic modelling and simulation software and measured weather data. This allows a more realistic reporting of the peak energy demand for sizing purposes, than simple static calculations.

Realistic diversity factors should be taken into account as this can reduce energy wastage through inefficient operation. The larger the facility the smaller the probability of simultaneous use of all available capacity. For example from personal practical experience fume cupboards are not all used with the sash fully open or simultaneously, a diversity factor of 65% is reasonable and applied in practice. Therefore HVAC (Heating, Ventilation and Air Conditioning) systems and process exhausts can be sized for less than peak requirements. Further to this equipment usage and subsequent heat gains should be realistically sized for actual heat outputs and frequency of use should be considered. All these items should be discussed and agreed with the facility operators.

Internal heat gains from occupants, equipment, and lighting combined with solar gains will offset a large proportion of the fabric and building heat loss in winter. These should be taken into account when sizing the central boiler plant and distribution system. In summer conditions the heat gains will contribute to the cooling load and should be minimised as follows:

- Daylight measurement and automatic switching off of electric lights when daylight levels are sufficient.
- Install 'T5' light fittings, as a minimum, with an average heat gain of 8 W/m^2 to ensure internal gains from lighting loads are not excessive.
- Switching off laboratory equipment when not in use. Particularly after hours and at weekends.
- Minimise solar heat loads through the use of performance glazing external shading and blinds.

5.2 Ventilation

Variable speed drives on supply and exhaust fans will allow the fan speed and hence energy consumption to reduce as demand reduces e.g. measured by occupancy detection. This is particularly relevant in laboratories that are fume cupboards and/or safety cabinet intensive. As the fume hood sash is lowered and the air quantity required for containment is reduced the exhaust fan should ramp down to compensate. Simultaneously the make up air supplied to the space should also reduce accordingly via the use of an electronic control system and variable speed drives on the supply fans. The variable speed drives on exhaust fans are typically controlled directly from the fume cupboard integral control panel via a measurement taken from a sash position sensor. The supply air fan and other exhaust fan variable speed drives are typically controlled by a static pressure sensor within the ductwork and measurement signals relayed through the BEMS.

Variable air volume systems are therefore recommended for supply and exhaust systems within laboratories. The system provides as much air as is needed within the lab to meet the requirements and take advantage of the diversity in process exhaust demand and varying loads, thus providing energy efficiencies. This system also has the advantage of ensuring pressure regimes are maintained and controlled for increased safety.

The pressure drop in the ductwork systems should be minimized. Fume cupboards and safety cabinets should be located on the upper levels of the building to minimize ductwork runs as exhausts must terminate above the highest accessible point of the roof. Low face velocity and low pressure drop coils and filters should be used and ductwork oversized where possible to minimise resistance.

Effective zoning and distributed plant should be employed to reduce the requirement for reheat. To avoid reheat localised cooling units could be provided in areas such as chilled water cassettes or chilled beams. Passive chilled beams are preferable, if heat loads can be handled sufficiently as there are no associated terminal fans and they operate with higher than conventional chilled water temperatures, $9^{o}C/15^{o}C$ flow/return as opposed to $6^{o}C$ /$12^{o}C$ flow/return.

Where possible process exhausts make up air should be supplied passively to the space from outside. This can be ducted directly from the façade, filtered and passed over a heating/cooling coil as required. The static can be overcome by virtue of the exhaust fan, which will draw the air as required. Consideration has to be given to comfort conditions and the turbulence cause by the supply air with regard to sash containment.

Direct evaporative cooling should also be considered where moisture is evaporated directly into a low humidity air stream to lower the air temperature; enthalpy or total energy content remains constant. This is suitable in dry climates or where humidification is required.

5.3 Process Exhaust

Laboratories typically have a once through ventilation system with no air recycling, 100% of the air supplied is exhausted. The supply air is used to meet comfort conditions, health and safety requirements and provide make-up air for process exhaust requirements, any remaining air is taken via the general exhaust. Hence conditioning and distributing the air is very energy intensive and reducing the exhaust air to the lowest safe level is essential in reducing energy consumption.

Minimum ventilation and exhaust rates are assessed based on building codes and standards as previously discussed. The rates are then subject to relevant occupational health and safety regulations and the facilities own risk assessment procedures. This should be approached with safety and energy efficiency in mind. Fume cupboards (used to protect users from contaminants), safety cabinets (used to protect users and experiments from contaminants) and equipment exhausts (used to remove exhaust fumes and heat gains) all combine to determine the process exhaust requirements and subsequent make up air allowance.

5.3.1 Fume Cupboards

The current industry standard for fume cupboards is a face and bypass system. A constant volume fan continuously exhausts a given airflow and as the sash is raised and lowered the face velocity is maintained. Face velocity has to be maintained for containment purposes. Additional air is allowed to enter the hood through a bypass opening. The base target for an energy conscious facility would be a variable air volume fume cupboard. This system varies the exhaust volume drawn from the cupboard depending on sash position, while maintaining a face velocity. The fan operates with a variable speed drive controlled via an electronic air velocity sensor, which is used to directly measure the face velocity along the outer edge of the fume cupboard just inside the sash.

Fume cupboards can each have individual dedicated exhaust fans and stacks or can be manifolded with a single exhaust fan for a subset of fume cupboards. The exhaust ducts from each individual fume cupboards are connected to a main header duct. A damper, located in the fume cupboard branch duct, is used to control the volume of air from each individual system actuated through an air velocity sensor. The variable speed drive for the combined system fan is then operated via a static duct mounted pressure sensor. This has the advantage of continually allowing the fan to operate as close to the maximum point of efficiency as possible and at reduced speeds while providing opportunity for centralised heat recovery. If the combined system fan is not variable speed energy savings can still be realised by operating a fresh air intake bypass to the header duct. This arrangement has no effect on the fan power component but allows savings in energy by drawing outside air to maintain flue stack velocity, instead of conditioned air.

Overall variable air volume fume cupboards allow minimisation of system energy by controlling the exhaust air flow to levels required to maintain safety and do not exhaust additional air beyond these limits. Energy consumption for exhaust and supply fans, conditioning of supply air and treatment of exhaust air is thus reduced. As laboratories often use 100% outside air, the energy reduction for conditioning of supply air associated with variable air volume control can be significantly more than that attainable in a typical building that uses a large proportion of recirculated air.

The stretch target for energy conscious facilities would be to utilise variable air volume fume cupboard exhausts combined with low face velocity models. These can achieve or exceed the containment levels attained by standard fume cupboards, but at lower face velocities, 0.3m/s (versus 0.5 or 0.6m/s), by aerodynamic design of the internal casing and baffles to achieve stable non-turbulent air flow within the cabinets. The adoption of this type of fume cupboard would effectively reduce supply and extract volumes by 40 to 50%.

5.3.2 Safety Cabinets

Similarly to fume cupboards, energy consumption with respect to operation of safety cabinets arises from the heating and cooling of the quantity of make-up air drawn into the laboratory to make up for extracted air and the fan power absorbed in the extraction processes. The optimum is achieved when the extraction rate for each laboratory does not greatly exceed that required to achieve the desired negative room pressure regime when in use.

Thimble extract systems have been adopted in recent installations as a means of combining room extract and safety cabinet extract functions. From an energy consumption view this should be avoided as they over ventilate the room if providing extract for every safety cabinet, possibly providing 20-30 air changes where 8-10 air changes per hour only are necessary for pressure regime maintenance.

5.4 Energy Recovery

Energy recovery devices can be utilised to recover temperature and/or humidity from exhaust air streams or waste heat from equipment to pre treat supply air streams. This saves a proportion of energy that would normally be required to heat and condition the supply air. Since laboratories often use 100% outdoor air with no recirculation energy recovery is an important consideration. The increased pressure drop caused by the devices must be accounted for in relation to distribution energy when evaluating. Heat recovery from water transfers only sensible heat, while energy recovery from air provides the opportunity to transfer both sensible and latent energy.

The intent of air-to-air heat recovery is to transfer heat (sensible) and energy (sensible and latent) between the supply and exhaust air streams. Several conventional devices are available for heat recovery: run around coils, plate heat exchangers and heat pipes and for energy recovery: hydroscopic fixed plate heat exchanger, heat wheels and liquid desiccants. Care has to be taken in direct air-to-air transfers to avoid cross contamination, purge sectors and good seals minimize this.

There are unique opportunities in laboratories for water to air heat recovery due to simultaneous demands for heating and cooling. Chiller heat recovery can be utilised through a dual air-cooled condenser provision. This should be considered where there is a perimeter-heating load and an internal cooling load. This is a common arrangement in laboratories where offices and write spaces are located on the facade with core equipment labs in the centre of the floor plate. Instead of rejecting the condenser heat to the outside it is rejected to the exterior zone supply air stream. This heat can be further upgraded through the use of a heat pump. Condenser water heat recovery can also be used in a similar arrangement with the heat rejected by the chiller recovered via a heat exchange.

5.5 Process Cooling Water

Within labs particular pieces of equipment may require cooling that cannot be effectively or efficiently supplied by air-cooled mechanisms, in this case cooling via process cooling water is necessary. This allows heat gain to be removed directly from the equipment such as lasers, centrifuges, vacuum pumps, incubator, blast ovens and furnaces. Instead of cooling the process water to low temperatures pumping higher volumes should be considered. This will lead to increased pumping energy but this will typically be less than the compressor power from the refrigerant system. Heat exchange with the chilled water return or the condenser water circuit (if water based heat rejection) should also be considered along with dry air cooler heat rejection, taking into account the additional fan energy associated with the latter.

5.6 Artificial Lighting

Natural daylight should be established as the primary light source and integrated with the artificial lighting through suitable controls where feasible. Automatic control strategies to be considered include; occupancy detection, infrared or CO_2 monitoring, time scheduling, daylight sensing and dimming. For industry best practice lighting systems should be zoned in areas no greater than 100m^2 with individual switching for each zone.

General lighting levels should typically not exceed 400 Lux with dedicated task lighting provided to appropriate areas. The most efficient equipment available should be selected for individual task lighting applications. General lighting power density should not exceed 3 W/m^2 per 100 Lux. (17) To achieve this high efficacy T5 lamps (90 Lumens/W) and electronic ballasts should be utilized in single rows, representative of current industry best practice.

5.7 Controls and Monitoring

A Building Energy Management System (BEMS) that incorporates direct digital control is necessary in laboratories to ensure energy efficient operation of the facility. This is achieved through monitoring, controlling and tracking energy consumption automatically through the BEMS. The BEMS provides a centralised user interface that can be used to optimise plant operation and interrogate the building systems for troubleshooting purposes. It allows dynamic and precise control, the co-ordination of facility systems operation, optimisation of facility diversity, trend and history data logging and customised energy reporting.

The design team is required to specify a sequence of detailed comprehensive control strategies that can be programmed into the BEMS to match the design intent with operational reality. The associated sensors and actuators should also be nominated at design stage. Operation of the BEMS should be demonstrated to the facilities management at handover stage.

Major control parameters within laboratory environments will include temperature and ventilation. Controls should be programmed to maximize safety and energy efficiency by varying airflow, tracking temperature set points and adjusting pressures, both air and water. Optimised responses to varying loads will maximise efficiency opportunities e.g. utilise variable speeds drives to reduce airflow when sashes are down on fume cupboards.

The optimal operation of the building as calculated based on design provides a base level of energy demand or a minimum level of energy expenditure. Any reduction in base energy requirement implies a change in building construction or use. The difference between actual energy expenditure and the base requirement represents avoidable waste. Avoidable waste in laboratories has many causes, including those listed below which are affected by the BEMS:

- Poor occupancy and temperature level control,
- Poor artificial lighting control,
- Ineffective use of internal heat gain,
- Excessive ventilation, fume cupboard or safety cabinet sashes left at full height,
- Excessive air conditioning use,
- Low operating efficiency of the HVAC system,

Major contributions of the control system in reducing waste are:

- Limiting heating and cooling to the minimum period necessary; this usually includes the use of optimum start controllers and occupancy detection to avoid excessive out-of hours use,
- Prevention of unnecessary central plant operation,
- Occupancy and daylighting sensing to control lighting,
- Fume Cupboard/Safety Cabinet sash position and containment,
- Varying air flow and water flow to match demand,
- Monitoring to give early warning of malfunction or inefficient operation.

6 Methodology and Design Parameters

This work thus far has endeavoured to identify the key factors associated with the successful achievement of low energy laboratory design. To provide high-level consideration on those key factors a methodology has been developed in the form of a step-by-step process to guide the design. In the proceeding chapters this is exemplified through the application of the methodology to a case study example. From the analysis of several low energy laboratories case studies, research and industry experience the key factors responsible for the success of the implemented energy measures were identified and are main stages in the flow chart below.

6.1 Methodology

The following flow chart outlines the recommend methodology for achieving low energy design in laboratory buildings and should be applied as a general approach to optimise design of laboratories.

SITE
- Climate; consider potential for passive design, influence of external conditions on HVAC loads - Orientation; consider potential for passive design measures, optimisation of solar heat gains - Surroundings; consider natural shading and potential heat sink/sources e.g. river

BRIEF
- True requirements; challenge the brief specified, internal conditions and loads - Operational considerations; understand the functional requirements of the laboratory

REGULATIONS
- Building regulations; consider legislated requirements - British Standards; consider legislated requirements - Health and safety requirements; consider industry guidelines and facility risk management policies

Continued on the next page.

DEFINE DESIGN PARAMETERS (For example parameters please see Section 6.2)
- Environmental conditions - Lighting loads and schedules - Occupancy density and schedules - Type, load and schedules of equipment operation -Air flow requirements

DEFINE LABORATORY TYPE (For Lab type description see Section 1.1)

Type	**Research**	**Biological**	**Instrumentation**
Ventilation Rate	High	Medium/High	Low
Equipment Load	Low	Medium	High
Laboratory Conditions	Low	High	Medium

- Ventilation rates; low = no fume cupboards or safety cabinets, high = fume cupboards and/or safety cabinets
- Equipment loads; low = 0 to 50 W/m2, medium = 50 to 100 W/m2, high = 100 to 150W/m2 (electrical and thermal)
- Laboratory conditions; low = 21/24oC and 40/60% RH, medium = 21 +/-1oC and 55% RH +/-5%, high = cold rooms to -5oC+/-1oC and hot rooms 40oC+/-1oC

Note: definitions outlined above are relative for the purposes of applying the methodology

RECOMMENDED DESIGN STRATEGIES (GENERAL)

BUILT FORM – INTEGRATED DESIGN TEAM APPROACH TO BE ADOPTED
- Space planning; group similar areas to allow effective zoning of services - Narrow/deep plan; consider passive, natural ventilation and daylighting strategies - Form and fabric; utilise to reduced mechanical and electrical services demands

Continued on the next page.

RECOMMENDED DESIGN STRATEGIES (GENERAL)

BUILDING SERVICES
- Condensing boilers - Modular plant for increased part load efficiencies - Variable speed drives on all central plant -Efficient lighting and lighting control systems -Low pressure drop ductwork and pipework design

⬇

SELECT APPROPRIATE LAB TYPE

RESEARCH
- Variable air volume supply and exhaust ventilation system, linked to fume cupboard operation - Size for fume cupboard usage diversity; see profiles in Section 6.2 - Unconditioned make up air drawn directly from the facade - Low face velocity fume cupboards - Sensible air to air heat recovery - Chiller heat recovery - Free cooling; dry air cooler, chiller bypass to cooling tower and direct supply of ambient air - Raises temperature CHW; raise space temperature and humidity limits

⬇

OR

BIOLOGICAL
- As Research plus - Chilled beams; increased CHW temperature (as less air movement but greater equipment load) - Direct humidification; provides evaporative cooling in the air stream - Cold room refrigeration system heat recovery

⬇

Continued on the next page.

OR

INSTRUMENTATION
- Storage of heat gain in thermal mass; control of response time and stabilising conditions
- Night purge cooling
- Free cooling; dry air cooler or chiller bypass to cooling tower
- Size for equipment load usage and diversity, see profiles Section 6.2
-Direct equipment process cooling water; circulate high volumes and reduce temperature
-Combined heat and power coupled with absorption cooling

6.2 Design Parameters

The profiles below are based on ASHRAE 90.1-1989 for office occupancy modified for use in laboratories. [(18)] Laboratories are classified as office in ASHRAE 90.1. As they are based on office schedules the profiles assume heavier loads during normal office hours typically 8am to 5pm. Modifications have been made to reflect potential 24 hour operation in laboratories.

6.2.1 Lighting Profiles

Lighting loads in laboratories can vary between 8 W/m^2 and 35 W/m$^{2.}$ The upper limit, 35W/m^2, is based on the maximum allowed lighting power outlined in the ASHRAE Laboratory Design Guide. [(19)] The lower limit is based on an industry standard T5 lighting solution with no additional task lighting component. Figure 4 below represents a typical weekday lighting profile while Figure 5 represents a typical weekend profile based on % usage.

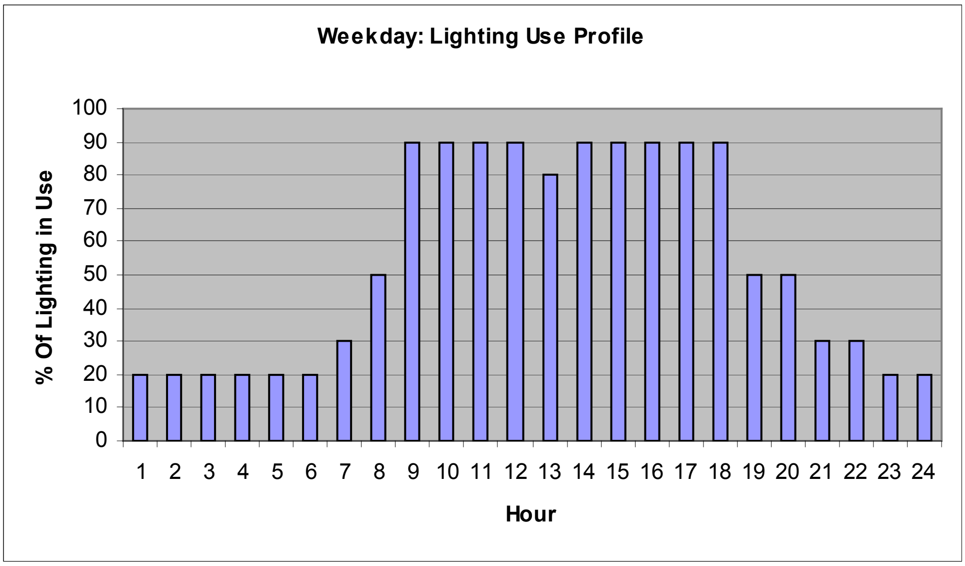


Figure 4: Weekday Lighting Use Profile

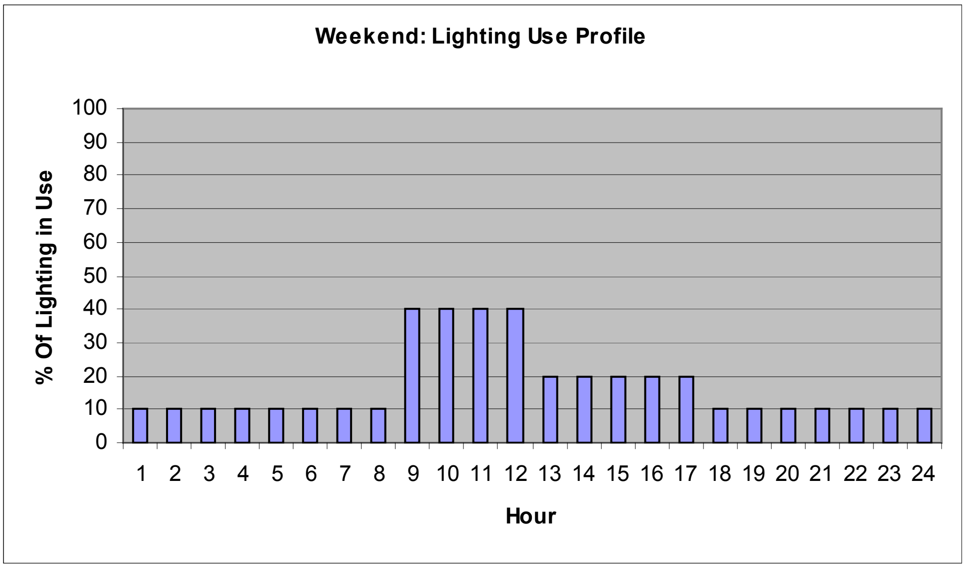


Figure 5: Weekend Lighting Use Profile

6.2.2 Occupancy Profiles

Occupancy densities in laboratories vary significantly with the type and purpose of the laboratory. The ASHRAE Laboratory Design Guide [20] nominates occupancy densities between 15.24 up to 76.2 m^2 per person. A typical office is 10 to 15 m^2 per person as comparison. Occupancy heat gain varies depending on activity, for an occupant moderately active walking and carrying out light work a figure of 90W-100W sensible heat gain and 50-60W latent heat gain can be assumed [21]. Figure 6 below represents a typical weekday occupancy profile while Figure 7 represents a typical weekend profile based on % usage.

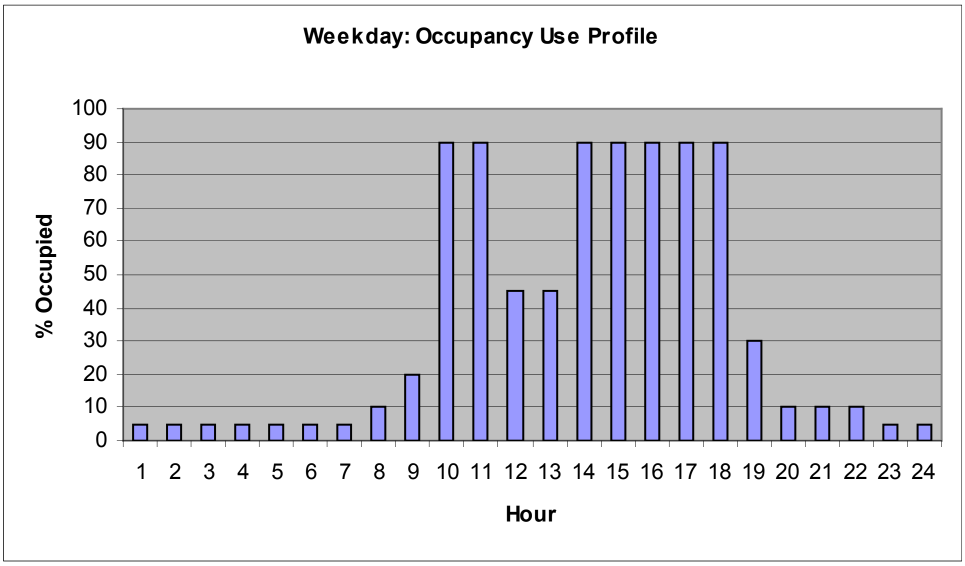


Figure 6: Weekday Occupancy Profile

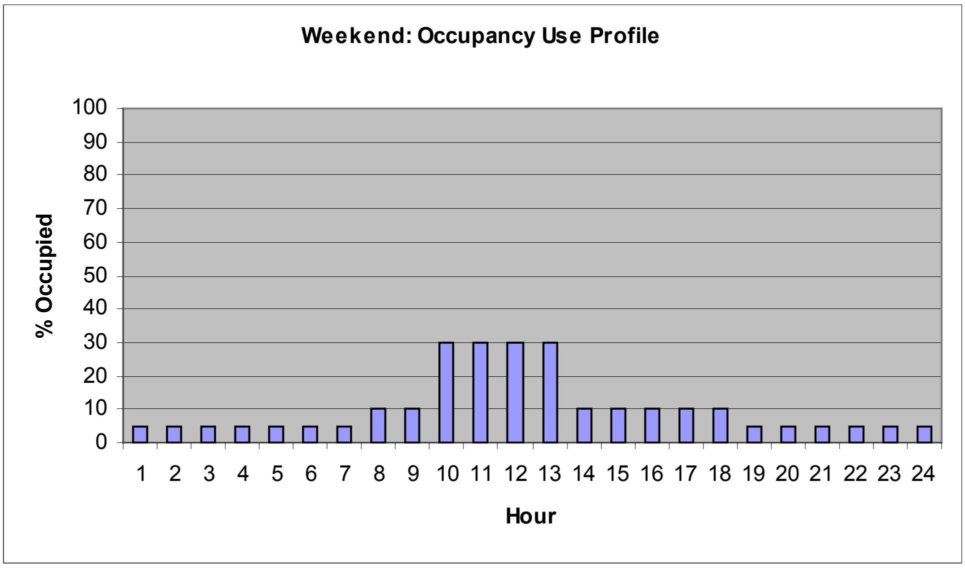


Figure 7: Weekend Occupancy Profile

6.2.3 Equipment Profiles

Equipment use in laboratories generates sensible and latent heat gains and as such associated electrical and thermal loads have to be estimated. The most accurate method of estimation is to schedule all the equipment expected within the laboratory and isolate the individual energy use associated with each item of equipment and the expected daily duration of use. This has to be done on an individual laboratory basis based on the equipment inventory. Industry based rules of thumb should be avoided but are typically between 50W/m^2 up to 150W/m^2. Figure 8 below represents a typical weekday equipment profile while Figure 9 represents a typical weekend profile based on % usage.

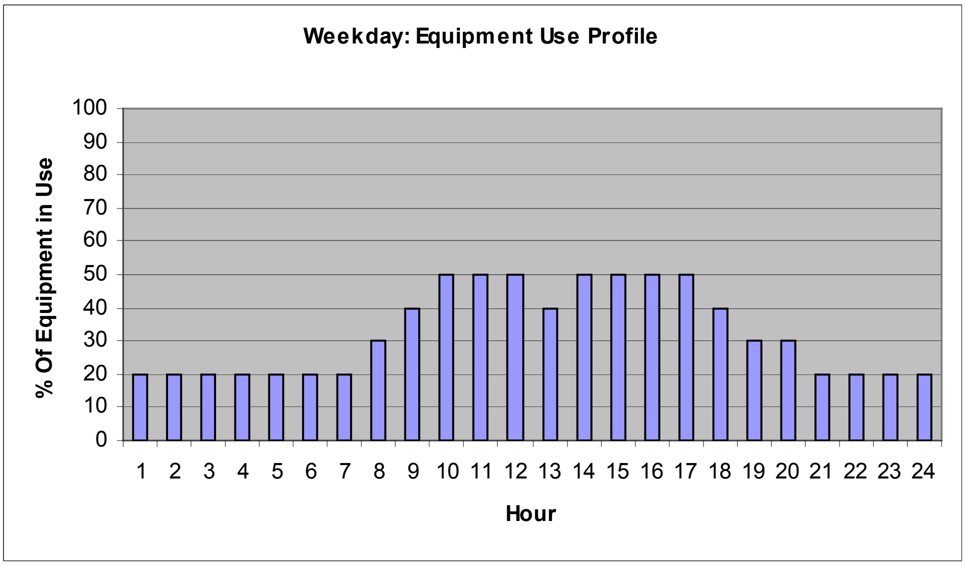


Figure 8: Weekday Equipment Use Profile

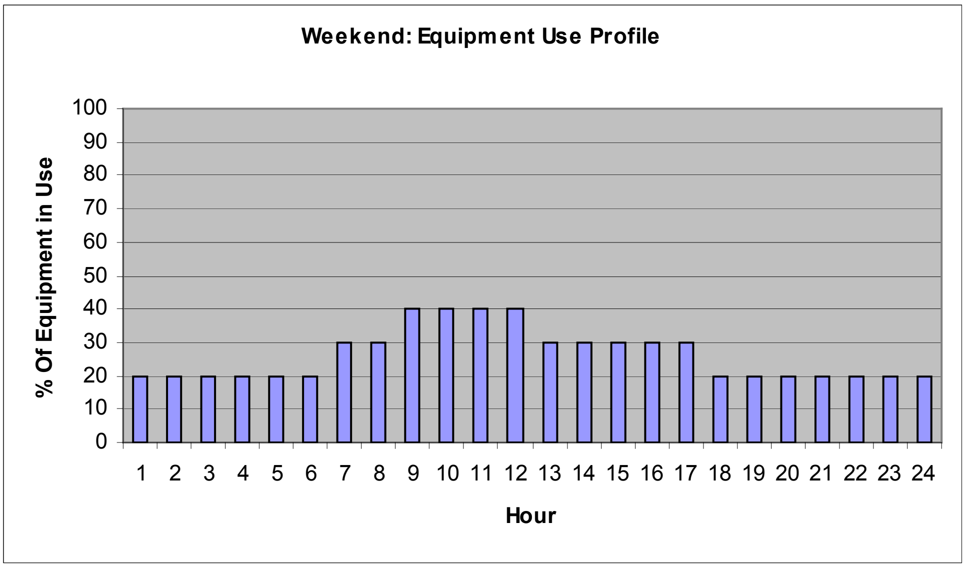


Figure 9: Weekend Occupancy Use Profile

6.2.4 Fume Cupboard Usage Profiles

The diversity is use of fume cupboards for a typical weekday and weekend is shown in Figures 10 and 11 below respectively. The schedule is based on the premise that fume hood use is directly related to occupancy and when in use the sash is fully open and the maximum volume of air is extracted. When not in use, 50% maximum airflow is assumed with the sash at half height. Based on current University facilities operating fume cupboards this can be reduced in reality to 20% maximum airflow when not in use or off based on the laboratory sash management policy.

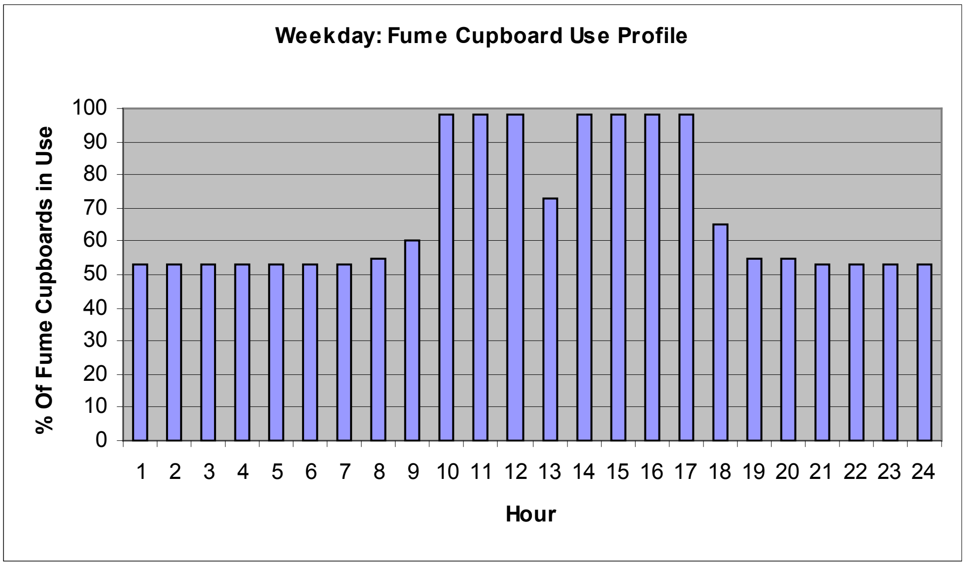


Figure 10: Weekday Fume Cupboard Use Profile

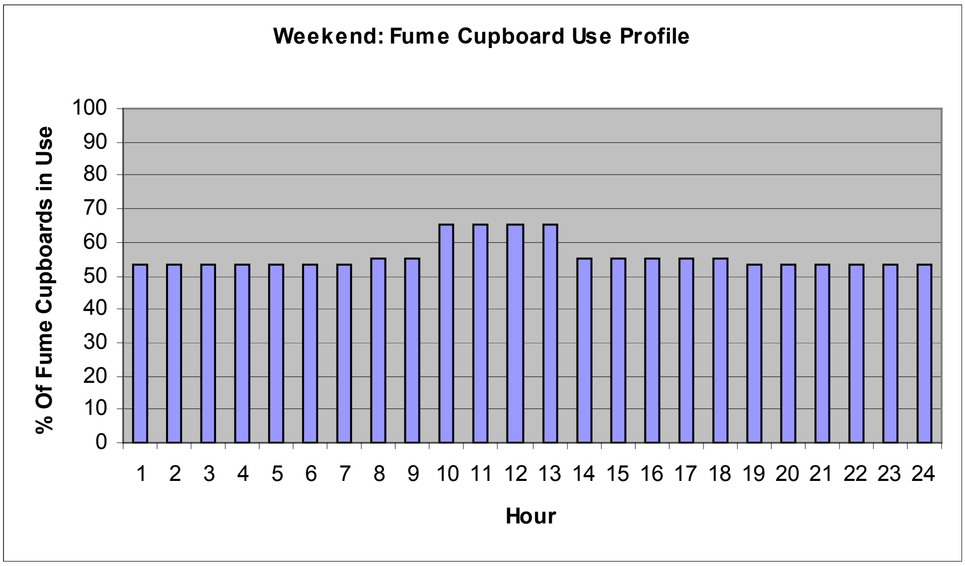


Figure 11: Weekend Fume Cupboard Use Profile

7 Case Study: Thermal Analysis

An energy analysis study was carried out to evaluate selected energy efficiency measures for a generic laboratory building. Computer modeling was used to compare results for a base case laboratory with results following application of specific energy reduction measures. The thermal analysis focuses on efficiency strategies designed to reduce the HVAC (Heating, Ventilation and Air Conditioning) system energy consumption.

7.1 General

The laboratory model is based on an existing University facility located in Central Scotland. The facility is research based with a mixture of under graduate and postgraduate research activities. The building is modelled with 24-hour operation based on the load profile diversities outlined in Chapter 6. A typical floor, Level 2, has been modelled in detail for the purposes of this study. Level 1 and 3 have also been included and controlled to meet the internal design conditions. This allows a more accurate representation of the heat transfer process through the floor slab. The energy used to meet the conditions in Level 1 and 3 have been excluded from the comparative results presented below. The window to wall ratio within the model is 40%, in accordance with the elemental method of the Building Regulations and the windows are distributed evenly on the facade. The laboratory typical floor houses 24 fume cupboards and the ratio of areas across the floor is as follows:

- Research Laboratory 43% (20 Fume Cupboards)
- Prep Laboratory 5% (4 Fume Cupboards)
- Instrumentation Laboratory 7%
- Office/Social Space 13%
- Circulation/Core 32%

Thermal modelling has been applied to simulate the dynamic performance of the building. A detailed model of the building was created and described within the model are:

- Geometry of building form and all associated exposure of surfaces
- All material constructions
- All windows and glazing

- All internal load profiles for people, lights and equipment

Strategies relating to passive design and building fabric optimisation were not addressed as part of this study. The application of the methodology as outlined in Chapter 6 relates to the latter building services sections. Based on the recommendations outlined the energy efficiency strategies analysed include; reducing air flow during unoccupied periods and with changing demand for fume cupboard make-up air, low face velocity fume cupboards, heat recovery by run around coils and lower static pressure drop in the air distribution system.

7.2 Description of Simulation Package

In order to predict the annual energy requirements, computer modelling was performed using Thermal Analysis Software (TAS). TAS uses fully dynamic calculations to provide an accurate insight into the building envelope response as well as space and surface temperatures, internal loads and energy consumption. 3D geometry was used to represent the building in TAS; an image from the 3D model is shown in the following diagram.

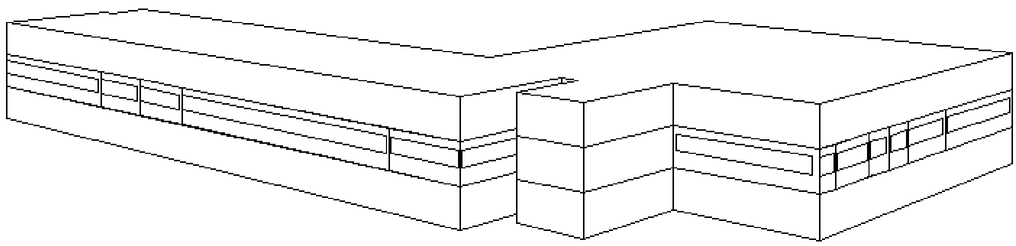


Figure 12 Image of 3D Thermal Model

The air conditioning system options are modelled using TAS Systems. TAS Systems is a component based simulation programme, which allows systems to be developed from their component parts and control arcs. These parameters are set for each of the components of the HVAC system. The simulation procedure traces the thermal state of the system and that of the building, enabling a detailed analysis for each hour throughout the year. The outputs from TAS allow plant sizing, prediction of energy consumptions, energy targeting and assessment of energy conservation options.

7.3 Weather Data

To accurately model the dynamic nature of the building thermal response, hourly-recorded weather data for Glasgow was used. The weather data contains hourly records of radiation, temperature, humidity, sunshine duration and additionally wind speed and direction for a whole year; known as ‘The Test Reference Year’.

The Test Reference Year is chosen by an ASHRAE (American Society of Heating, Refrigeration and Air Conditioning Engineers) approved procedure. A Test Reference Year is hourly weather data for a year for use in simulation of the performance of active and passive solar energy systems, building energy consumption and indoor climate calculations. It contains hourly values of a number of weather parameters for the above-mentioned purposes. The most important weather parameters have mean monthly values and monthly diurnal variations typical for the location. Because of the large amount of data (8760 hourly sets of weather parameters) Test Reference Years are used only in connection to computerised calculation methods.

7.4 Materials

Basic materials within the thermal model are shown below:

- Ceiling: Ceiling tile, 500mm services void
- Floor: 200mm concrete slab, carpet
- External walls: Plaster/insulation/air gap/concrete block. Overall U-Value 0.3 $W/m^2 K$
- Internal walls: Plasterboard/air gap/plasterboard
- Glazing: 6mm clear float/12mm air gap/6mm Low ‘E’ coated clear float. Overall U-Value 2.2 $W/m^2 K$

7.5 Zoning

The laboratory floor has been divided in multiple zones. Each zone represents an occupied space.

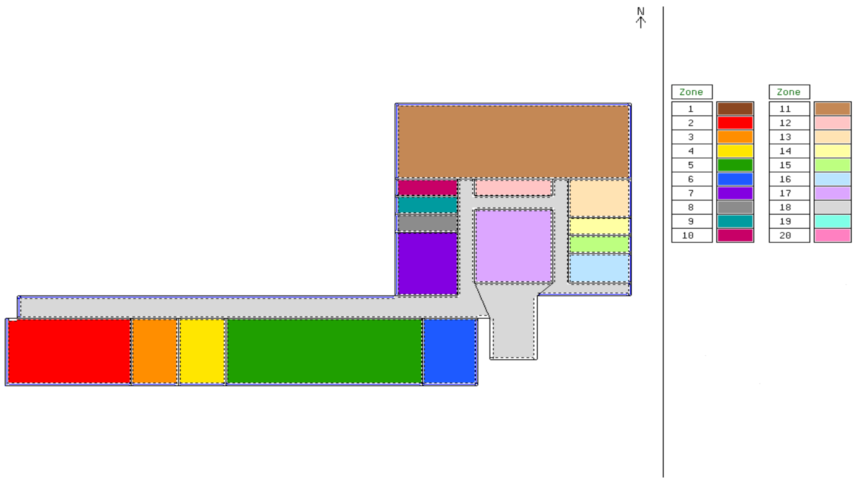


Figure 13 Thermal model zoning for a typical lower floor

Figure 13 above shows the zoning scheme used within the model. Zoning allows the load profiles for occupancy, lighting and equipment to be allocated to the specific areas to allow for part load diversity in equipment, lights and occupancy, which assists in energy conservation. It also allows varying design conditions to be assigned to each zone within the model.

An air handling plantroom is located on each floor of the building on each wing, east and west, while fume cupboard exhaust fans are located at roof level.

7.6 Internal Conditions

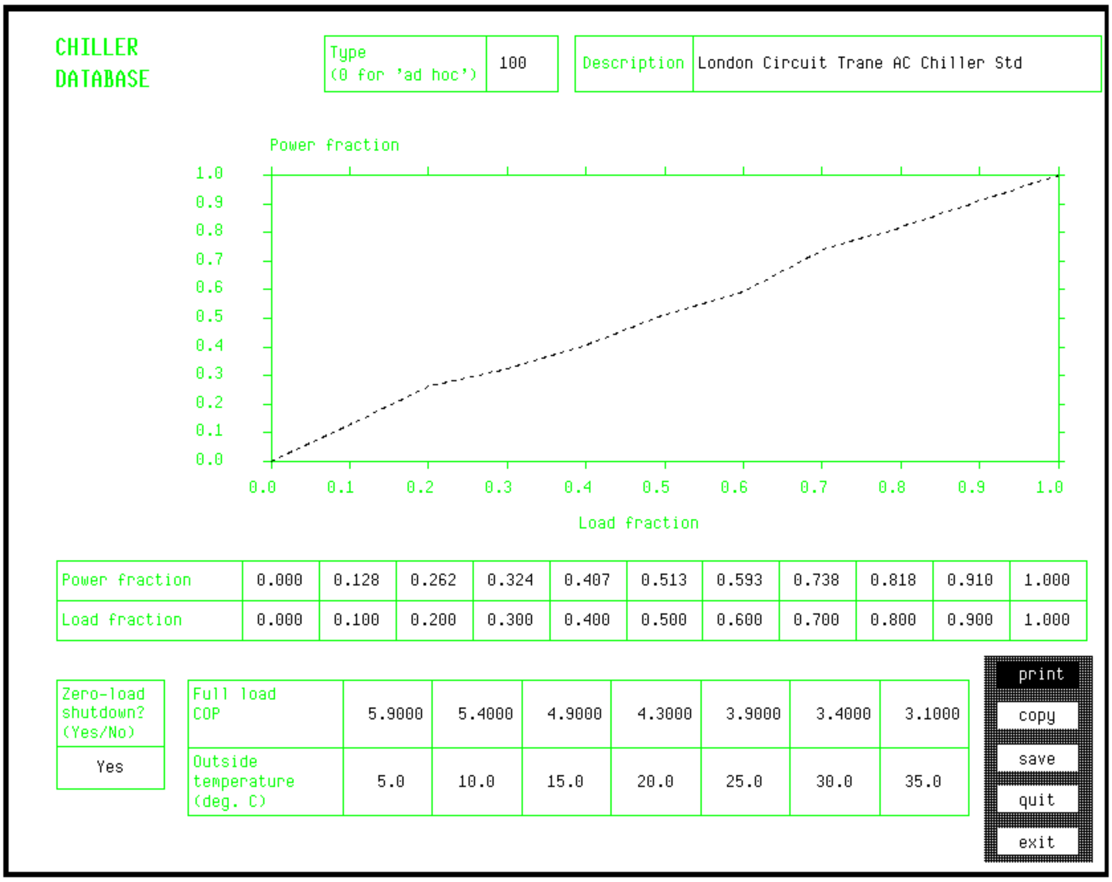
The internal conditions that have been inserted into the thermal model are described in Figure 14 below.

Internal Temperature	22.5°C +/- 1.5°C
Occupancy	70W/person sensible, 60W/person latent, 1 person per 10m^2
Lighting	8W/m^2
Equipment	15W/m^2 Office 60W/m^2 Research and Prep Laboratories 120W/m^2 Instrumentation Laboratories

Figure 14 Internal Conditions

7.7 HVAC Description

The proposed HVAC system was modelled in TAS. This consists of central plant, air handling units and an air distribution system. The central plant includes chillers, boilers, pumps and associated piping. The air-handling units include a hot water heating and chilled water-cooling coil to control to the desired set points. Primary heating and cooling is performed by an all air system, which also provides the make up air for the fume cupboards. The base case model is a constant volume system, which is then substituted for a variable air volume system. An air-cooled chiller with zero load shut down was modelled with a performance curve as shown in Figure 15 below. A condensing boiler with zero load shut down was modelled with a performance curve as shown in Figure 16 below.



Power fraction	0.000	0.128	0.262	0.324	0.407	0.513	0.593	0.738	0.818	0.910	1.000
Load fraction	0.000	0.100	0.200	0.300	0.400	0.500	0.600	0.700	0.800	0.900	1.000

Full load COP	5.9000	5.4000	4.9000	4.3000	3.9000	3.4000	3.1000
Outside temperature (deg. C)	5.0	10.0	15.0	20.0	25.0	30.0	35.0

Figure 15 Chiller Performance Curve

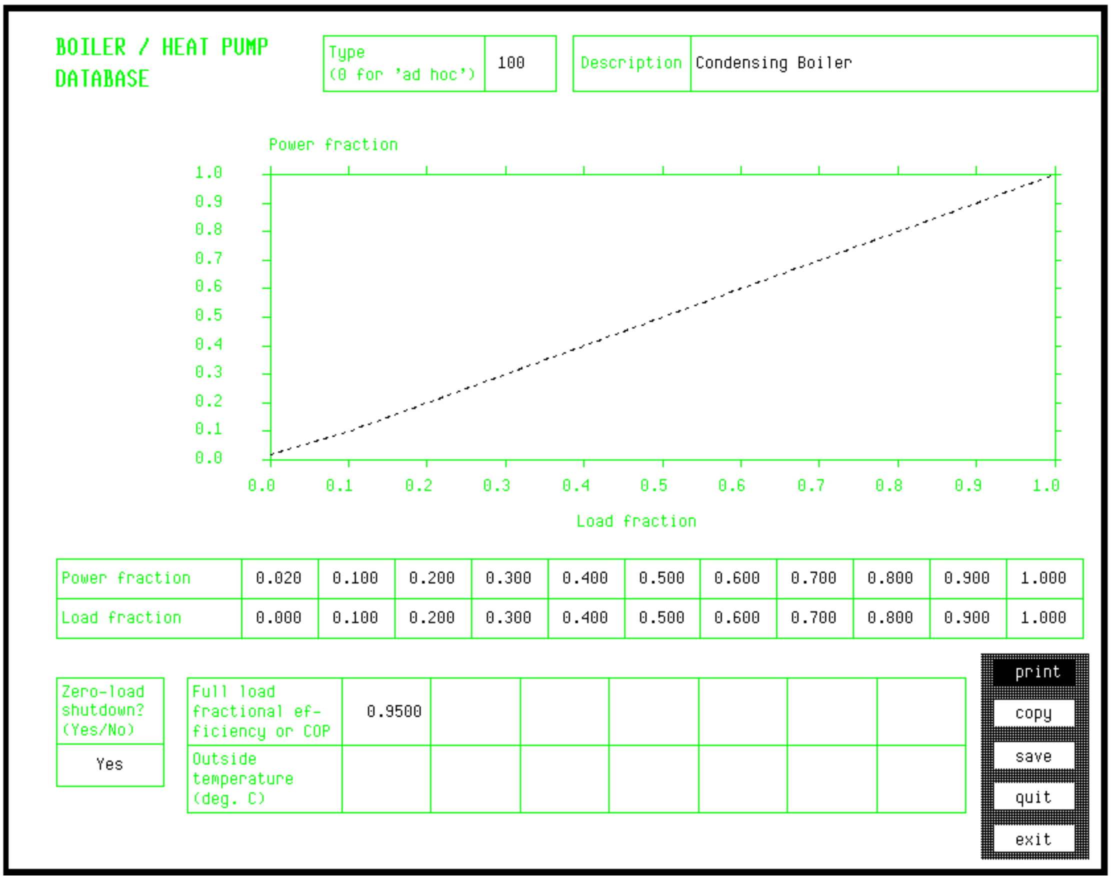


Figure 16 Boiler Performance Curve

8 Case Study: Thermal Simulation Results

The results of the thermal modelling and simulation are presented within this Chapter. The geometric building model as described in Chapter 7 remained constant for all options. The internal conditions and internal heat gains from occupancy, lighting and equipment also remained constant, modelled as per the profiles in Chapter 6. The HVAC (Heating, Ventilation and Air Conditioning) system was modified in TAS systems to allow assessment of each of the options in terms of energy reduction.

8.1 Base Case: CAV

A Constant Air Volume (CAV) system was modelled to represent the base case. The HVAC system was specified to supply a set flow rate of air to each space to meet the following criteria:

- Minimum fresh air requirements at 8 litres/second per person for peak occupancy
- Make up air for fume cupboards. Fume cupboards were assumed to be face and by-pass type, 2 metres long with a sash opening of 0.5m and face velocity of 0.5m/s. A constant air volume of $0.5m^3/s$ was allowed per fume cupboard.
- Peak cooling loads. The airflow rate was determined by the volume of air required to remove the equipment heat load from the space with a minimum supply temperature of 14^oC.

The supply and extract fan to each zone was therefore set to a specified airflow rate and the temperature of the supply air varied to meet the comfort conditions. This was achieved through a heating and cooling coil in the supply air duct that is controlled via sensors within each zone. Pump water flow rates have been modelled as being variable in response to demand. A schematic of the system modelled is shown in Figure 17 below.

The energy required to run the system for a year was predicted by simulating the model using the Glasgow U.K. weather file. The results are presented in Figure 18 below and the energy has been broken down into each major component of the HVAC system.

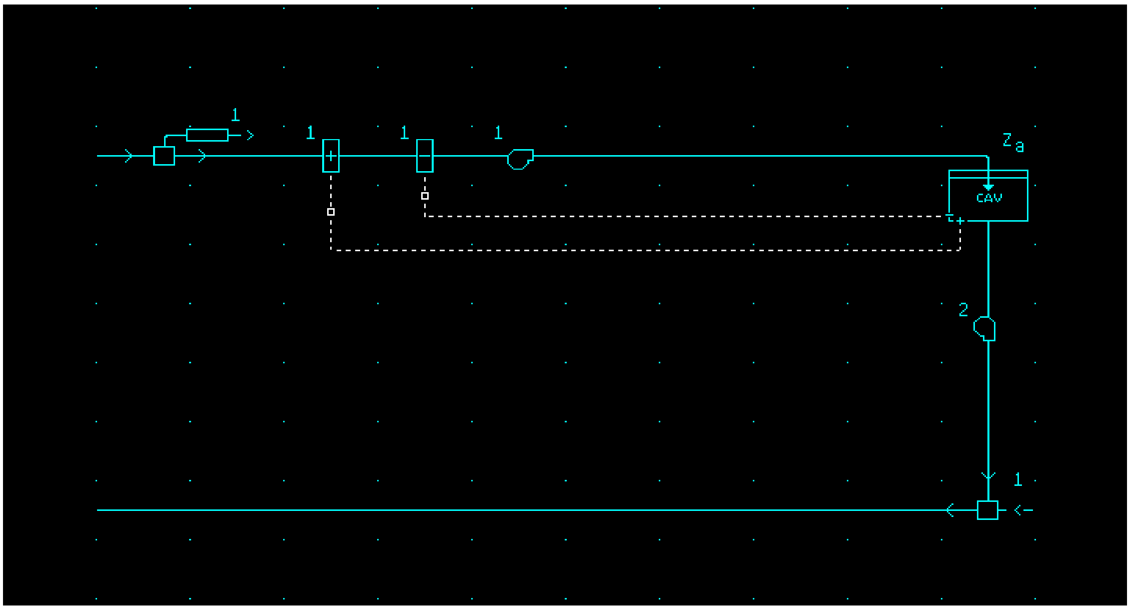


Figure 17: CAV TAS System Model Schematic

Month	Gas Boiler kWh/yr	Electrical Chiller kWh/yr	AHU Fans kWh/yr	Pumps CHW kWh/yr	Pumps HW kWh/yr	Total Electrical kWh/yr
1	194160	0	9760	0	3689	13449
2	188734	0	8815	0	3586	12401
3	175223	0	9760	0	3329	13089
4	163274	0	9445	0	3102	12547
5	122074	7	9760	2	2313	12083
6	74184	266	9445	74	1391	11176
7	57299	740	9760	209	1068	11776
8	65162	1088	9760	323	1223	12393
9	86130	47	9445	13	1622	11127
10	122150	3	9760	1	2318	12081
11	182837	0	9445	0	3474	12919
12	184137	0	9760	0	3499	13258
Total	1615364	2151	114913	622	30612	148298

Figure 18: Base Case HVAC Energy Consumption

8.2 Option 1: VAV

A Variable Air Volume System was (VAV) system was modelled as Option 1. Using a VAV system for the laboratories has potential to reduce air handling unit fan, fume cupboard extract fan and space cooling and heating demand. The air supply and extract to each zone was modelled to meet changing demands in occupancy, heat load and fume cupboard usage. Minimum airflow rates were set for each zone based on minimum fresh air requirements. The HVAC system was controlled to vary the air supply as required to meet comfort conditions. A heating and cooling coil in the supply air duct controlled the air temperature to ensure that the zone air temperatures meet the comfort criteria. This was achieved through measurement via off coil sensors and sensors located in the extract air duct. An individual trimmer heating coil is also used to offset the fabric losses in each zone controlled through a local temperature sensor. A schematic of the system modelled is shown in Figure 19 below.

The diversity in the fume cupboard demand was based on the usage profiles outlined in Chapter 6. It was assumed that when the fume cupboards were in use the sash was fully open and the air volume demand was $0.5m^3/s$. When the fume cupboard is not in use the fume cupboard fans were assumed to be off. This is a simplified worst-case scenario assumption for the purposes of energy assessment. In reality the air volume demand would vary continually between, $0.15m^3/s$ to $0.5m^3/s$ depending on the sash height, while in use. The sash is likely to only be at full height for a small proportion of the usage time.

The energy required to run the system for a year was predicted and is presented in Figure 20 below.

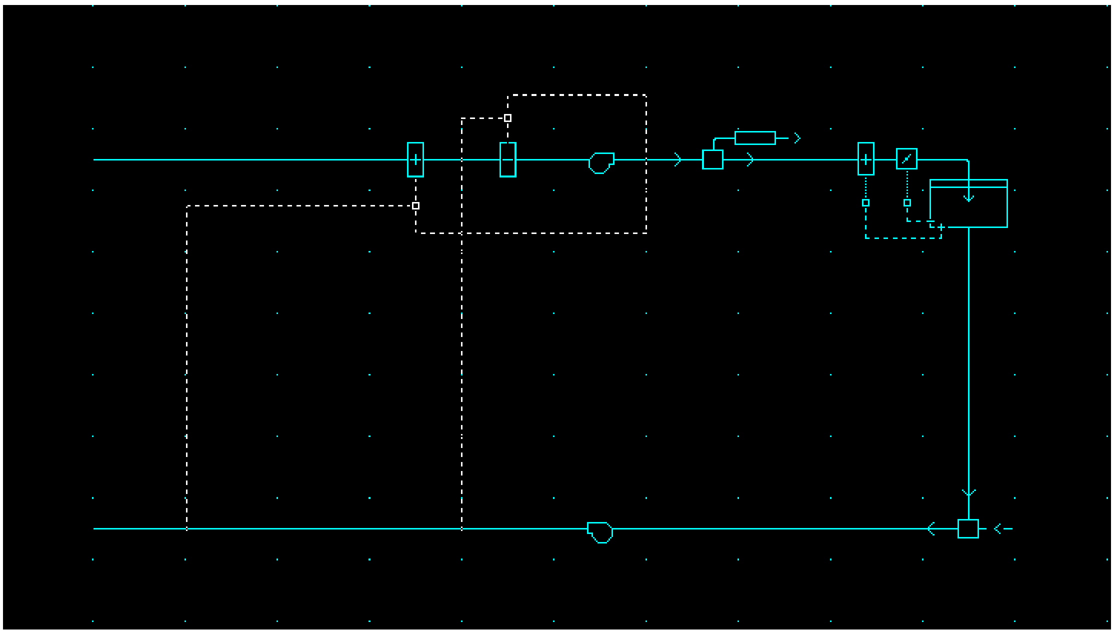


Figure 19: VAV TAS System Model Schematic

8.3 Option 2: VAV & Low Face Velocity Fume Cupboards

Option 2 is as Option 1 described above but with the replacement of the standard fume cupboards with low face velocity fume cupboards. Low face velocity fume cupboards can achieve or exceed the containment levels attained by standard fume cupboards but at lower face velocities, 0.3m/s, by aerodynamic design. The adoption of this type of fume cupboard could effectively reduce make-up air supply and extract volumes by 40%.

The energy required to run the system for a year was predicted and is presented in Figure 21 below.

Month	Gas Boiler kWh/yr	Electrical Chiller kWh/yr	AHU Fans kWh/yr	Pumps CHW kWh/yr	Pumps HW kWh/yr	Total Electrical kWh/yr
1	119120	40	5911	14	2263	8228
2	115809	53	5338	19	2200	7611
3	108196	184	5921	67	2056	8228
4	101134	228	5741	83	1922	7973
5	76343	302	5959	109	1447	7817
6	47062	580	5795	196	883	7454
7	36980	967	6017	311	689	7984
8	41292	1125	6003	351	775	8254
9	54253	381	5773	135	1022	7311
10	76305	305	5937	112	1448	7802
11	112468	112	5724	42	2137	8015
12	112786	28	5906	10	2143	8087
Total	1001749	4305	70025	1448	18986	94764

Figure 20: Option 1 HVAC Energy Consumption

Month	Gas Boiler kWh/yr	Electrical Chiller kWh/yr	AHU Fans kWh/yr	Pumps CHW kWh/yr	Pumps HW kWh/yr	Total Electrical kWh/yr
1	73859	40	3642	14	1403	5099
2	71847	53	3289	19	1365	4726
3	67264	184	3651	67	1278	5181
4	62937	228	3545	83	1196	5051
5	47643	301	3689	109	903	5003
6	29554	526	3599	181	554	4860
7	23389	807	3748	266	436	5257
8	25855	886	3733	281	485	5385
9	33963	372	3577	132	640	4721
10	47641	305	3667	112	904	4988
11	69837	112	3528	42	1327	5008
12	69881	28	3637	10	1328	5002
Total	623671	3843	43305	1314	11820	60282

Figure 21: Option 2 HVAC Energy Consumption

8.4 Option 3: Heat Recovery

Option 3 is as per that described previously in Option 2 but with the inclusion of heat recovery on all extract systems. A run around coil has been included within the model with an assigned heat transfer efficiency of 55%. Run-around coil systems consist of water coils located in the exhaust and supply. A heat transfer fluid is pumped between the two sets of coils to affect the continuous transfer of heat from exhaust to intake air during the heating season. The fluid can transfer only sensible heat, although latent heat can be transferred from the warmer air stream to the heat transfer fluid if the coil temperature falls below the air dew point temperature, in which case condensation occurs. The run-around coil negates any possibility of cross-contamination of airflows and can be used for transferring heat from the contaminated fume cupboard exhaust streams. As the supply and exhaust systems are located separately, a local plantroom and roof respectively, it allows the heat transfer without the need for adjacency. There will be an additional energy consumption associated with the run around coils; pump energy for the circulating fluid and increase in fan energy due to additional pressure drop created by the coils. This has not been quantified explicitly for the case study but a 5% reduction in efficiency has been allowed to compensate. A schematic of the system modelled is shown in Figure 22 below.

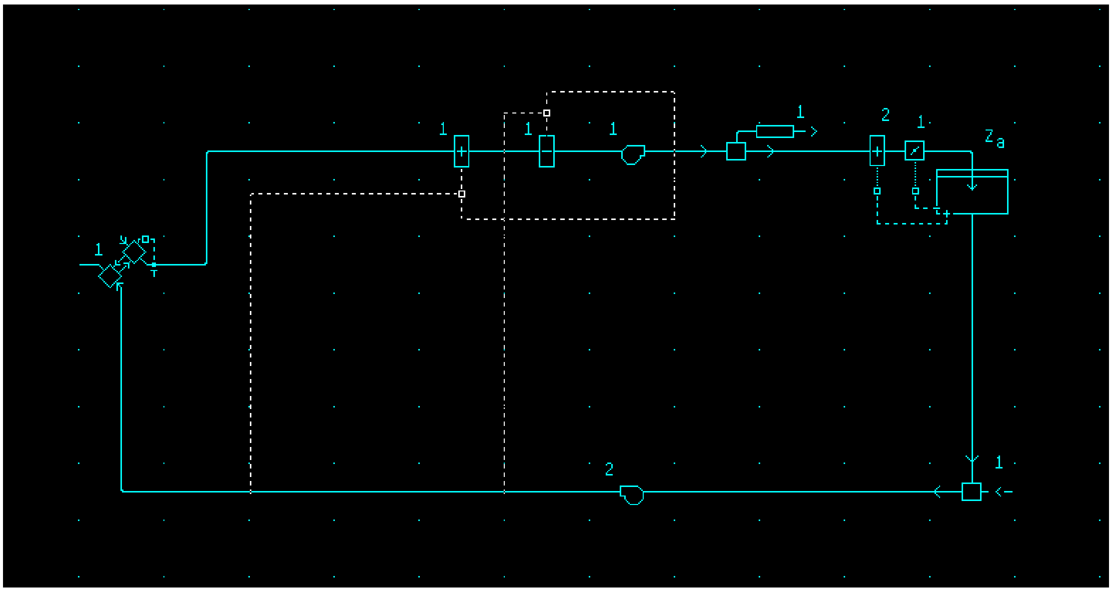


Figure 22: VAV with Heat Recovery TAS System Model Schematic

The energy required to run the system for a year was predicted and is presented in Figure 23 below.

8.5 Option 4: Low Pressure Drop Ductwork Design

Option 4 is as per that described previously in Option 2 but with a change to the ductwork design. The ductwork sizes, with the exception of fume cupboard exhausts, were selected based on the maximum flow rate and maximum velocity as per industry standard; 5m/s in a main branch and 3m/s in a terminal branch. For a particular air flow rate, increasing the duct cross sectional area reduces friction loss and hence the system pressure drop that the fans have to overcome. Frictional pressure losses are inversely proportional to duct diameter raised to the fifth power. The initial ductwork selections were increased by one size assuming increments of 100mm, which lead to a decreased velocity. The system pressure drop was reduced from 300Pa to 250Pa for the supply and from 200Pa to 150Pa for the extract. The fume cupboard exhaust ducts have to maintain a set exhaust velocity as outlined in the British Standard hence this strategy was not applied to the fume cupboard exhausts.

The energy required to run the system for a year was predicted and is presented in Figure 24 below.

Month	Gas Boiler kWh/yr	Electrical Chiller kWh/yr	AHU Fans kWh/yr	Pumps CHW kWh/yr	Pumps HW kWh/yr	Total Electrical kWh/yr
1	39298	40	3642	14	1403	5099
2	38347	53	3289	19	1365	4726
3	35784	184	3651	67	1278	5181
4	33473	228	3545	83	1196	5051
5	25144	301	3689	109	903	5003
6	15609	526	3599	181	554	4860
7	12619	807	3748	266	436	5257
8	13914	886	3733	281	485	5385
9	18104	372	3577	132	640	4721
10	25221	305	3667	112	904	4988
11	37035	112	3528	42	1327	5008
12	37000	28	3637	10	1328	5002
Total	331548	3843	43305	1314	11820	60282

Figure 23: Option 3 HVAC Energy Consumption

Month	Gas Boiler kWh/yr	Electrical Chiller kWh/yr	AHU Fans kWh/yr	Pumps CHW kWh/yr	Pumps HW kWh/yr	Total Electrical kWh/yr
1	39298	40	3474	14	1403	4931
2	38347	53	3138	19	1365	4575
3	35784	184	3477	67	1278	5007
4	33473	228	3367	83	1196	4873
5	25144	301	3479	109	903	4792
6	15609	526	3352	181	554	4613
7	12619	807	3466	266	436	4974
8	13914	886	3469	281	485	5121
9	18104	372	3352	132	640	4496
10	25221	305	3474	112	904	4795
11	37035	112	3363	42	1327	4843
12	37000	28	3473	10	1328	4838
Total	331548	3843	40883	1314	11820	57860

Figure 24: Option 4 HVAC Energy Consumption

8.6 Results Summary

The primary objective of the case study was to assess the impact of energy efficiency strategies on reducing energy use for HVAC purposes in laboratories. The results are summarised in Figure 25 below and graphically in Figure 26 to demonstrate the effectiveness of each of the options in reducing energy consumption.

Item	Description	Gas (kWh/yr/m^2)	Electrical (kWh/yr/m^2)	Carbon Emissions (kgCO_2/yr/m^2)
Base Case	CAV	924	85	212
Option 1	VAV	573	54	132
Option 2	VAV + low face velocity fume cupboards	357	34	83
Option 3	VAV + low face velocity fume cupboards + heat recovery	190	34	51
Option 4	VAV + low face velocity fume cupboards + heat recovery + low pressure drop	190	33	50

Note: Conversion factors used to calculate the carbon dioxide emissions for the fuel use are: Grid Electricity 0.43 kgCO_2/kWh Natural Gas 0.19 kgCO_2/kWh. [22]

Figure 25: Results summary based on gross floor area.

The benchmarking data outlined in Chapter 3 is limited as discussed and the performance data for Research laboratories in cool climates, akin to the case study, ranges from 102 to 746 kWh/yr/m^2 for gas and 239 to 445 kWh/yr/m^2 for electricity. The gas consumption predicted within the model therefore appears to be within the lower end of the range at 190 kWh/yr/m^2.

In terms of electrical energy the case study prediction appears low. However it is not stated in the tabled data for each of the facilities benchmarked what allowance has been included for lighting and small power electrical usage. Assuming lighting is approximately 15-20 W/m^2 and small power is 50-150 W/m^2 the lower electrical limit becomes more realistic in comparison to what was predicted by the case study model.

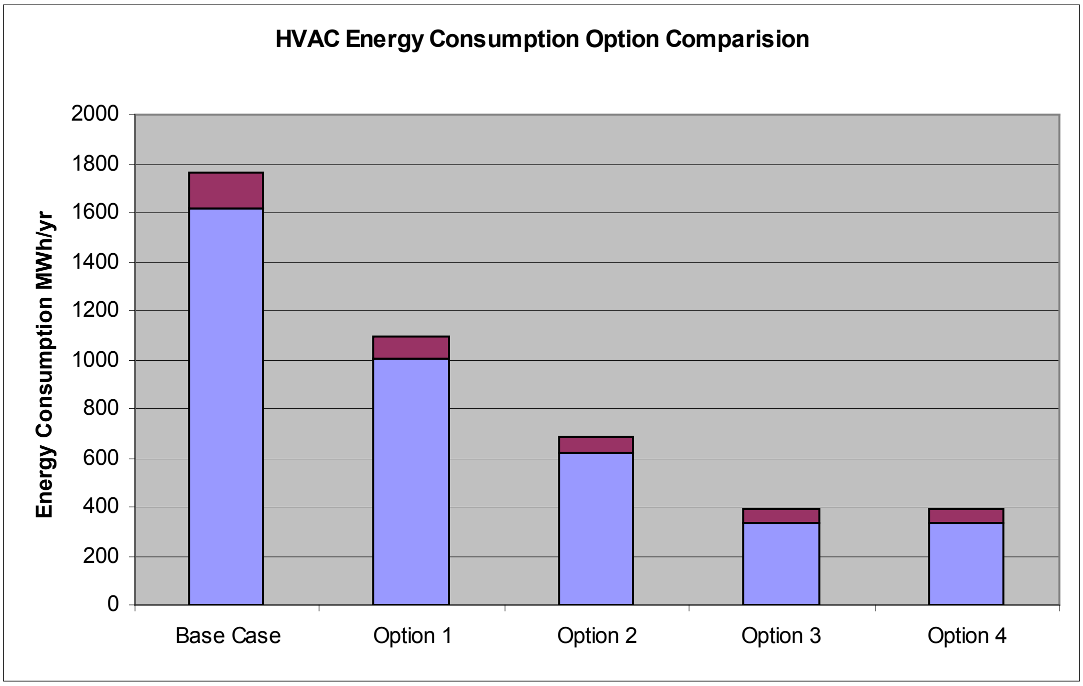


Figure 26: HVAC Energy Consumption Option Comparison

9 Case Study: Daylight Analysis

The following daylight modelling was performed to demonstrate the energy savings that can be achieved by virtue of effective daylighting and artificial lighting control. The laboratory model used for the thermal case study and described in Chapter 7 was also used for the daylighting study.

9.1 General

The artificial lighting in perimeter areas with access to glazed façade can be controlled via daylighting sensors. This allows individual lamps or banks of lamps at the perimeter to be dimmed or switched off when not required, as daylight levels are sufficient. Computer modelling was used to predict the level of daylight penetration into the space based on the nominated façade design. The results demonstrate the Lux levels that can be achieved internally for an averaged sky profile. Further to this a second option was modelled with increased glazing height to allow a comparison with the base case. The daylight factor achieved for both options was calculated to allow a meaningful comparison.

Images were produced showing the Lux level contour lines to allow the area receiving useful daylight to be calculated. Levels greater than 375 Lux were considered sufficient to allow artificial lighting to be switched off.

The Daylight Factor describes the proportion of internal illuminance over external horizontal illuminance and is expressed as a percentage. Daylight Factor is a useful method for benchmarking the effectiveness of a design because it measures the proportion of daylight entering a building but is not climate specific. If data is available with regard to daylight availability in the location under consideration accurate estimations of specific Lux levels can be made and building envelope designs can be optimised to achieve specific Lux targets to reduce the need for artificial lighting as much as possible.

Images showing the Daylight Factor contour lines were also produced to compare the Base Case and Option 1 on the percentage of areas which received a daylight factor greater than 2.5%, which was taken as the benchmark performance.

Internal zone artificial lighting can also be controlled to reduce energy consumption through motion sensors, either infrared or carbon dioxide monitoring. The saving associated with this light switching can be predicted based on occupancy profiles but is highly variable. This is not considered within the scope of this study.

9.2 Approach

Radiance and Ecotect software were employed for the study to generate and analyse a 3D model of the building. Described within the 3D model are all surface geometry, as well as surface reflectance, specularity and roughness. The simulation applies a radiosity method in the assessment of the illumination conditions within the space and provides photo-accurate representations of the lighting conditions that are expected within the space.

A 3D model of each option was generated using Ecotect software, and then Radiance software was used to render images showing the natural daylight performance throughout the building.

Radiance is radiosity software for prediction of natural light. It was developed by Lawrence Berkeley Laboratories in the U.S. and has been independently validated as the most accurate computation method that is capable of photo-realistic rendering for accurate assessment of visual comfort and glare issues. The model included a number of design criteria regarding building materials including both the reflectance of the material and the colour.

9.3 Model Data

The typical laboratory floor layout used for the daylighting analysis is as per that described in Chapter 7. Two options for the façade were modelled as follow:

- Base Case - Equivalent of 40% glazing applied to the façade:
  External wall 1200mm / Glazing 1200mm/ External wall 600mm

- Option 1 - Increased glazing height as follows:
  External wall 800mm / Glazing 1600mm/ External wall 600mm

The sky was simulated as a standard uniform design (diffuse) sky with the latitude, longitude and meridian values representative of a West of Scotland location. The diffuse sky (similar to a cloudy winter sky) simulates light levels, which would typically be exceeded between 9am and 5pm for 85% of the year. If the light levels are deemed satisfactory for this design day, then they will be satisfactory for 85% of the year (between 9am and 5pm).

The material properties for the walls, floors and ceilings have been modelled using industry-accepted values with the red, green and blue visual transmittance specified as follows:

Material	Visual Transmittance	Total Reflectance
Floor	0.3	0.3
External Wall	0.502	0.5
Internal Wall	0.5	0.5
Ceiling	0.7	0.7

Figure 27: Radiance material properties

The glazing properties have been estimated using output generated from a Transmittance Calculator. (23) The inputs used for the glazing description are as follows:

- Red, Green and Blue visual transmittance 0.3348
- % of visual light transmittance which passes through material 1%
- % of visual transmittance which is direct 0.153%

9.4 Base Case: Daylighting Results

The results for the base case Lux levels are shown in Figures 28 and 29 below. The building has been split across two images nominated as East and West. From these images it was calculated that 28% of the floor area located at the perimeter experienced Lux levels greater than 375 Lux. Importing the images into Ecotect and tracing the relevant contour line allowed this to be calculated.

The artificial lighting for 28% of the perimeter floor area is therefore not required for 85% of the year between the hours of 9am to 5pm. Based on a lighting electrical consumption of $8W/m^2$, with the use of daylight sensing control the lighting consumption can be reduced by 9,729 kWh/yr, from 40,857 kWh/yr to 31,127 kWh/yr between the hours of 9am to 5pm for this typical floor.

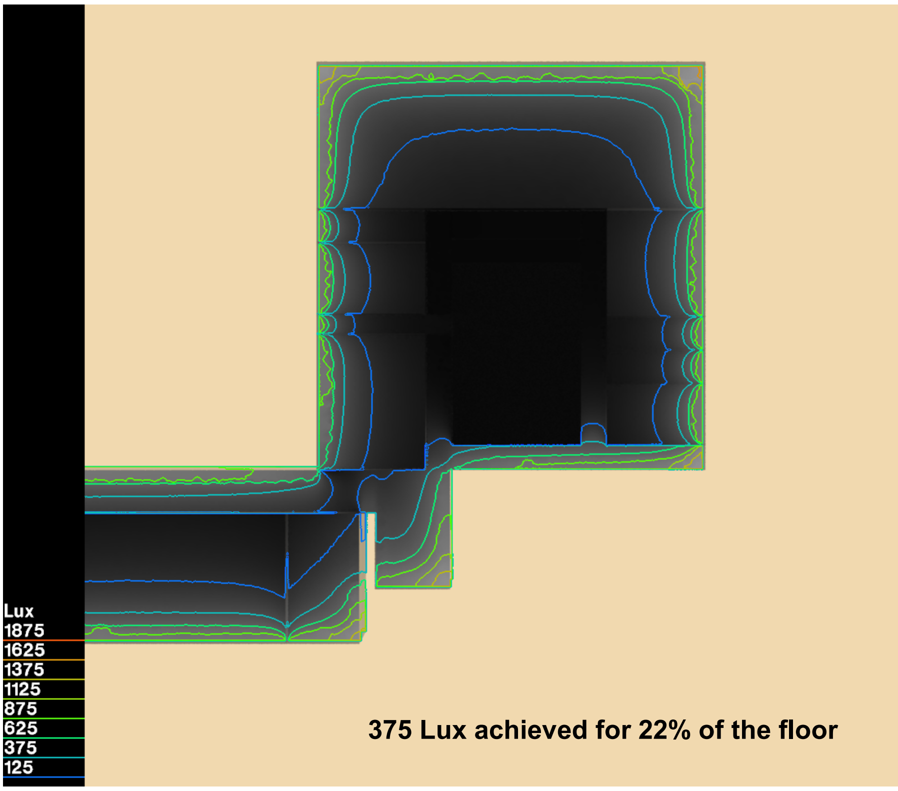


Figure 28: Base Case East Lux Levels

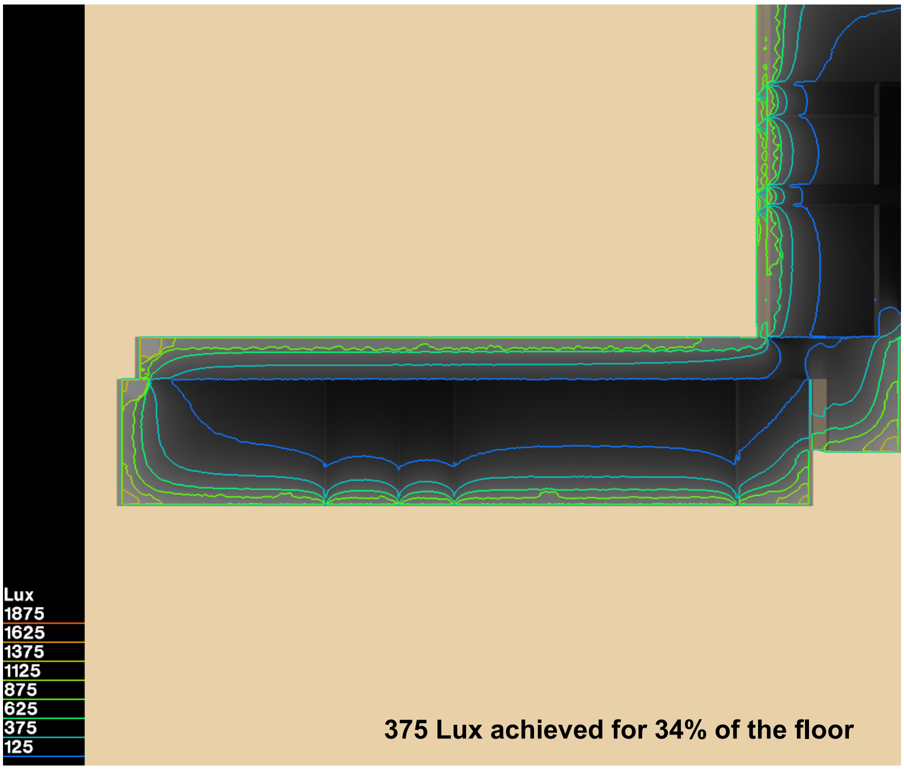


Figure 29: Base Case West Lux Levels

The results for the Base Case Daylight Factor prediction are shown in Figures 30 and 31 below. From these images it was calculated that a daylight factor of greater than 2.5% was achieved for 30% of the floor area in the East wing of the building and 46% of the floor area in the West wing.

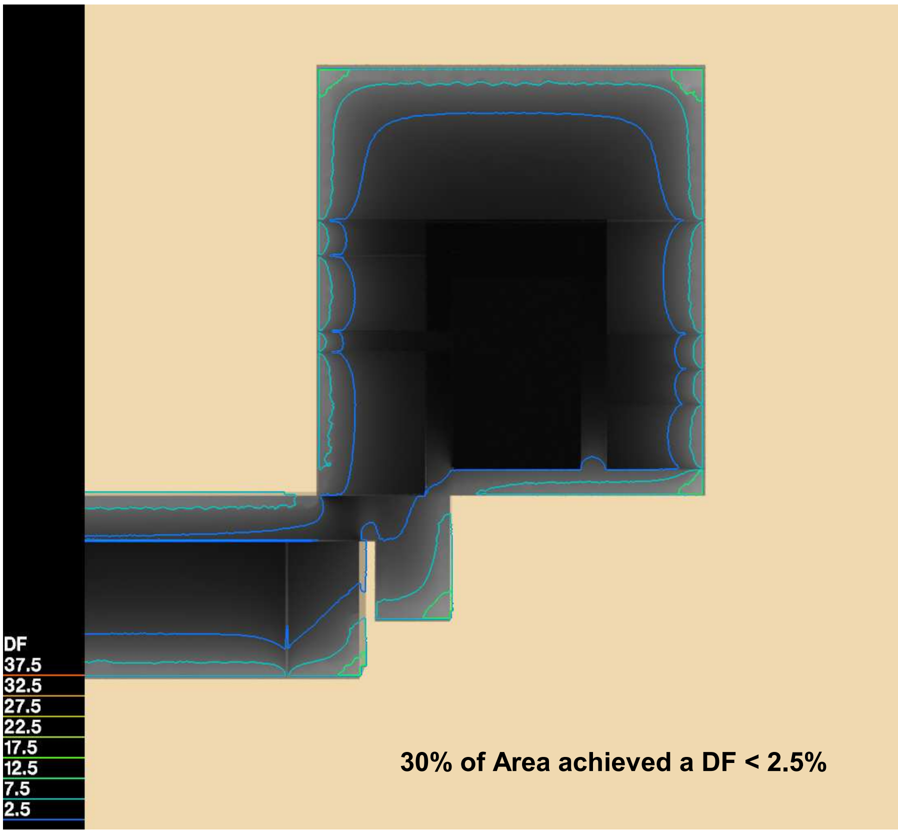


Figure 30: Base Case East Daylight Factor

9.5 Option 1: Daylighting Results

The results for the Option 1 Lux levels are shown in Figures 32 and 33 below. From these images it was calculated that 31% of the floor area located at the perimeter experienced Lux levels greater than 375 Lux. The artificial lighting for 31% of the perimeter floor area is therefore not required for 85% of the year between the hours of 9am to 5pm. Based on a lighting electrical consumption of 8W/m^2, with the use of daylight sensing control the lighting consumption can be reduced by 10,762 kWh/yr, from 40,857 kWh/yr to 30,095 kWh/yr between the hours of 9am to 5pm for this typical floor.

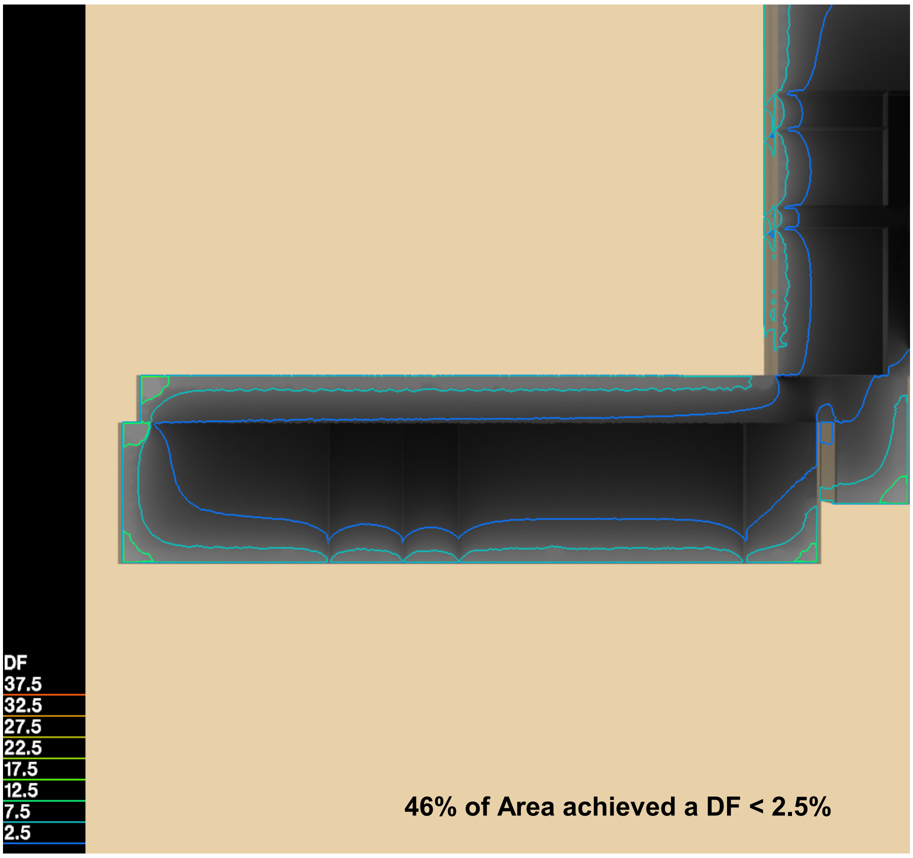


Figure 31: Base Case West Daylight Factor

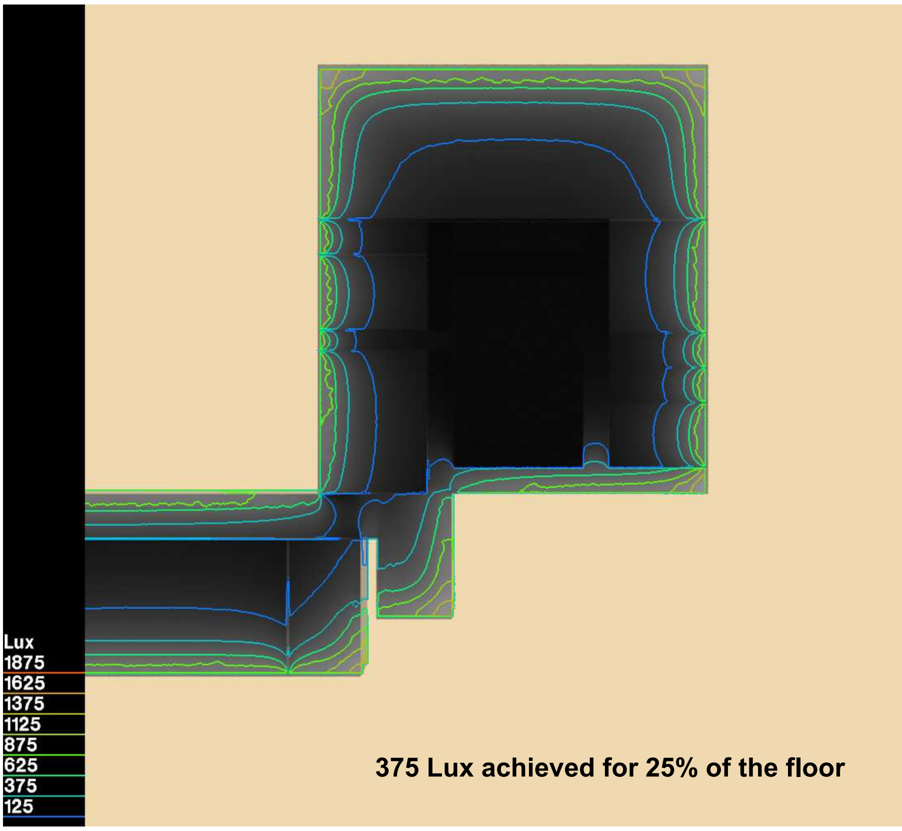


Figure 32: Option 1 East Lux Levels

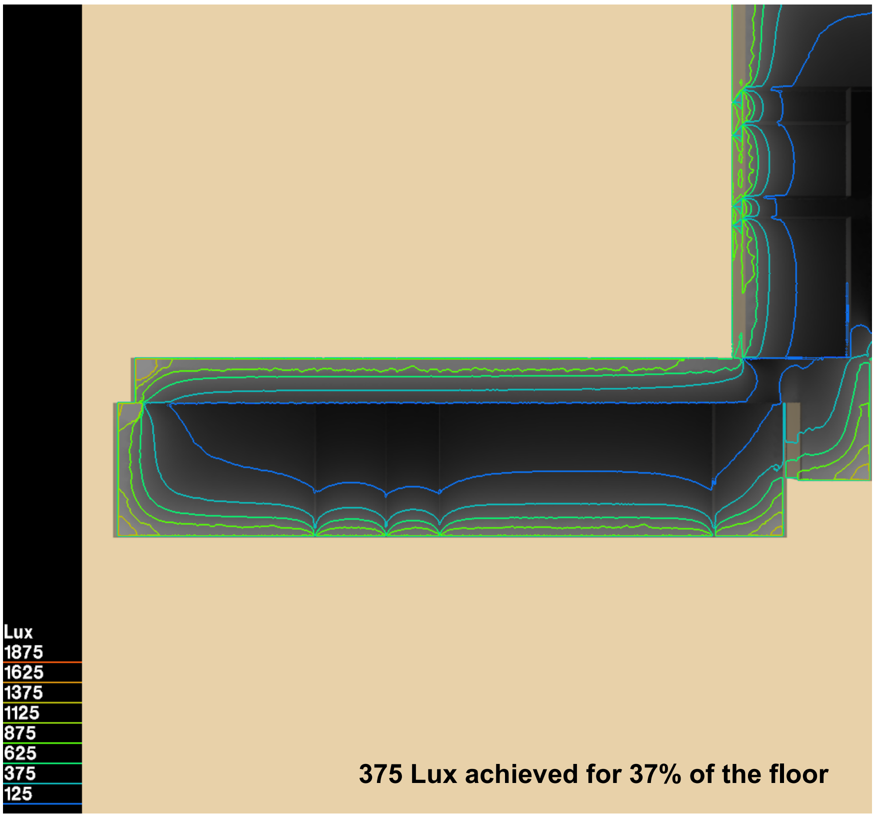


Figure 33: Option 1 West Lux Levels

The results for the Option 1 Daylight Factor prediction are shown in Figures 34 and 35 below. From these images it was calculated that a daylight factor of greater than 2.5% was achieved for 32% of the floor area in the East wing of the building and 49% of the floor area in the West wing.

9.6 Results Summary

The primary objective of the case study was to assess the extent to which the artificial lighting energy consumption could be reduced within the laboratory through the use of daylight sensing and switching. The results are summarised in Figure 36 below. The secondary objective was to compare two façade options using the daylight factor as a benchmark comparator. This is also outlined in Figure 36 below.

Option 1 performed the best in terms of daylight penetration due to the increased area of glass on the facade. However the increased heat loss associated with the additional area of glass should also be calculated and compared against the electrical energy saving to achieve an optimised performance.

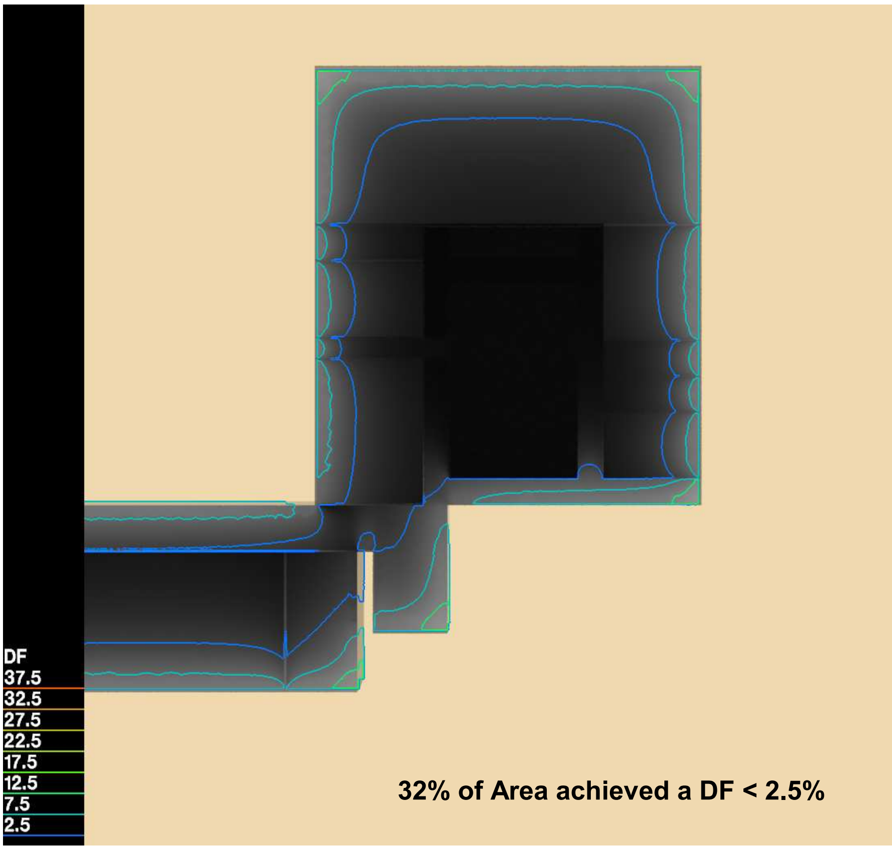


Figure 34: Option 1 East Lux Levels

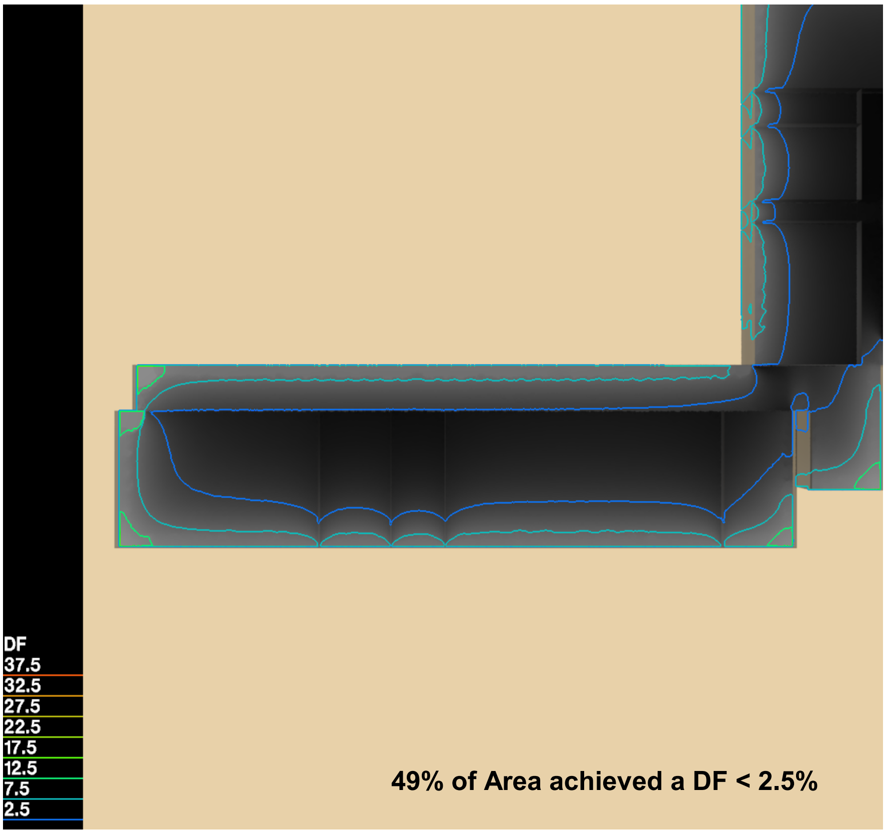


Figure 35: Option 1 West Lux Levels

Overall the case study demonstrates how daylight model can be used to assess the benefits of different façade options in a design and this can be extended to included not just area of glazing but position, orientation and performance of the glass type.

The results also demonstrate that the long narrow planning of the Western wing, as opposed to the deeper planning of the Eastern wing, is more effective in introducing natural light into the laboratory spaces.

Description	% Floor Area achieving < 375 Lux	% Floor Area achieving < 2.5% DF	Lighting Electrical Saving kWh/yr
Base Case East	22%	30%	
Base Case West	34%	46%	9729
Option 1 East	25%	32%	
Option 1 West	37%	49%	10762

Figure 36: Results Summary

10 Discussion

The aim of this work has been to provide a framework for energy efficient laboratories. To identify laboratories as high-energy users and investigate how the energy consumption can be reduced. The intent is to provide knowledge of principles and strategies that can be adopted to reduce energy consumption in a range of laboratory types. The recommended approach outlined is holistic and is carried through from concept design and to system selection. This has been summarised and presented as a general approach methodology in the form of a flowchart to assist laboratory designers and operators in identifying and applying energy efficiency features that will increase the energy efficiency and performance of new and existing laboratory facilities.

The methodology aims to encourage the introduction of energy decision making into projects as early as possible. Beginning at concept stage where the building form and fabric can be manipulated and energy supply technologies can be considered. It focuses on: correct briefing and sizing, building form and fabric, passive systems, supply technologies, individual building side technologies and control principles. These all combine to attempt to reduced the energy consumption of the facility.

It was found that there was in depth technical literature available on whole lab design but only limited resources available with respect energy efficiency in these highly engineered environments. The focus is largely placed on meeting the functional criteria of the laboratory within energy efficiency as a secondary consideration. However these objectives do not have to be considered in isolation and as outlined in this work. A low energy performance laboratory building can still achieve its functional requirements.

The application of the methodology was partially demonstrated through application to a particular case study. The case study, representative of a fume cupboard intensive research laboratory, was used to demonstrate the potential energy savings that can be achieved through the use of a number of the energy efficiency strategies suggested. The purpose of this study was to demonstrate the effectiveness of the concepts but also to explore how these are tested and comparatively measured against each other using computer aided analysis. It has become clear that computer modelling and analysis is essential in laboratory design for benchmarking purposes and to provide meaningful presentations to stakeholders.

Published data sets with regard to laboratories energy usage are not readily available in the U.K. Laboratories for the 21ST Century Group are currently addressing this in the U.S. through the development of a benchmarking tool based on a number of case studies. Recently this programme has been extended to the U.K. where in conjunction with the Higher Education Environmental Performance Improvement (HEEPI) group a number of University facilities have begun to be measured to generate benchmarking data. This is an arduous process regardless of building type but with the variable and complex nature of laboratories operational characteristics it becomes increasingly difficult.

To understand the relative performance of a laboratory building will give confidence that it is operating optimally it is important to model the building under the nominated conditions to predicted energy benchmarks. These figures can be used during the commissioning process to optimise performance and for ongoing monitoring and targeting by facilities management. Computer modelling and simulation also allows design options to be analysed and compared for potential energy savings as demonstrated in the case study. This information can be used to assess payback periods and give confidence to investors that capital cost expenditure will be recovered within acceptable periods.

The modelling and simulation process is dependent on realistic inputs with particular focus on internal gains profiles. There is a requirement within the industry to move away from out of date rules of thumb, which can inadvertently lead to increased energy consumption, and focus on ‘right sizing’ through detailed briefing and detailed design analysis and proving through computer aided simulation tools.

Detailed briefing is often by passed due to project time constraints but is possible. For example during the design of the University of Edinburgh Research Institute the manufactures data sheets for all new and existing equipment were collated and electrical consumption and heat gains calculated based on the measured allowances and projected operational hours. This was time consuming but reduced the electrical and thermal design loads considerably in comparison to rules of thumb. Diversities of usage should also be applied as per the profiles presented within this work although this is best achieved through historical data collection or based on projected occupation.

Laboratories are ideally very responsive buildings for changeable; occupancies, loads and ventilation requirements based on the activities carried out. In this sense the control strategy can provide the biggest energy saving by setting back or switching off plant when not required. The application of inverter drive controls to pumps will allow the flow rate and system head to be matched in the most efficient manner to the system operating conditions at any particular time. Occupancy and daylight sensing allows lights to be switched off when not required. Occupancy controls can be used to re-schedule temperature set points and schedule ventilation plant off. Inverter drive controls with automatic shut-off dampers will reduce fan energy and finally zone controls to match HVAC system demand to operational requirements.

This level of control should be incorporated into all new energy conscious laboratory facilities through the installation of a fully integrated DDC Building Energy Management System (BEMS), which should facilitate full automatic control and monitoring. As a minimum the following programmable functions should be provided:

- Weather Compensation
- Optimum Start and Stop
- Zone Control
- Temperature Setback
- Time Scheduling
- Set-point Adjustment and Monitoring
- Trend Logging
- Monitoring and Metering

To achieve optimised design energy performance during operation the laboratory building must be commissioned successfully. It is recommended that a party independent from the installation contactor carry out the commissioning to achieve more accurate results. Typically buildings are not commissioned properly and design potential is not realised. This is largely because commissioning traditionally takes place at the end of a project when the handover deadline is approaching and is rushed. To overcome this commissioning should be integrated into the process from the onset by an independent engineer whose responsibilities involve co-ordinating and managing the commissioning process only. The responsibilities should include reviewing drawings and specifications to verify that the systems have been installed correctly and operational assessments to measure each system against target performance figures as predicted for the laboratory through modelling and simulation processes.

Building tuning should be continued throughout the first year of occupation, as a minimum, to allow for load variations caused by occupancy and seasonal changes. The BEMS should be used to monitor the building performance throughout the first year to track changes and benchmark monthly energy consumption. Finally at building handover the facilities management team should receive comprehensive training in relation to the facilities environmental systems and control sequences, this should preferably be documented as a guide for future.

11 Conclusion

Laboratory buildings are large energy consumers due to the ventilation rates and the air conditioning loads associated with meeting defined environmental temperature and humidity criteria. The research has focused on the procurement of laboratory buildings with an environmental agenda with regard to reducing carbon dioxide emissions related to excessive energy consumption while providing a functional and safe environment. There has been considerable investment in this sector of the construction industry in the U.K. in the past 5 years. In Scotland in particular there has been a particular focus on academic research laboratories with new facilities constructed at the University of Glasgow, University of Edinburgh and the University of Dundee.

Barriers to energy efficiency in laboratories vary and include but are not limited to the following; standard design practices including inaccurate assumptions and rules of thumb, too much focus on capital cost without consideration of operational savings and paybacks, lack of time and resources given to design team members to produce new energy efficient solutions and evaluate options, lack of innovators on the design team, conservative building owner with no environmental agenda, lack of information relating to energy benchmarking and best practice targets and stringent performance criteria that limits energy efficacy strategies. These barriers can be potentially overcome through education of the building owner and design team and adoption of an approach as outlined within this work.

There are limited guidelines available in industry at present, particularly in the U.K., for developing energy efficient laboratories and this work is intended to contribute to filling this gap. Current legislation nominates minimum energy efficiency requirements which are applied across all commercial building sectors but do not addressed the unique nature of laboratories. Voluntary schemes come the closest to addressing this by including prescriptive additional environmental criteria to encourage more efficient labs. It would beneficial to create an environmental assessment tool specifically for laboratories in the U.K. with a weighted focus on energy consumption.

The methodology generated as part of this research is intended to assist designers and provide a starting point for the development of low energy laboratory facilities. The appropriate treatment for a given facility can only be determined through analysis of design options as an integral part of the design process. This approach means that brief requirements will be satisfied but in a manner understanding the need to reduce our depletion of fossil fuels and environmental impact. Computer modelling and simulation is endorsed as and essential step of the process to prove laboratory health and safety and comfort are maintained while reducing energy consumption.

The principles developed in this research were in the context of a laboratory building but could be adapted for other applications, e.g. hospitals or for specific laboratory types i.e. clean rooms. The general approach could be adapted to include strategies specifically suited for the alternative building types and exclude those not applicable within the framework provided. It would also be beneficial to expand the methodology to include cost analysis, which was considered out with the scope of this work, and more detailed benchmarking data.

11.1 Further Work

Capital, maintenance and energy costs have not been consider in the scope of this research but are an essential consideration in the commercial sector. Laboratory owners require knowledge of the additional capital cost associated with the strategies employed and this is typically assessed against a reference scheme. The reference scheme is used to assess cost increase and as such the financial viability. University developments generally accept paybacks up to 10 years while commercial or privately owned facilities are typically up to 5 years, dependent on the contract structure and the owner/operator relationship.

Costs would be a useful additional section to this research and further work would include the incorporation of costs and indicative paybacks into the methodology. This would be a valuable resource for designers particularly at concept design strategies for easy reference.

Further work would also include development of the benchmarking data set with eventual creation of an energy-benchmarking tool for laboratories in the U.K. This would provide realistic usable data and provide designers with targets to assess projects against industry best practice.

The benchmarking would include whole building energy use data and metrics. These would be normalised for key variables and used to set overall energy targets for a specific facility and also to rank facilities. System energy use data and metrics would also be developed and again normalised for key variables. Finally a performance rating relative to a base case laboratory would be created to nominate good or best practice. This would be used to establish a base line target for new facilities taking into account location impacts, variable equipment and occupancy loads, operating hours and the facility size. Such a benchmarking tool would be very valuable with growing interest across the industry particularly by building owners and operators.

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