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Investigation of Dynamic and Steady State Calculation Methodologies for Determination of Building Energy Performance in the Context of the EPBD

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Investigation of Dynamic and Steady State Calculation Methodologies for Determination of Building Energy Performance in the context of the EPBD

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Thesis submitted for the award of

Master of Philosophy

at

Dublin Institute of Technology

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ABSTRACT

The aim of this thesis was to investigate the ability of a dynamic and a quasi-steady state calculation methodology to capture the heating and cooling aspects of a buildings energy performance in the context of the requirements of the EU Energy Performance of Buildings Directive (EPBD). Chapters 1 and 2 provide a general background review and description of the implementation of the directive's requirements in Ireland. Chapter 3 established the usefulness and relevance of building energy benchmarks, traditional approaches to building energy performance calculation and methods employed in the establishment of building energy performance calculation methodologies. Chapter 4 established the ability of a sample of simplified and dynamic calculation tools to deal with the requirements set out in the directive and the extent the requirements are dealt with. This investigation observed that the underlying calculations and assumptions vary across different calculation tools; resulting in a variety of energy performance solutions. Chapter 5 investigated the ability of a dynamic methodology (IES<VE>) and simplified quasi-steady state methodology (SBEM / prEN 13790) to capture the effects of variation of key parameters of a buildings design in order to generate an improvement in energy performance. The investigation analysed the sensitivity of both methodologies to the variation of design parameters and their effect in terms of the annual energy performance calculation. In addition, the calculation algorithms of both IES <VE> and SBEM were summarised and analysed to account for the difference in results obtained. This investigation established that a dynamic methodology rewards design improvements with greater magnitude than a quasi-steady state methodology.

DECLARATION PAGE

I certify that this thesis which I now submit for examination for the award of Master of Philosophy, is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

This thesis was prepared according to the regulations for postgraduate study by research of the Dublin Institute of Technology and has not been submitted in whole or in part for an award in any other Institute or University.

The work reported on in this thesis conforms to the principles and requirements of the Institute's guidelines for ethics in research.

The Institute has permission to keep, to lend or to copy this thesis in whole or in part, on condition that any such use of the material of the thesis be duly acknowledged.

Signature__________________________________ Date ___________

Candidate

ACKNOWLEDGEMENTS

Firstly, I would like to thank, my supervisor Dr. Ken Beattie for his help, enthusiasm, advice and support over the duration of this research. His supervision has gained me an excellent knowledge into the use of simulation in building design.

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I would like to thank Sustainable Energy Ireland; in particular Kevin O'Rourke, Paula Rice and Deirdre Flood for inviting me to part take in the workshops regarding the software specification for the DEAP procedure, the workshop for the non-domestic calculation methodology and workshops regarding training. This gave a great insight into the implementation of the EPBD and matters pertaining to the selection of a calculation methodology.

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CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION

The EU has issued a directive that requires the provision of an energy rating certificate for all new and existing buildings [European Parliament 2003]. The production of the rating certificate will require calculation of a new buildings' annual energy performance at design stage. This is a completely new requirement to be integrated into the building services design process. Currently, many methods are in use for the calculation of building energy performance, all varying in terms of complexity and calculation approach. In order to provide a desired building energy performance rating, the building design process and building energy performance calculation must be an integrated process, therefore a calculation methodology that functions both as a design tool and rating methodology would generate more informed design decisions.

The aim of this thesis was to investigate the ability of a dynamic and a quasi-steady state calculation methodology to capture the heating and cooling aspects of a buildings energy performance in the context of the requirements of the new EU energy performance of buildings directive.

In the literature it has been shown that although comparisons against measured data and other calculation programs have been carried out on a wide range of building energy performance calculation methodologies, no research has been carried out in this regard in the context of the EPBD. Furthermore this thesis investigated the reason for disparity in energy performance results by an investigation and comparison of the underlying calculation algorithms.

The objectives of this thesis were as follows:

To investigate building energy performance benchmarks and their reliability in predicting building energy consumption.

To establish calculation methodologies most commonly used in current building services design practice for the purpose of calculation of annual building energy performance.

To establish approaches to building energy performance calculation and methods employed in the establishment of building energy performance calculation methodologies.

To establish the ability of currently used calculation methodologies to capture the requirements of a calculation methodology as set out in Article 3 of the EPBD.

To establish the ability of a dynamic calculation methodology to investigate key parameters of a buildings design in order to generate an improvement in building energy performance by application to a building typical of a standard commercial building undergoing a design process.

To establish the ability of a quasi-steady state calculation methodology to investigate key parameters of a buildings design in order to generate an improvement in building energy performance by application to a building typical of a standard commercial building undergoing a design process.

To compare the ability of both a dynamic and quasi-steady state calculation methodology to capture the effects of variation of key parameters of a buildings design in order to generate an improvement in annual energy performance.

To quantify the difference in the ability of a dynamic and simplified methodology to reward energy saving measures, by investigation of the underlying calculation process.

1.2 ENERGY USE IN THE BUILT ENVIRONMENT

In recent years due to depleting fossil fuels, reduction of the ozone layer and the increase in atmospheric greenhouse gasses, society has had to implement changes in order to reduce energy consumption in buildings. The petroleum crisis of the seventies highlighted our national dependence on sources of imported fuel and hence our accompanying strategic vulnerability. Since then, concern has shifted to the impact of human activity on the ecological stability of the planet, particularly on the effects of emissions from such activity on the ecological fabric.

The use of energy in Ireland is significant, based on the 2006 annual energy balance for Ireland, [SEI 2006a] the total final consumption was 12,768 kTOE and associated carbon dioxide (CO_2) emissions of 48.9 MT. The built environment represents a considerable consumption of energy. In 2006 it was responsible for 36% of the total energy consumption, which contributed to 42% of the total energy related CO_2 emissions. As our energy sources are predominantly fossil fuels, this brings about its own sustainability issues, in terms of the fossil fuel reserves and the release of greenhouse gasses such as CO_2 into the atmosphere.

Figure 1.1 illustrates the contribution of each economic sector to the total final energy consumption in 2006. This figure illustrates that the built environment i.e. the tertiary and residential sectors are responsible for a significant proportion of the total energy consumption and the total energy related CO_2 emissions [SEI 2006a].

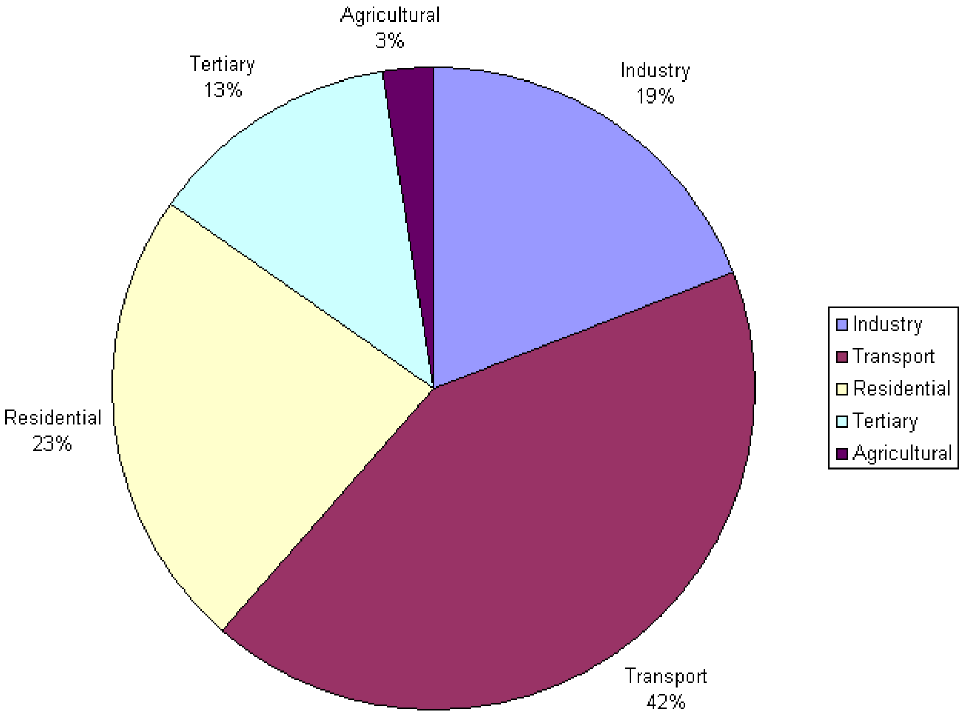

Figure 1.1: Total final energy consumption by sector 2006

In an effort to reduce this consumption of energy and associated CO_2 emissions Directive 2002/91/EC, the EU Energy Performance of Buildings Directive (EPBD) has been issued by the European Parliament [European Parliament 2003].

1.3 CURRENT BUILDING DESIGN PRACTICE

Current building design practice in Ireland in terms of building energy performance is concerned with compliance with the Building Regulations Part L [DEHLG 2005].

Under the 2005 regulations, non-domestic buildings must demonstrate limitation of heat loss through the building fabric. Limitation of heat loss through the building fabric can be demonstrated by either the elemental heat loss method or the overall heat loss method. The elemental and overall heat loss methods require that the thermal transmittance coefficient of the external envelope does not exceed either a maximum elemental or average thermal transmittance coefficient.

In the design of non-domestic buildings, a building services consulting engineer is normally required. The engineer assists in achieving an appropriate elemental or overall thermal transmittance coefficient of the building fabric envelope with the project architect. The plant and systems for the building are normally designed using either manual calculations or specialist computer aided software, i.e. steady state heating and cooling loads are obtained for the building and the building services plant sized to offset these loads.

As the non-domestic sector buildings rely totally on the elemental or overall heat loss methods for compliance, no cognisance is taken for the positive effects of building orientation, thermal mass of building fabric, passive solar gain, daylight, efficiency of the heating system, efficiency of the cooling system or efficiency of ventilation system.

In Ireland, pre-EPBD, there is no legislative requirement for the building services consulting engineer or the architect to take account of the energy performance of non-domestic buildings.

1.4 FUTURE BUILDING DESIGN PRACTICE

Following the implementation of the Building Energy Performance Directive (EPBD) all buildings will be subject to an energy audit by an independent accredited assessor. Therefore, during the design process the designer must take the energy performance of the building into account in order to achieve the desired energy rating for the building.

Many different methodologies can be used to calculate the annual energy performance of a building, particularly in terms of heating and cooling energy consumption. Methodologies differ in terms of ability and complexity, from simple manual calculation techniques to full dynamic simulation models.The way in which design improvements are represented and their effect on annual energy performance is critical to the success of the energy certification process.

This research analysed which methodologies are best to capture the heating and cooling aspects of a buildings energy performance particularly the sensitivity of methodologies to the variation of design parameters and their effect in terms of the annual energy performance calculation.

This research also analysed which would be suitable for integration into a building services design practice on the basis that the EPBD should aim for a better energy performance by better building design.

CHAPTER 2: THE ENERGY PERFORMANCE OF BUILDINGS DIRECTIVE

2.1 OBJECTIVES OF EPBD

Directive 2002/91/EC of the European Parliament and of the Council of 16th December 2002 on the energy performance of buildings was adopted by the European parliament and published in the Official Journal of the European Communities on 4th January 2003 [European Parliament 2003]. The Energy Performance of Buildings Directive, now referred to as the EPBD, was transposed into all member states' legislation by 4th January 2006. Member states have an additional 3 years to bring the legislation into practical effect i.e. 4th January 2009.

The objective of the EPBD, as stated in Article 1 is,
"*to promote the improvement of the energy performance of buildings within the community taking account of climatic and local conditions as well as indoor climate conditions and cost effectiveness'*[European Parliament 2003 pp 1/67].

The EPBD was proposed in order to enhance a number of previous European Union directives and objectives, specifically, Directive 93/76, Directive 89/106 and the treaty of the European Community.

Council directive 93/76/EEC of 13th September 1993, requiring limitation of CO_2 emissions by improving energy efficiency, required member states to develop and implement programmes for energy efficiency in the building sector [European Parliament 1993 pp28]. Council directive 89/106/EEC of 21st

December 1988 relating to construction products requires construction works and their heating, ventilation and air conditioning systems be designed and built to limit energy use [European Parliament 1989 pp12]. The EPBD gives member states a practical legal obligation in order to achieve the objectives of the aforementioned directives. One of the many requirements of the Treaty of the European Community is that environmental protection requirements be integrated into community policies and actions and also that member states employ the rational use of fossil fuels. The EPBD provides a mechanism to reduce consumption in a sector responsible for considerable consumption of fossil fuels. This directive is also part of the European Union strategy to achieve Kyoto obligations and enable greater security of energy supply.

2.2 REQUIREMENTS OF EPBD

The EPBD is divided into seven articles, within which there are five basic requirements, as follows:

- Adoption of a calculation methodology
- Setting of energy performance requirements
- Investigation of the feasibility of alternative energy systems
- Energy performance certification
- Inspection of Boilers and Air Conditioning Systems

2.2.1 Adoption of a calculation methodology (Article 3)

This article requires that member states must apply a methodology for the calculation of the energy performance of buildings. The directive allows that the calculation methodology may be applied on a national or regional level and the energy performance of a building must be expressed in an obvious and clear manner [European Parliament 2003 ppL1/67].

Each member state must adopt a specific methodology. This requirement is pertinent as at present there is a wide range of calculation tools and methodologies used for the calculation of heating loads, cooling loads and the calculation of building energy performance within the EU member states. Many member states have existing calculation tools tailored to specific climatic conditions and construction methods employed.

The EPBD sets out a framework for the calculation methodology to be adopted. The framework specifies that the methodology should include at least the following aspects [European Parliament 2003 ppL1/71]:

- Thermal characteristics of the building
- Air-tightness
- Heating installation and hot water supply
- Insulation characteristics of heating installation and hot water supply
- Air-conditioning installation
- Ventilation
- Built-in lighting installation
- Position and orientation of buildings, including outdoor climate.
- Passive solar systems and solar protection
- Natural ventilation
- Indoor climatic conditions, including the designed indoor climate.

In addition, the methodology should have the ability to capture the positive influence of the following [European Parliament 2003 ppL1/71]:

- Active solar systems and other heating and electricity systems based on renewable energy sources.
- Electricity produced by combined heat and power (CHP)
- District or block heating and cooling systems.
- Natural lighting

The general framework also states that buildings may be defined into the different categories depending on their use.

The requirement for the adoption of a calculation methodology at a national or regional level is pertinent to the success of the directive in having an impact on the energy use in the community. Each building in a particular geographical area has different heating and cooling requirements and hence different energy requirements. Also, in order for comparison to be made at a regional level, the calculation methodology must be sufficiently robust to enable excessive energy consumption to be highlighted and energy efficiency to be rewarded. If a standard methodology is not adopted, different calculation methods may yield different results and hence scepticism of the process may arise.

2.2.2 Setting of energy performance requirements (Article 4)

This article requires each member state to set minimum energy performance requirements for buildings. The minimum energy performance requirements must be based on the calculation methodology adopted by the member state and must be reviewed at least every five years [European Parliament 2003 ppL1/67].

This requirement is significant, as each member state may apply different minimum energy performance requirements based on the adopted calculation methodology. Each member states' calculation methodology will be linked to their individual climatic conditions i.e. specific requirements for cooling in Southern Europe and heating in Northern Europe. The specification that performance requirements to be reviewed regularly takes into account technological developments in the construction sector i.e. as insulation products with lower thermal conductivities are developed; lower thermal transmittance values are possible for building fabric elements. The directive also states that in setting minimum energy performance requirements, each member state may differentiate between different building usages, types and age of building [European Parliament 2003 ppL1/67].This specification is pertinent as it is difficult to achieve the energy performance requirements of new buildings in existing buildings without significant renovation. In addition, one would expect a significant variation in the energy consumption of different building types.

2.2.3 Feasibility of alternative energy systems (Article 5)

This article requires that the; technical, environmental and economic feasibility of alternative energy systems should be taken into account where a building has a useful floor area greater than 1,000m^2 [European Parliament 2003 ppL1/68]. The article gives examples of systems such as, decentralised energy supply systems based on renewable energy, combined heat and power (CHP), heat pumps and district or block heating or cooling.

This article is noteworthy, as it requires design teams to actively engage in the creation of a report specific to the proposed building in the proposed location. Although individual design teams are not bound to use such systems should they be deemed as technically, environmentally or economically unfeasible.

2.2.4 Energy performance certification (Article 7)

This article requires that when a building is constructed, sold or rented out, an energy performance certificate should be made available to the owner or by the owner to the prospective buyer or tenant [European Parliament 2003 ppL1/68]. The certificate is required to include reference values and benchmarks to enable consumers to compare and assess the energy performance of a building. An additional requirement is that the certificate should be accompanied by recommendations for cost effective improvements of the buildings' energy performance. This article also requires that buildings occupied by public authorities or institutions, where the useful floor area is in excess of 1,000 m^2, the energy rating certificate is to be placed in a prominent position within the building. The recommended indoor and current indoor temperatures and other relevant climatic factors are also required to be displayed.

The requirement for an energy performance certificate is the element of the directive that directly affects the general public. A poor energy rating or certificate may yield a lower price for the property concerned; as it would be considered to consume more energy and therefore have greater annual running costs. The inverse applies for a good energy rating or certificate, which may yield a better price. Hence, it is in the best interest of the vendor to have as reasonable an energy rating as possible as the consumer will have the ability to make an informed decision as to the property they want to purchase or lease. The recommendations for cost effective improvements is a measure designed to stimulate building owners to improve the energy rating of their properties.

2.2.5 Inspection of Systems (Articles 8 & 9)

These articles require the inspection of boilers and air conditioning systems. Article 8, regarding the inspection of boilers, provides member states with two options. Member states can either choose to establish measures to inspect boilers, inspect entire heating systems or to provide advice on boiler replacement, modifications to heating systems and alternative solutions to users. The directive provides that the impact of both options should have the same effect and that member states opting for option 2 must report on the equivalence of their approach every 2 years [European Parliament 2003 ppL1/68-69]. Article 9, regarding the inspection of air conditioning systems provides that each member state must establish measures to inspect air conditioning systems with a rated output in excess of 12 kW [European Parliament 2003 ppL1/69].

The requirements of article 8 and 9 are pertinent to achieving the objectives of the directive as a significant portion of the building stock have oversized and inefficient heating and cooling plant resulting in excessive energy consumption and hence CO_2 emissions.

2.3 ASSET OR OPERATIONAL RATING

Two methods of energy rating of buildings may be employed, asset rating or operational rating.

An asset rating may be defined as a rating based on the intrinsic performance capability of a building based on a standardised pattern of usage in a standardised climate. An operational rating may be defined as a rating based on measurement of actual metered consumption of energy based on the actual pattern of usage in the actual climate. Both have their own relative merits. For a new building, an asset rating would seem most appropriate, as operational information would not be available. For an existing building however, while an asset rating can inform the potential purchaser or occupier of the energy performance capability of the building, an operational rating can inform the potential purchaser or occupier of the actual energy performance of the building.

However, the actual energy consumption of a building may be a reflection of the usage and management of the building rather than the intrinsic performance capability of the fabric, systems and controls. As different owners may have a different operating regimes and hence different energy consumption; a standardised asset rating may be of more use.

2.4 NATIONAL IMPLEMENTATION OF EPBD REQUIREMENTS

In Ireland, the responsibility for implementation of the EPBD requirements rests jointly with The Department of Communications, Marine and Natural Resources; The Department of the Environment, Heritage and Local Government and the semi state agency, Sustainable Energy Ireland (SEI).

In order to implement the directive in Ireland, a working group was established with SEI and representatives from the above government departments. SEI was given a lead role in supporting the funding and development required for implementation of the EPBD.

The EPBD has been legally transposed into state legislation from 4th January 2006 as per the requirements of Article 15(1) of the directive. Ireland is then opting to use the three year additional time period to fully practically implement the directive in a staged basis as allowed by Article 15(2) of the directive. The following applies.

- New domestic buildings require energy certification from 1st January 2007.
- New non-domestic buildings require energy certification from 1st July 2008
- Existing domestic and non-domestic buildings will require energy certification from 1st January 2009.

A transitional exemption exists for new non-domestic buildings, in that buildings for which planning permission was applied for before 1st July 2008, and substantially complete before 1st July 2010 will not require an energy rating certificate as a “new building”. When sold or leased they will require certification as an “existing building”.

In its’ lead role in the implementation of the EPBD, SEI published a “Draft Action Plan for the Implementation of the EU Energy Performance of Buildings Directive in Ireland” in April 2005, which was subject to a public consultation period up to 29th July 2005 [EPBD Working Group 2005]. After the public consultation comments were taken on board, “The Action Plan for the Implementation of the EU Energy Performance of Buildings Directive in Ireland” was then published in July 2006 [EPBD Working Group 2006].

This section sets out to explain the implementation of the EPBD requirements in Ireland. Regarding each of the five requirements of the EPBD, the strategy adopted in Ireland for dealing with each, is as follows.

2.4.1 Adoption of a calculation methodology (Article 3)

As stated previously, many methodologies are used in EU member states in order to calculate the energy performance of buildings. Methodologies range from fully dynamic procedures to steady state procedures, differences exist between results generated by each of these procedures but also differences exist in results generated by different types of dynamic or steady state procedures. In order to harmonise standards, the EU commission have issued a mandate to European Committee for Standardisation (CEN) to produce a suite of supporting European standards for the calculation of the energy performance of buildings. While it is not mandatory for each state to use the CEN standards as a calculation methodology, Ireland and other member states intend to use the standards which are presently being developed by CEN. In the Action Plan the EPBD working group state that some of the standards are only a framework and guidance and significant work is required at a national level in order to convert the standards into practical working procedures [EPBD Working Group 2006 pp23].

The EPBD working group state in the Action Plan, that the energy performance calculation will be based on the characteristics of the actual building and recognises that in the public consultation process on the Draft Action Plan. Significant comment was received on the potential for disparity between a nominal design rating predicted off the plans and an asset rating based on the constructed building. In order to overcome this, the Action Plan states that design ratings will need to be revised and amended as necessary to ensure that the final rating relates to the actual building [EPBD Working Group 2006 pp24]. Also, in the Action Plan, the EPBD working group addressed the reason for the application of an asset rating rather than a operational rating as there is a need for a consistent basis on which to compare the energy performance of buildings, and the usage pattern of an existing building user is not necessarily a reliable guide to the intrinsic energy performance potential of a building.

Non-domestic buildings differ significantly in terms of complexity, scale and usage. In addition many can be subject to multiple occupancies. The EPBD working group propose to use an official national methodology for non residential buildings, provisionally entitled "*Non-domestic Energy Assessment*

Procedure" or *"NEAP"* [O'Rourke 2008] [EPBD Working Group 2006 pp25]. However the working group state that this does not preclude the recognition of other methods [EPBD Working Group 2006 pp25].

2.4.2 Setting of energy performance requirements (Article 4)

The setting of minimum energy performance requirements required the amendment of the Building Control Act and hence the amendment of the Building Regulations Technical Guidance Document (TGD) Part L, Conservation of Fuel and Energy [DELG 1997] [DELG 2002].

The SEI draft action plan indicated a two phase revision of TGD L.

Phase 1 was issued in 2005 and came into effect on 1st July 2006 and included the following:

- Higher energy performance standards for new non-domestic buildings
- Revised energy performance assessment methodology for new domestic buildings
- Energy performance standards for major renovations of large existing buildings.

And Phase 2, to be operative from 1st July 2008, to include the following;

- Setting energy performance assessment methodology for new non-domestic buildings [EPBD Working Group 2005 pp19].

2.4.3 Feasibility of alternative energy systems (Article 5)

In order to facilitate this aspect of the directive, SEI has commissioned a national feasibility study to provide generic reference sources to design teams. The national feasibility study is to include alternative energy supply options for circumstances such as building scale, type, usage pattern, energy prices and site and local environmental conditions. [SEI July 2006 pp1 (8)]. This requirement has been implemented from 1st January 2007. In order to comply with this element of the EPBD a copy of the feasibility study should be made available to the Building Control Authority [EPBD Working Group, 2005 pp 20].

2.4.4 Energy performance certification (Article 7)

As set out in the EPBD, the energy rating must be carried out by a qualified, accredited professional in an independent manner. SEI has stated that the certification shall be carried out by an accredited assessor, having completed an approved training course.

The SEI draft action plan states that the building energy rating will be based on calculations using data derived from drawings and specifications to facilitate the sale of buildings off the plans, for existing buildings the data will be derived from a physical survey. The building energy rating format will be different for residential buildings and non-residential buildings but the same for new and existing buildings within the same functional class.

2.4.5 Inspection Systems (Articles 8 & 9)

The EPBD provided two options in article 8 regarding the inspection of boilers and one option in article 9 regarding the inspection of air conditioning systems.

Ireland has chosen to use the option to provide advice to users, although this option must be shown to be as effective as the inspection option: [EPBD Working Group 2006 pp 33-34]. Both of these requirements have been implemented since 1st January 2008.

To conclude, the obligation to adopt a calculation methodology for the energy performance of buildings is of particular importance. The EPBD requires specific capabilities of such a methodology. Although the EPBD identifies the items that should be included as part of the calculation it makes no reference to the depth of the calculation in terms of its’ complexity. An energy performance calculation methodology should have the ability to capture the use of space heating, cooling, ventilation and lighting systems employed typically in non-domestic buildings. In addition, the calculation methodology should have the ability to act as a design tool in order to provide the ability for an iterative design process.

CHAPTER 3: LITERATURE REVIEW

3.1 BUILDING ENERGY CONSUMPTION AND CO_2 EMISSIONS

The building stock in Ireland may be divided into three sectors; the industrial sector, the residential sector and the tertiary sector. The tertiary sector refers to non-residential and non-industrial buildings. This thesis is mainly concerned with tertiary sector buildings

The tertiary and residential sectors are responsible for 16% and 25% of energy related CO_2 emissions respectively, 41% of total energy related CO_2 emissions [SEI 2006a]. Figure 3.1 illustrates a breakdown by sector.

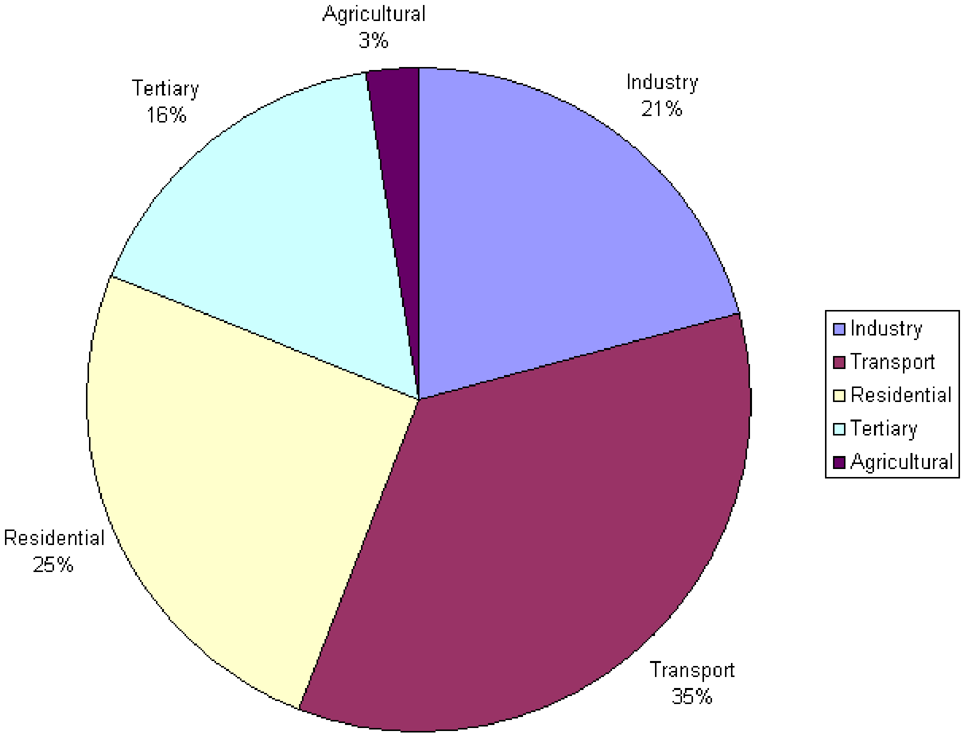

Figure 3.1: CO_2 Emissions by Sector 2006

Although 41% appears high in comparison to sectors which would be considered energy intensive such as the industry and transport sectors, when one considers the building stock and the application of energy use in buildings i.e. space heating, water heating, cooling, motive power and lighting, such statistics appear to represent the current position.

Figure 3.2 illustrates a breakdown of energy use in the tertiary sector by source and application. Of the 1,629 kTOE of energy use in the tertiary sector, 42% is electricity usage, 37% is consumption of oil, 19% consumption of natural gas, and 2% from the consumption of coal.

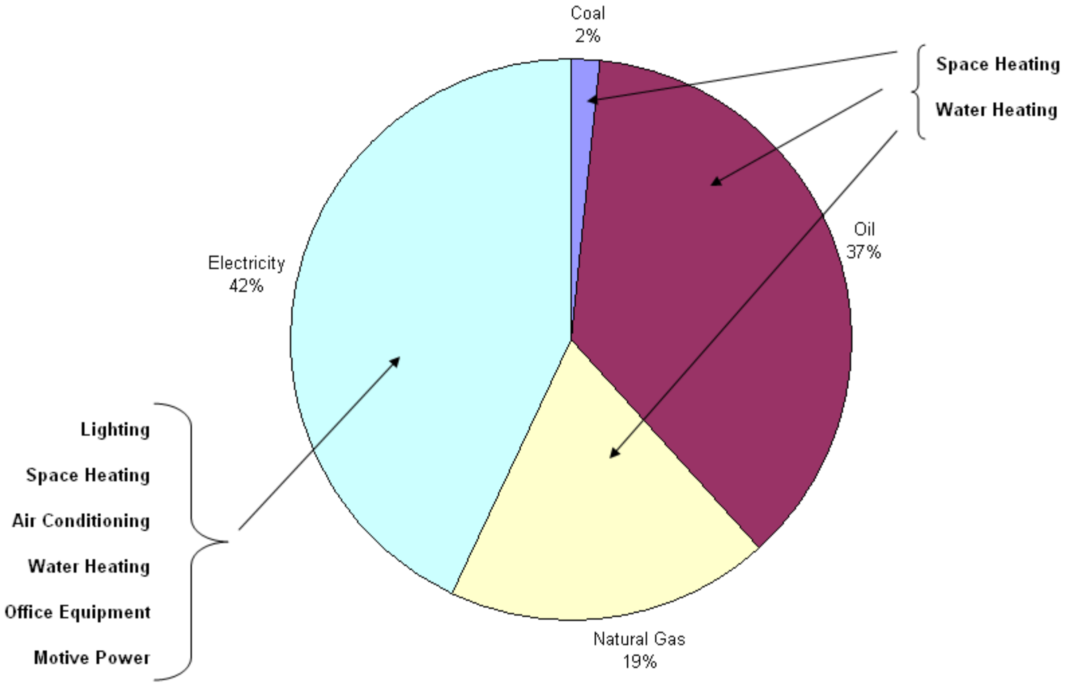

Figure 3.2: Energy Use in Commercial Sector by Source and Application

Therefore, 58% of our energy usage in this sector i.e. oil, natural gas and coal; is used for space heating and water heating. Of the 42% electrical energy usage, 5%-9% [DETR 2000] of this is used for the running of office equipment; the remainder is used for air conditioning, motive power and lighting.

There is significant scope in the tertiary sector to reduce the overall energy consumption by reducing heating loads, cooling loads and use of artificial lighting. This can be achieved by better design of building fabric, the use of more efficient plant and equipment and also the regular maintenance of plant and equipment. Miguez et al [2006] indicated that presently there are approximately 10 million boilers in European homes which are over 20 years old. Miguez et al stated that replacing these boilers for more efficient units would result in a 5% reduction in the energy used for space heating in the EU. Although measures such as this would result in capital expenditure to the consumer, the resulting annual savings would be considerable.

The increasing use of space heating and air conditioning in buildings in Ireland, the EU and indeed worldwide has contributed to an increase in atmospheric concentrations of CO_2 and hence a reported global warming and climate change of which there is increasing evidence of in recent years. Hitchin [2000] reported that building energy consumption and related CO_2 emissions for most buildings are falling in the UK. However the energy consumption and CO_2 emissions associated with air conditioning is increasing as more buildings are becoming air conditioned, a trend which Hitchin states, is set to increase. The reported fall in CO_2 emissions is due to an improvement in building fabric and more efficient services plant and systems, driven by technological improvements and legislative changes. However more buildings are air conditioned due to increased internal heat gains from IT equipment.

Atmospheric CO_2 levels are indeed rising; Wright [2002] indicated that atmospheric CO_2 concentrations had increased by 3.4% from a *"natural level"* of 290ppm in 1860 to 300ppm in 1930. In recent years that rate of change has increased with concentrations recorded as 370ppm in 2001, an increase of 28% above the natural level. In terms of climate change or an increasing temperature, Wrights research deduced that the Central England Temperature is showing a rising trend, in the last 15 years the rate of rise has increased with 1997-2000 the warmest on record.

These statistics are put in perspective by Wyatt [2006] in a paper presented at the 2006 Chartered Institution of Building Services Engineers (CIBSE) Republic of Ireland Conference; Wyatt used the statistic of 370ppm as close to the atmospheric CO_2 concentration at nearly the same level as the Cretaceous / Tertiary divide at 70 Million BC. One could conclude that mankind has done significant damage to the climate in the last 146 years, with buildings playing a considerable part in this.

3.2 BUILDING ENERGY PERFORMANCE BENCHMARKS

Building energy benchmarks provide representative values of energy consumption from common building types, against which a buildings' actual energy performance can be compared.

Establishing benchmarks for building energy consumption can improve building design and operation by providing *yardsticks* and setting maximum levels as to what is regarded as acceptable. This is complicated by the fact that non-domestic buildings are diverse in their design, operation and management and hence have a wide range of energy consumptions that would be regarded as acceptable.

Various studies have been undertaken in order to catalogue and categorise building energy consumption. In order to establish patterns and trends extremely large amounts of data must be analysed. A large volume of research has been carried out on the benchmarking of UK office buildings. Jones et al [1996] carried out a study on "*Bulk data for Benchmarking Non-domestic Buildings Energy Consumption"*. Grigg et al [1996] carried out a study on *Rating the Energy Efficiency of Air Conditioned Buildings*. The aim of the research undertaken by Jones et al was to establish building energy benchmarks to improve the understanding of the energy consumption of buildings and to set standards for the future. The study analysed at least 150 buildings from each sector, 7,000 buildings in total and established the following:

- There is a correlation between total energy consumption and floor area.
- Electricity consumption is less related to floor area than fossil fuel consumption.
- Electricity consumption can be targeted more effectively than fossil fuel consumption.

The findings of Jones et al are significant in terms of providing benchmarks for building energy consumption. The correlation between total energy consumption and floor area is in the region of what one would expect i.e. the larger the building the greater the energy consumption. The fact that electricity consumption is less related to floor area than fossil fuel consumption is pertinent; the reason for this is that the installed equipment in buildings is related to the function of the building rather than the size of the building, which is a significant finding in terms of benchmarking. The fact that electricity consumption can be targeted more effectively than fossil fuel consumption is related to the fact that the use of equipment in buildings can be time scheduled and is not related to external factors as the heating and cooling systems are. The main conclusion of the work of Jones et al was that energy consumption patterns were successfully established and that it is possible to gather bulk data and develop a useful yardstick for building designers.

The aim of the research by Grigg et al [1996] was to establish an energy performance indexing method. The indexing method was based on the theory that the multidisciplinary decisions regarding site, fabric and services made during the design process are reflected in the heating, cooling and ventilation plant capacities installed. In addition, provisions made to manage the plant and internal conditions effect the annual operation hours per year together with the seasonal efficiencies. The index is derived from the estimated likely annual energy consumption on the basis of a notional base case, and is an index that would rise as annual energy consumption falls. The index was tested against the energy use data from existing buildings and showed a correlation and therefore concluded as a useful comparator of energy efficiency. At the time

Grigg et al proposed that this method could be used as an energy targeting or energy labelling exercise.

A measurement of annual energy use per square metre of floor area will allow the efficiency of a building to be assessed against a benchmark, and allow remedial action to be taken. However Chung et al [2006] have shown that *Energy Use Intensities* (EUI's) established by normalising energy use with floor area have their limitations and are not sufficient for a credible energy performance rating. In support of these findings, Sharp [1996] made the argument that a simple EUI was not good enough for a credible energy-consumption performance rating. Other factors that affect the energy consumption of a building should be taken into account. Sharp developed benchmarks using a linear-regression approach to correlate other factors representing some important characteristics of buildings with EUI. Sharps' method has been used in the Asia-Pacific Economic Cooperation Energy Benchmark System and slightly modified as the basis of the US Energy Star benchmark [Energy Star 2005].

The UK Department of the Environment, Transport and the Regions (DETR) has a range of publications regarding energy efficiency, particularly a series on energy efficiency best practice i.e. benchmarking buildings in a number of different sectors. The guide, *Energy consumption Guide 19* (Econ 19) provides benchmark data for office buildings [DETR 2000].

3.2.1 Energy Consumption Guide 19 (Econ 19)

Energy Consumption Guide 19, Energy use in offices (Econ 19); published by the UK DETR provides benchmarks for the energy consumed by air conditioning, mechanical ventilation, heating and lighting services in office buildings [DETR 2000].

The benchmark figures provided refer to office buildings described as representing 'typical' and 'good practice' for the sector. ‘Typical’ values are consistent with median values of data collected in the mid 1990’s by the DETR from a broad range of office buildings, ‘Good Practice’ values are examples in which significantly lower energy performances have been achieved using well established energy efficient features which fall in the lower quartile of the data collected. Econ 19 uses a division of four different types of office building as follows [DETR 2000]:

Type 1 - *Naturally Ventilated Cellular*

This category of building assumes a simple building with a typical size of 100m^2 to 3,000m^2. Econ 19 states that this type of building may be in converted residential accommodation with individual windows, lower illuminance levels and local control over lighting and heating.

Type 2 - *Naturally Ventilated Open Plan*

This category of building assumes a typical size of 500m^2 to 4,000m^2. Econ 19 states that this type of building may be a purpose built building with illuminance levels, lighting power densities and occupancy hours in excess of the type 1 building.

Type 3 - *Air Conditioned Standard*

This category of building assumes a typical size of 2,000m^2 to 8,000m^2. Econ 19 states that this type of building may be a purpose built or speculatively developed building, similar in occupancy and planning to type 2 but with a deeper floor plan. Benchmarks for space heating and cooling systems are based on variable air volume (VAV) with air cooled chillers.

Type 4 - *Air Conditioned Prestige*

This category of building assumes a national or regional head office with a typical size of 4,000m^2 to 20,000m^2. Econ 19 states that this type of building may be purpose built or refurbished to extremely high standards. Plant running hours are considered to be longer. Also the buildings are considered to include catering kitchens as well as extensive air conditioning for server and communications rooms. Econ 19 states that mixed mode buildings may use a choice of benchmark data.

Table 3.1 illustrates the benchmark data for heating, hot water, cooling and the associated fans, pumps and controls for the different building categories [DETR 2000 pp 20].

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	Good Practice	**Typical Practice**
	kWh m^{-2}	**kWh m^{-2}**
Type 1		
Space Heating	79	151
Cooling	0	0
Fans, pumps and controls	2	6
Type 2		
Space Heating	79	151
Cooling	1	2
Fans, pumps and controls	4	8
Type 3		
Space Heating	97	178
Cooling	14	31
Fans, pumps and controls	30	60
Type 4		
Space Heating	107	201
Cooling	21	41
Fans, pumps and controls	36	67

Table 3.1: ECON 19 annual delivered energy consumption benchmarks

The data provided in Econ 19 is extremely useful in targeting and assessing the energy performance of office buildings, however the data is appropriate to the UK climatic conditions and constructional standards. No such publications are available in Ireland for the benchmarking of commercial buildings; however Hernandez et al [2008] provided benchmarks for primary school buildings in Ireland. The research by Hernandez et al established 96 kWh m^{-2} per year as a stock reference benchmark and 65 kWh m^{-2} per year as a regulation reference benchmark. This data was established using detailed questionnaire data from a sample of existing Irish primary school buildings. Although this research did include estimations of infiltration rates and boiler efficiency it illustrates the difficulties in obtaining benchmark data and also the usefulness of such information in an energy rating scheme.

3.2.2 Relevance of Building Energy Benchmarks

As regards the usefulness and accuracy of indices such as building energy benchmarks, the Probe studies on buildings in use [Asbridge et al 1996] [Bordass et al 1995a, 1995b, 1996a, 1996b, 1998a, 1998b, 1998c] [Cohen et al. 1996a, 1996b, 1996c] and associated research papers by Bordass et al [2001], carried out studies on 16 different buildings in use between 1995 and 1999 and made comparisons to established benchmark figures. Also Knight et al [2005] carried out research to measure the energy consumption and carbon emissions associated with air conditioning in 32 UK office buildings.

The research carried out by Bordass et al [2001] was carried out under the Probe research project and managed by the Building Services Journal. The study carried out post occupancy surveys on 16 buildings, 6 of which were educational buildings, 7 offices, a medical centre and a warehouse. The aim of the post occupancy surveys was to measure occupant comfort, operation of services and energy consumption of the buildings.

Figure 3.3 was compiled from data extracted from the above cited publications. The figure illustrates the range of annual energy consumption across the different building types, from annual gas consumption of 32 kWh m^{-2} to 400 kWh m^{-2}, and annual electricity consumption of 33 kWh m^{-2} to 451 kWh m^{-2}. Figure 3.3 also shows gas and electricity consumption for the Econ 19 building types, for comparison purposes. It can clearly be seen from this figure that lower energy consumption is possible and achievable in the educational buildings, but at the upper end of the scale are the office buildings, particularly the air conditioned offices buildings.

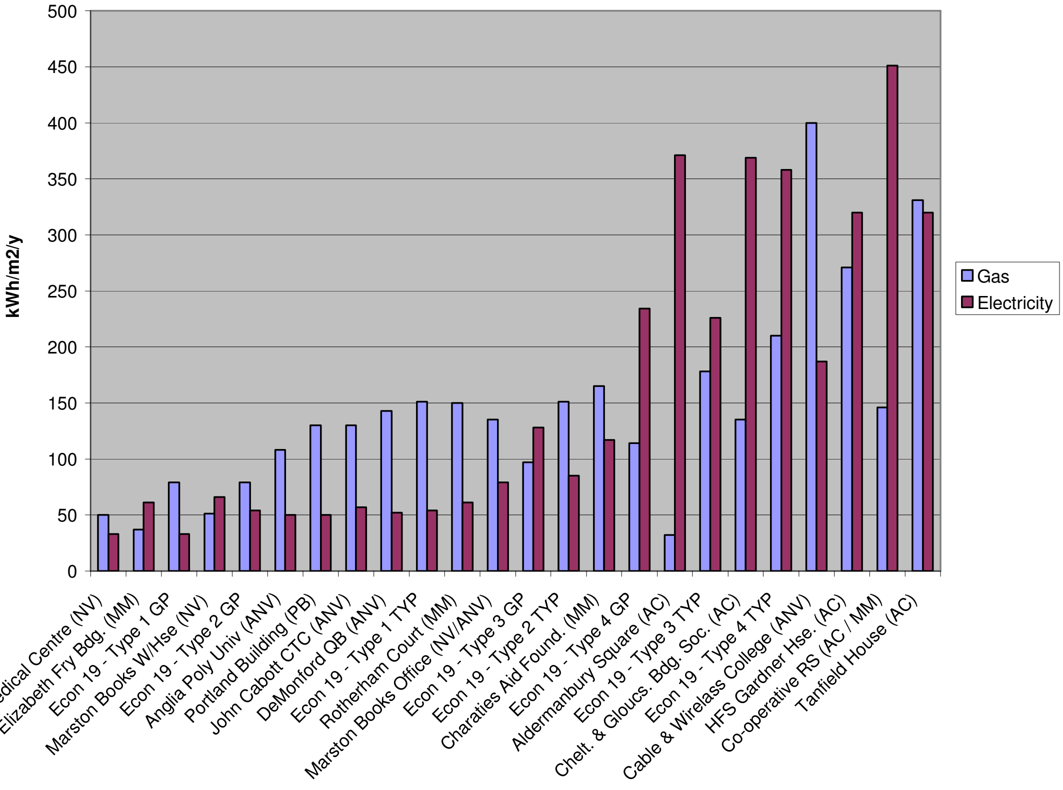

Figure 3.3: Probe Buildings total gas and electricity consumption

It can be seen from Figure 3.3, that of the buildings studied by Bordass et al [1995a], only 2 achieved their respective benchmark figure for both gas and electricity energy consumption; the Cheltenham and Gloucester Building and the Charities Aid foundation building. The remaining buildings did not achieve the benchmark figure in either fuel for a number of reasons. Albermanbury Square utilised an ice storage system, with little control over chiller operation, resulting in high electricity consumption. The remaining buildings reported problems due to air tightness, inefficient lighting, high office equipment loads, lack of heat recovery, high unnecessary humidification and poor control.

The research illustrated that although buildings may be designed to achieve low energy consumption, issues such as construction quality control together with the operation of a building are equally as significant as the design parameters.

Research carried out by Knight et al [2005] measured the actual energy consumption and carbon emissions associated with air conditioning in 32 UK office buildings. The research consisted of a 2 year field study of 32 buildings. The sample of buildings monitored included fully air conditioned buildings requiring cooling only, which was supplied using refrigeration plant and buildings serviced using reverse cycle air conditioning systems providing both heating and cooling. The monitoring exercise consisted of the monitoring of; air conditioning energy consumption, external and internal environmental temperatures and regional weather conditions. The measured energy consumption of the buildings was compared to the Econ 19 benchmark data [DETR 2000] the benchmark used for the study was the Econ 19 Type 3 building “Air Conditioned Standard”.

The study established the following:-

- Chilled ceiling systems consume less energy than the other system types studied. The majority were below the good practice benchmark and a portion of the all air and fan coil systems exceed the typical practice benchmark.
- Reverse cycle chilled ceiling systems performed extremely well, below good practice benchmarks, while the other reverse cycle systems performed between good practice and typical practice.

- The high use of electricity exasperates the annual carbon emissions associated with the reverse cycle systems compared to benchmark figures. Therefore some reverse cycle systems that performed well in terms of typical and good practice energy consumption, performed less well in terms of carbon emissions.
- Reverse cycle heating systems preformed similarly to gas fired heating systems
- Reverse cycle heating systems emitted 50% more carbon than a standard gas fired heating system, (Although they also provide cooling within this figure).

Knight et al illustrated that the choice of system in a building is directly related to the energy consumption and carbon dioxide emissions.

To conclude on building energy benchmarks, a variety of benchmarking tools are available which provide a useful method of comparing a buildings energy performance against what is regarded as good practice or typical practice. The studies on buildings in use have shown that although a building may be designed to achieve good practice in terms of consumption, it may not due to factors determined by the occupancy and use of the building. Factors such as control and air leakage have a huge bearing on a building achieving its design intent.

It has been shown that different systems are more capable of achieving a good performance than other systems. According to Knight et al, chilled ceilings are capable of achieving a good practice performance. But in terms of carbon emissions, a designer must be mindful of the conversion factors particularly when choosing systems that operate from electricity, such as reverse cycle heat pump systems, although these systems consume little energy for heating / cooling input they have significant carbon emissions.

3.3 PLANT SIZING AND ENERGY CALCULATION

Many different methods are employed for the calculation of building heating loads, cooling loads and plant sizes. Also many methods are employed for the calculation of building energy performance. Methods range from simplified steady state methods to full dynamic methods.

3.3.1 Plant Sizing Calculation Methods

Load calculation and plant sizing methods may be divided into the following categories as illustrated in Table 3.2.

Method Category	**Example**
Empirical Methods	• Rules of Thumb
Steady State Methods	• Approximate Steady State Methods • CIBSE Simple Steady State Methods
Dynamic Methods	• Simple Cyclical Admittance Method • Transient Temperature Method

Table 3.2: Load and Plant Sizing Calculation Methods

Empirical methods would typically be employed at the concept stage of a project to estimate heating and cooling loads and plant size on a W m^{-2} basis. Publications are in use with tabulated data for different types of buildings, an example of such data is the BSRIA *Rules of Thumb* [BSRIA 2003].

Steady state methods are used for the sizing of heating emitters and plant. These methods are divided into two areas in Table 3.2, *Approximate Steady State Methods* and *CIBSE Simple Steady State Methods*. Using the *Approximate Steady State Method* as set out in CIBSE Guide A [CIBSE 2006] fabric heat loss is calculated as the product of the thermal transmittance, surface area and temperature difference across a fabric element. The total building heat loss is the sum of fabric heat loss, infiltration heat loss and ventilation heat loss. However using the *CIBSE Simple Steady State Method*, [CIBSE 2006] a factor is applied to the calculation in order to size the heat emitter to achieve a specific operative temperature. The CIBSE simple steady state method takes into account the radiant and convective heat output of the heat emitter to achieve the comfort conditions of the space. Heating plant selection also depends on the use of the heating system i.e. intermittent or constant.

Dynamic Methods are most commonly used to calculate cooling loads and peak temperatures in naturally ventilated buildings as it is necessary to take account of the dynamic response of the building as fabric storage will attenuate heat gains in the space [CIBSE 2006 pp 5-55]. Table 3.2 separates dynamic methods into two areas, *Simple Cyclical Admittance Methods* and *Transient Temperature Methods*.

The Simple Cyclical Admittance Method assumes a cyclical sinusoidal wave representation of external and internal load fluctuations within a 24 hour period. The thermal response of the space is the sum of a daily mean value and a daily cyclical value. The admittance and decrement factors of the building fabric elements relate to the cyclic response of the building fabric, the mean response is characterised by the thermal transmittance. The surface factor is used to quantify the absorption and subsequent release of the cyclic component of the transmitted solar radiation. This method does not take into account the effects of rapid load changes or the effects of long term storage.

Transient Temperature Methods refers to full dynamic methods where the thermal response of all the building elements is solved in terms of conduction, convection and long and short wave radiation. This method uses a detailed numerical model of the building with external parameters modelled as a geographically specific real sequence.

3.3.2 Energy Performance Calculation Methodologies

Similar to the calculation methods available for the calculation of heating and cooling loads and associated plant sizes, many methods exist for the calculation of building energy performance. Methods for calculation of building energy performance act by averaging the internal and external factors that would affect the energy performance of a building. Methods for calculation of building energy performance may be considered under two groups, simple methods and complex dynamic (simulation) methods. Simple methods generally average variables over a diurnal or annual basis, whereas complex methods average variables on an hourly basis or even shorter.

Dynamic or simulation methods use real time external data in order to solve the conduction, radiation and convective processes in relation to heat transfer and storage in a space. Although, the admittance method mentioned previously would be considered to be dynamic, internal and external variables are considered to be sinusoidal, which is unrealistic as external conditions do not vary as a sinusoid. Simulation methods however represent the fluctuations of internal and external variables based on their realistic rates of change. Such methods were referred to previously as *Transient Temperature Methods.*

Simple methods would be considered to be steady state in most cases. No account taken for thermal storage and external variables based on worst case conditions or averaged values. Some methods may be considered to be quasi-steady state, in that the thermal storage within the space is represented as a utilization of heat gains or a utilization of heat loss based on the internal thermal capacity (kJ m^{-2} K) of the fabric elements.

The most common simulation methods are dealt with in detail in Chapter 4, as a scoping exercise of the most common methods in use. The common non-simulation methods employed are Bin Methods, accumulated temperature difference (degree days), simplified heat balance (monthly) calculations and equivalent full load hours. Each method is described briefly in the following sections.

Bin Methods

Bin Methods involve determining the frequency of particular types of external conditions and putting them into “Bins” [Knebel 1983]. The energy consumption of the building within each Bin is calculated. The most common type of Bin is external temperature, but Bins may also be applied for multiple ranges of data [Grigg 2003]. Calculations are then carried out for each period or Bin, usually with steady state load calculations. Part load performance information is required for the building services that would be influenced by the varying loads. Energy use is calculated at a series of external conditions and the result weighted by the number of hours temperatures in each Bin are expected to occur over the year [Grigg 2003].

Bin Methods are relatively simple procedures that can reflect system operation with weather, such as the use of free cooling with air conditioning. The weaknesses of Bin Methods is that they do not realistically account for the interactions between weather variables (bright sun, low temperature) and the effect such interactions might have on different design strategies. They often miss trigger points when energy use suddenly increases, for example when dehumidification or humidification is required in addition to cooling or heating and they also fail to take account of the dynamics of building response as there is no time sequence for information [ASHRAE 2001a].

Accumulated temperature differences (Degree Days)

Accumulated temperature differences or ‘Degree Days’ are used as an index of climatic severity as it affects energy use for space heating or cooling [CIBSE 2006].

Accumulated temperature differences are calculated as the difference between the prevailing external dry-bulb temperature and a base temperature. The base temperature is the external temperature at which, in theory, no artificial heating or cooling is required to maintain an acceptable internal temperature.

Two types of degree-day are used in building services engineering; heating degree days and cooling degree days. Heating degree days i.e. when the external temperature is below the base temperature indicates the severity of the heating season and therefore heating energy requirements. Cooling degree-days i.e. when the external temperature exceeds the base temperature indicates the warmth of the summer and hence cooling requirements [CIBSE 2006].

The most widely used form of accumulated temperature difference is heating degree-days. The air temperature in a building is on average 2°C to 3°C higher than that of the air outside. A temperature of 18°C indoors corresponds to an outside temperature of 15.5°C. If the air temperature outside is below 15.5°C, then heating is required to maintain a temperature of 18°C. The sum of the degree-days over periods such as a month or an entire heating season is used in calculating the amount of heating required for a building [CIBSE 2006].

Grigg [2003], in a review of methods of calculation of building energy performance indicates that cooling degree days are not yet established as indicators of building cooling requirements. Also, Hitchin [2003], in an analysis of simplified calculation methods for cooling energy, indicated that results from a degree day calculation, while repeatable are not credible.

The degree day method is only of use if the use of the building and efficiency of the equipment is constant as it is difficult to predict part load system performance.

Simplified Monthly Heat Balance

Simplified monthly heat balance calculations act to calculate annual energy consumption based on averaging the effect of monthly external and internal variables. Monthly heat balance calculations combine the effect of seasonal changes in loads with relatively simple heat balance equations. This type of calculation has been used extensively in the UK and Europe for heating calculations for dwellings [Grigg 2003]. In particular the EU standard EN ISO 13790:2004 describes a procedure for calculation of energy use for space heating, and is established as a reasonably reliable methodology [CEN 2004]. Roulet [2002] has shown that as this method uses default data, it requires less data input, and is therefore easier to apply than dynamic methods. The accuracy results are as good as that obtained from dynamic simulations. EN ISO 13790 2004 has been revised to incorporate cooling energy consumption, this standard is presently entitled EN 13790, *Thermal performance of buildings - Calculation of energy use for space heating and cooling* [CEN 2008].

Equivalent Full Load Hours

This method calculates the annual energy consumption of a building by combining the full load capacity of plant with their full load hours of operation. Annual energy use can be estimated by combining the full load capacities of building services plant, their efficiencies and their equivalent full load hours of use in particular applications. Factors can be included to improve accuracy, but the method is limited to the availability of benchmark data for the hours of use of building services plant. The office sector is best suited to such a method as little equivalent information is available for other building types [Grigg 2003].

The Carbon Performance Rating (CPR) for offices in the UK Building Regulations is a based on this approach, using the rated input capacities of plant as a measure of full load output and efficiency, the CPR introduces factors to quantify the effect of controls and management of the systems [DETR 2002].

Hitchin [2003] carried out an analysis, which was presented at a seminar on "*Meeting the Requirements of the EPBD*". The analysis was a subjective assessment based on Hitchin's' own findings, a star rating was awarded to each methodology on the basis of what is required of a calculation methodology for the EPBD. The analysis is presented in Table 3.3 [Hitchin 2003].

	Credibility	Repeatability	Transparency	Ease of Use
Simulation	*****	****	**	**
Reduced parameter Dynamic	****	****	**	***
Bin Methods	***	*****	****	***
Degree Day	**	****	***	**
Monthly Balance	***	****	****	***
Full Load Hours	**	*****	*****	****

Table 3.3: Analysis of energy performance calculation methods

The aspects required of a calculation methodology, as identified by Hitchin are as follows:

- Credibility, i.e. the relative accuracy of the results.
- Repeatability i.e. the ability of another user to achieve the same results using the same method.
- Transparency i.e. the ability to analyse the calculation process
- Ease of Use: i.e. the relative usability of the method by a standard building professional.

Hitchins' analysis illustrates that simulation, although credible in terms of results is difficult to use and lacks transparency in terms of auditing the calculation process. The simplified methods, on the other hand, proved easier to use but generated results lacked credibility, but in most cases results were repeatable and transparent.

This is pertinent in terms of implementing an energy rating scheme. Although relative accuracy is important, it is of equal importance that there is transparency to facilitate error checking and auditing.

3.4 BUILDING SIMULATION PROGRAMS

Before the advent of complex simulation methods, complex manual calculations were applied by building designers. Pre-selected design conditions, rule of thumb methods and extrapolations were used, which often resulted in oversized plant and poor energy performance due to excessive part load operations.

Building Simulation Programs were developed to reduce the complexity of the underlying algorithms and lessen the computational load and the input required of the user. Detailed Simulation Programs have strived to develop a complex mathematical model to represent each possible energy flow path in a building.

3.4.1 History of Simulation

Clarke [2001] provided an evaluation of the evolution of building design tools. Clarke summarised the evolution of tools based on traditional calculation methods that were relatively easy to apply but difficult to interpret to contemporary simulation with knowledge based user interfaces, application quality control and user training. Morbitzer [2003] provided an analysis of Clarkes' evolution of simulation, in his analysis; he stated that the evolution of simulation is based on data which represents a closer assumption of reality. As the development of simulation tools progressed, the ability to accurately predict building heat transfer mechanisms improved.

Clarke [2001] used the analogy shown in Figure 3.4 to demonstrate the calculation process behind dynamic thermal simulation. Figure 3.4 shows the energy flowpaths both inside and outside buildings and shows how they dynamically interact to dictate inside comfort levels and building energy requirements.

Clarke stated that in order to understand this approach, one should visualise the energy flowpaths as an electrical network of time dependant resistance's and capacitance's which are subject to time dependant potential differences.

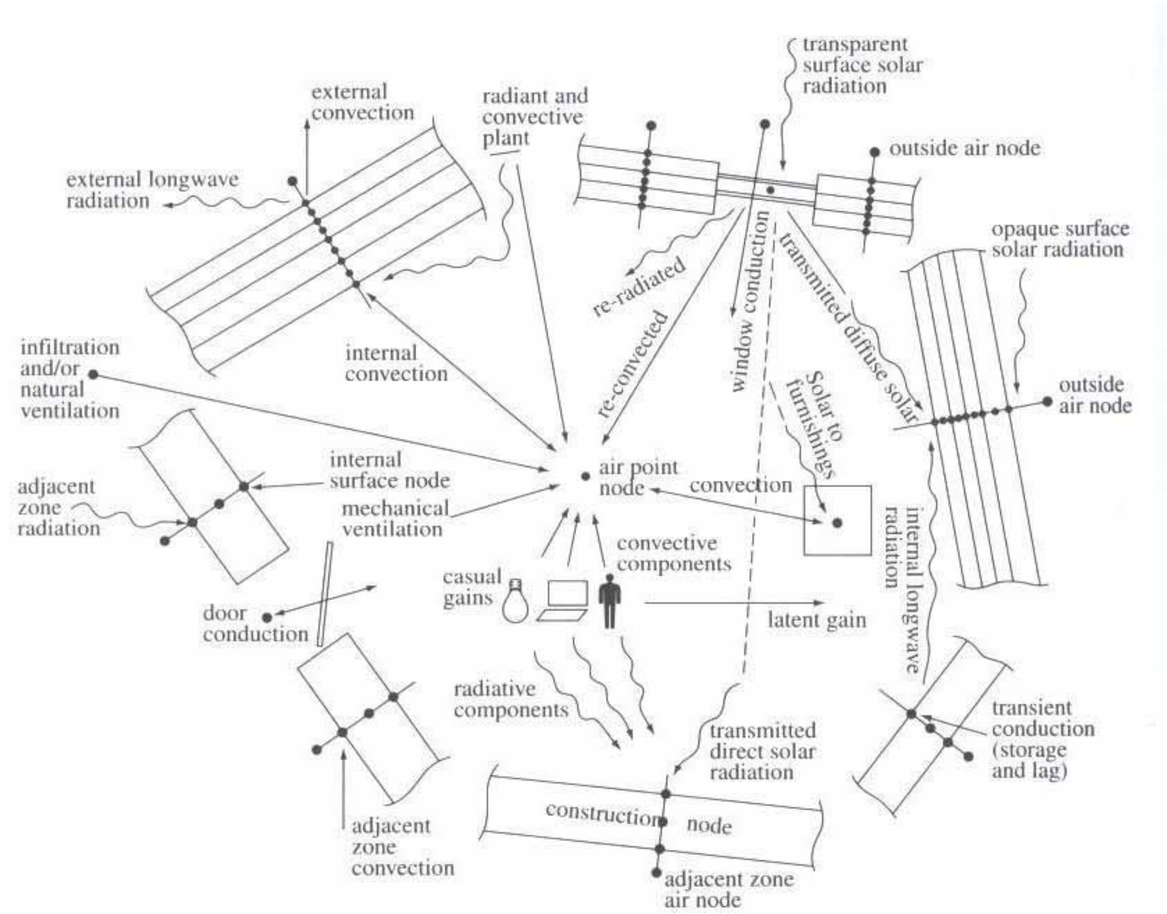

Figure 3.4: Building Energy Flowpaths

[Clarke 2001]

The energy flowpaths can be considered as equivalent to electrical current, constructional elements are characterised by electrical capacitance and treated as nodes, inter-node connections are characterised by electrical conductance. Each node possesses variables such as temperature and pressure i.e. a potential difference, analogous to voltage. Each node responds at a different rate to compete with other nodes to capture, store and release energy (electrical current). Clarke states that several complex equations must be solved to accurately represent such a system. As the heat transfer processes are interrelated, it is necessary to apply simultaneous solution techniques to maintain accuracy.

3.4.2 Validation of Building Simulation Programs

In order for building simulation tools to become more widely used in practice, designers need to have confidence in the results generated. Therefore, building simulation programs need to be validated. Validation refers to the process of ‘validating’ or checking the results and algorithms of a calculation tool against either other tools or against a series of standard tests. This validation procedure can range from the simplistic procedures set out by CIBSE [2004] to verify that programs produce results within good practice ranges. Such a procedure as set out by CIBSE may be used on steady state and dynamic procedures. However, dynamic calculation procedures, by their nature have complex calculation algorithms and require a more complex process of validation. A variety of validation exercises exist. Analytical tests provide comparison against mathematical solutions for example Building Environmental Performance Analysis Club (BEPAC) conduction tests [Bland 1993] and the American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) 1052RP analytical tests for building fabric [Spitler et al 2001]. Comparative tests provide comparison against other software programs, for example Building Energy Simulation Test (BESTEST) [Judkoff 1995a] and ASHRAE Standard 140 [ASHRAE 2001b, 2004]. Sensitivity and range tests exercise a program over a wide range of input values. Crawley et al [2001] states that sensitivity and range test suites would be carried out prior to public release of a software product or version. Empirical tests provide comparison against experimental data for example the IEA empirical validation procedure [Lomas et al 1994].

3.5 ANNUAL ENERGY PERFORMANCE ASSESSMENT

From the previous sections it has been established that many traditional methods are in use for the calculation of building energy performance. The majority of these traditional methods focus on temperature difference and transmission rates through building fabric such as the Bin methods and Degree Day methods. In some cases the method includes the plant load performance such as the simplified monthly heat balance and equivalent full load hours methods. Of these methods, the simplified monthly heat balance is most holistic in its approach, taking account of fabric transmission rates, solar gains, internal gains and thermal capacitance in addition to plant efficiencies for heating and hot water.

3.5.1 Approaches to Development of Calculation Methods

Various studies have been undertaken in the area of building energy performance assessment, particularly those of Richalet et al [2001], Lee et al [2001] and de Santoli et al [2003, 2005].

Richalet et al [2001] developed a methodology for the calculation of the normalised heating energy consumption of occupied dwellings; essentially a measurement based dwelling energy labelling approach termed the *House Energy Labelling Procedure* (HELP). The main aim of this research was to derive the thermal behaviour of a building from a continuous recording of internal temperature in response to external parameters and internal loads. The derived parameters were used to calculate the *Normalised Heating Annual Consumption* (NHAC) for a standard climate and standard operation.

The project initially comprised of a phase termed, *theoretical studies*, which consisted of data collection and testing. The data collection phase was a measurement exercise, monitoring parameters such as, appliance energy readings, temperature, air change rate and solar radiation over a 3-4 week period. The testing phase included the testing of a non-controlled model based on a global heat balance and a controlled dynamic whole building model. The HELP procedure was developed from the theoretical studies. The parameters were then fitted to a thermal model using a linear regression technique.

Richalet et al proposed to calculate the NHAC using a set of measured and derived parameters together with standardised degree days and casual gains. Ventilation, infiltration, heated volume, inhabited area and global solar radiation were measured. While, the heat loss coefficient, heat gain utilization factor and glazing areas were derived from fitting the thermal building model to a series of recorded data. Data such as external climatic data was used from test reference year data, zone setpoints and occupancy schedules were based on EU standards.

This procedure was tested on a variety of buildings. The research found that:

- Occupied dwellings provided larger uncertainties than unoccupied dwellings
- Large uncertainties occurred when a building did not fit into the boundary conditions offered by the model
- Large uncertainties were obtained in mild climatic conditions, which established the heat gain utilization factor as uncertain

- Thermal capacitance was found to have no relevance in the calculation

Richalet et al concluded that it is possible to derive the NHAC of a building using derived parameters. In addition, measurement of indoor air temperature, ventilation rate and heating power lead to an error band of less than 10%. The method proposed by Richalet et al has limitations as follows:

- The assumption of a single zone model,
- The need for a cold climate during monitoring
- The assumption of a 100% efficient heating system

The research established 4 weeks as the optimum length of monitoring period to extrapolate annual energy performance data. A mean indoor temperature accuracy of less than 5% was obtained with 4 weeks of monitoring. However mild weather was found to lead to inaccuracies with the utilization factor. In all the method achieved an error band of less than 10% in comparison to measured data over the stated monitoring period.

The research by Lee et al [2001] developed a simplified method of building energy performance assessment. The method was based on multiple regression models relating the maximum electricity demand associated with office air conditioning to key parameters affecting their energy performance.

This research was carried out in an effort to provide a simplified method for the Hong Kong Building Environmental Assessment Method [HK-BEAM 1996]. The HK-BEAM used dynamic thermal simulation to predict the air conditioning electricity consumption and maximum electricity demand for both new and existing buildings. Lee et al state that this method of assessment was particularly time consuming for use on existing buildings due to the number of data input parameters. In addition, due to the fact that envelope characteristics and system information are often incomplete for existing buildings, default values are used, resulting in under or over credit in the scheme.

The development of the methodology consisted of initially identifying key influencing building envelope and air conditioning system parameters and establishment of suitable mathematical forms for the regression models.

In order to create the multiple regression models, generations of predictions of electricity use and maximum electricity demand for a sufficient number of buildings with a wide range of design features were obtained. Coefficients associated with each independent variable were determined by multiple regression analysis of the simulation result.

The research achieved two items of significance;

Firstly, criteria were set for using a simplified method, which illustrates the restrictions of the method. Specifically, buildings must have; the same indoor design conditions, occupancy density and fresh air rate; no recessed windows or overhangs in addition air conditioning systems are limited to VAV at a specific operational range.

Secondly Lee et al established that assessing the "*Overall Thermal Transfer Value*" (OTTV) of the building did not provide a good reflection of building energy performance, thus establishing no correlation between fabric transmission rates and air conditioning energy consumption. The contribution of occupancy and infiltration were also identified as insignificant.

Research in the area of building energy certification was carried out by de Santoli et al in two stages [2003, 2005]. The objective of the research was to develop an energy certification scheme using simple procedures that could easily be stored in a database. de Santoli et al proposed that the stored data could be used for statistical purposes. This research was carried out to create a calculation methodology to satisfy the needs of the EPBD in Italy.

The system works by filling out a simple online form with the aim of identifying the building typology, orientation, climatic zone, installations and the importance of satisfaction of the users to indoor climate.

The work by de Santoli et al [2003] concluded with the development of a simple procedure for the calculation of the energy performance of existing buildings and the collection of data from a series of existing office buildings.

The aim of de Santoli et al [2005] was to develop a self learning expert system of building energy certification, which also provides a textual advisory report. The tool was designed for use by persons of a non-technical background. Data input consisted of a series of evaluation forms with diagrammatic assistance for the technical issues. The system combined five *votes*, which were attributed to different aspects of the building. A unique score was calculated from the five *votes* via a set of logic rules in the self learning algorithm. The logic rules were determined by a panel of experts and programmed into the system.

The intended process is carried out online where the user fills out a five simple evaluation forms providing information on the dimensional form, year of construction and number of windows. Using this information, the set of logic rules would determine the five initial *votes*. In the case of building fabric, the *vote* is based on calculating the heating energy consumption and a *vote* is applied by comparison to the Italian limit value. Similarly, in the case of building services the *vote* is calculated by comparison of the measured heating energy consumption (by way of bills) and the calculated heating energy consumption with a seasonal efficiency factor applied.

The annual energy performance calculation is performed online and the certificate is made available through a web based interface. The certificate also contains an advisory report regarding the energy performance of the building and suggests possible improvements. This body of text resembles an evaluation of a human expert based on the available knowledge.

The process was validated by comparison to a number of residential buildings in Rome, with an error less than 20%. This is a novel application in an effort to provide a system that can be used by the general public in a web based fashion, due to the popularity of such systems presently. The main advantage being, the ability of a non expert to use it. However in the context of a national energy rating system one must question the conflict of interest of a building owner having the ability to rate their own building. Although de Santoli et al recommend that a detailed assessment be carried out if a building achieves favourable results in the first stage. However, the system is a useful method of compiling information and data on existing buildings in use.

Each of the annual energy performance assessments proposed by Richalet et al [2001], Lee et al [2001] and de Santoli et al [2005] approached the area in different ways. Richalet et al [2001] used the measurement of a minimum number of parameters in order to derive specific data from which to extrapolate annual heating energy consumption data. The approach of Lee et al [2001] was to use a multiple regression model to predict annual air conditioning electricity consumption and maximum demand. Commonality between both methods was the identification of parameters that had a negligible effect on annual heating or cooling energy consumption. The thermal capacitance and mean internal temperature in the case of Richalet et al and the *OTTV* (equivalent to heat loss coefficient), occupancy and infiltration in the case of Lee et al. The derivation of the heat loss coefficient and glazing area by Richalet et al demonstrates the insignificance of the accuracy of these items in terms of the annual heating energy consumption. Although the geographical position of the building must be taken into consideration with these findings.

The work of de Santoli et al [2003, 2005] did not identify any parameters that were pertinent to the calculation. It did however demonstrate that an artificial intelligence can be used to mimic the decisions of an “expert” and provide advice on energy improvements based on a set of rules.

3.5.2 Comparison of Calculation Methods

Comparison of calculation methods have been applied by Roulet [2002], Corrado et al [2007] Rey et al [2007], Karlsson et al [2007], Kokogiannakis [2002] and Burke et al [2005].

Roulet [2002] proposed a simplified methodology for the calculation of annual heating energy consumption. This method was proposed as the European Standard EN 13790 2004 *Thermal performance of buildings - Calculation of energy use for space heating* [CEN 2004].

Roulet stated that the methodology could be used for applications such as:

- Judging compliance with regulations.
- Comparison of annual energy performance design alternatives for a building at design stage.
- Displaying a conventional level of energy performance of existing buildings.
- Assessing the effect of energy conversation measures on a national and EU level.
- Predicting future energy resource needs.

Roulet proposed heating energy consumption be calculated using a monthly heat balance that applies a quasi-steady state approximation. The dynamic effect of internal and solar heat gains are quantified using a utilization factor based on the thermal capacity of the building. The methodology includes the calculation of:

- Heat losses of the building when heated to a constant internal temperature

- Internal, passive and solar heat gains
- Annual heat input required to maintain specified set point temperatures

Standardised parameters are applied for items such as occupancy, ventilation and infiltration. Roulet [2002] stated that multizone airflow simulation may be applied to generate the associated heat losses but it has been found that this does not improve the accuracy of the results obtained due to the complex input data required.

The accuracy of the method is influenced by the input data. Uncertainty in input data was found to propagate through the formulae and equations, resulting in larger relative errors. Roulet also found that different users obtain results that differ by as much as 20% due to interpretation of input data. Roulet indicated that this is a particular problem when heat gains are high resulting in a gains to loss ratio of 0.75, an uncertainty of 20-35% on heat use occurs.

Reference was made to validation of the methodology. Comparisons to the performance of actual buildings lead to a disparity in energy use of 50% - 150%, due to assumptions on occupant behaviour and airflow rates. Roulet states that the relative influence of different design options is well predicted and there is good agreement to results achieved by dynamic methods. Results generated by the methodology are within the range of results generated by different dynamic programs. Comparisons have indicated that more complex methodologies do not yield significantly better results. The advantage of this calculation approach as stated by Roulet, is that it provides an approach that can be easily programmed to a computer and requires limited input parameters while providing a comparable result to full dynamic simulation.

This research illustrates that an accurate simplified annual energy performance calculation methodology that mimics the time related thermal storage processes of a full dynamic thermal simulation may be applied. Annual energy performance results generated in this case were in range of dynamic methodologies but fewer input parameters are required, resulting in a reduced possibility of error.

Corrado et al [2007] carried out a validation exercise of prEN 13790 *Thermal performance of buildings - Calculation of energy use for space heating and Cooling* [CEN 2005]. A comparison to dynamic methods was applied to the cooling energy requirements of Italian buildings. The analysis focused on the determination of dynamic parameters to take into account the mismatch between heat gains and heat losses. Of the simulations carried out by Corrado et al, different design options were applied to buildings, particularly changes in glazing ratio, thermal inertia and solar control.

A correlation was achieved between the heat losses and the indoor-outdoor temperature difference using both methodologies. Corrado et al state the driving force for the heat transfer as the indoor – outdoor operative temperature difference, which is stated as being dependant on the sky vault temperature. As a result, when no temperature difference exists, a net heat gain is achieved with the dynamic methodology. The disparity in heat gain was accounted for due to the fact that the quasi-state methodology ignores the effect of the sky vault temperature and therefore applies a reduction in solar heat gain received in the space. In addition, the comparisons noted a difference in heat transfer between both methodologies which was attributed to the variation of the internal surface heat transfer coefficient with changing set point temperature.

The analysis of the results also allowed some general considerations:

- Attention must be paid to the calculation of heat transfer giving consideration to the operative temperatures and the non-linearity effects on surface heat transfer coefficients.
- Before choosing a correlation for the dynamic parameters detailed knowledge of the thermal features of the building and the occupancy schedule are required.

The analysis provided that a simplified quasi-steady state method is capable of accurate prediction of annual energy needs provided the dynamic parameters are correctly determined.

Rey at al [2007] proposed a methodology termed *"Building Energy Analysis"*. (BEA). The methodology sets out to apply the calculation of annual energy performance and certification of buildings. Rey et al state that given the relevance of energy consumption in the building sector, the introduction of energy analysis tools with the ability to assess the energy implications of different design options must be promoted.

The research by Rey et al proposed both an annual energy performance calculation methodology and provided a comparison of results obtained by two dynamic thermal simulation programs. All three methodologies were applied to a health care building.

In its application, the BEA methodology initially obtained the thermal loads using the thermal properties of the building and monthly climatic data (dry bulb temperature, relative humidity and solar radiation). Peak heating and cooling loads were obtained from a dynamic methodology (DPClima). The calculation produced a minimum, maximum and mean load curve. Monthly energy consumption was calculated by applying the loads to the seasonal performance of the HVAC equipment. The energy consumption was determined by the energy demand of the building and the performance of the HVAC systems. Rey et al compared the ECON 19 [DETR 2000] benchmark figures to the results obtained for certification purposes.

Application of the BEA methodology and two dynamic thermal simulation programs to the health centre building generated a difference in annual energy consumption between 5% and 17%. Rey et al state the disparity in results as logical, as the comparison was between a statistical model and two detailed hourly simulation tools.

Karlsson et al [2007] carried out a study on low energy housing in Sweden using three different dynamic thermal simulation tools. The aim of the study was to compare measured and simulated annual energy demand of different aspects of low energy housing. A parametric study was carried out to investigate the fluctuation in space heating energy requirement by variation of electrical power, heat exchanger efficiency and supply airflow. Karlsson et al state that these parameters were chosen as they are common design variables that are difficult to predict.

The building used in the study was a low energy house with a good overall thermal transmittance value together with mechanical ventilation heat recovery. The good thermal properties were reflected in the installed space heating load of 900W.

Each of the three software tools were applied to the building. Karlsson et al noted some difficulty in inputting the same information in each software tool due to differences in the capabilities of the programs. This had an effect on how objects were modelled, specifically; the number of zones, modelling of the heat exchanger, airflow network, temperature control system and the simulation time step. The maximum difference achieved between the simulated total energy demands was 2%. The authors noted that in spite of the differences in heat exchanger modelling across the programs, the differences in annual energy demand were relatively small.

Regarding the parametric study, adjustment in heat exchanger efficiency was shown to have the greatest effect on annual energy consumption when the efficiency was adjusted by +5% and –5% differences in annual energy consumption of 20% and 23% respectively were obtained, thus illustrating the importance in obtaining accurate manufacturers data. Changes in airflow rates had a linear effect on annual energy consumption i.e. an airflow increase or decrease by 10% showed a corresponding increase or decrease in annual energy consumption. In addition an adjustment in internal gains of +10% and -10% showed an annual heating energy consumption reduction of 7% and increase of 7.8% respectively.

The conclusion of this research was that changes in occupant behaviour are more important and more difficult to predict than changes in simulation programs.

Kokogiannakis [2002] carried out research, the purpose of which was to examine and discuss the implications of the EPBD and to introduce the concept of using dynamic thermal simulation to assess the EPBD requirements. Kokogiannakis established ESPr as a methodology with the ability to integrate all aspects required to calculate the annual energy performance of buildings. In addition Kokogiannakis examined ESPr in the context of dealing with the complexity of integrating all of a building’s energy performance aspects to answer the requirements of the Directive.

Kokogiannakis modelled a case study building using ESP-r. The building used was an arbitrary 2 story office building. An examination was carried out to establish the way in which thermal insulation and space heating are dealt with, combined and integrated within ESPr.

Kokogiannakis stated that the results obtained would be very difficult to calculate in such detail using other methods. It was established that dynamic thermal simulation has the flexibility to produce hourly and overall annual performance results. It was proposed that in order to make the presentation of information clearer, the integrated performance view produced by ESP-r could be used for all simulation tools if used to address the EPBD. However, Kokogiannakis recognised that using simulation to produce results and improve the energy performance of the buildings is a complicated process and users have to be trained in these techniques. The research concluded that the available simulation tools would have the ability to address the requirements of the EPBD.

Burke et al [2005] carried out research on the use of dynamic thermal simulation as a building energy performance certification tool. The research was based on the potential for inaccuracy due to the wide range of input data required for dynamic thermal simulation. The aim of the work was, to highlight the parameters required for the determination of a building energy performance rating which are least likely to be repeatable and transparent and to investigate the consequence of variations in the input parameters on the energy performance grade as derived from simulation.

This research was carried out in the area of existing school buildings and considered the typical data potentially available to an assessor in the form of historical design information and information obtainable from a physical survey. A parametric data gathering exercise was carried out, the main energy consuming aspects of a buildings energy performance were identified as part of the research i.e. space heating and electrical energy consumed by lighting and appliances.

The dynamic thermal simulation tool, EnergyPlus was used as a calculation engine in conjunction with the DesignBuilder user interface. Base case models were constructed in DesignBuilder / EnergyPlus to simulate thermal; and electrical annual energy performance.

Burke et al defined energy performance regulation and building stock reference benchmarks based on prEN15217; 2005 *Energy performance of buildings - Methods for expressing energy performance and for energy certification of buildings*. [CEN 2005b] Based on information obtained during the data gathering exercise a regulation and stock reference specification was created for the fabric elements, boiler efficiency and infiltration. On this basis Burke et al classified the building certification grade in comparison to building stock and current regulation reference.

Burke et al indicated that the calculation methodology was heavily dependant on the assessors' interpretation of the data, particularly; boiler efficiencies, air change rates and glazing types. The effect of these uncertainties on the energy performance rating of the schools was assessed using parametric sensitivity analysis. Infiltration rates were varied between 0.5 and 5 Air changes per hour. Glazing was applied different thermal transmittance values. Boiler efficiencies of 40% to 90% were applied depending on the base case efficiency values.

The research concluded with the finding that boiler efficiency and infiltration had the most substantial impact on the energy performance grade of the buildings. Over the range of boiler efficiency parameters the grade could differ by as much as 1.2 energy performance grades. An important distinction was drawn in that boiler efficiency has a substantial effect on the energy performance grade. Sensitivity to infiltration rate was found to alter the energy performance grade between 0.72 and 1.12 grades. The inappropriateness of a default figure for infiltration was discussed in terms of the balance between the repeatability of the process while diverging from the ability of the dynamic thermal simulation to predict reality.

The research also found that the specification of glazing, as long in the same category i.e. single or double glazed had a minimal effect on the energy performance grade.

The work by Roulet [2002], Corrado et al [2007] Rey et al [2007], Karlsson et al, [2007] Kokogiannakis [2002] and Burke et al [2005] all discussed the input data required of a dynamic calculation methodology and the potential for error as a result. Another source of potential error discussed was the dynamic parameters in the simplified methods i.e. heat gain and heat loss utilisation factors.

A great deal of research has been carried out on the development of building energy performance calculation methods. Particularly measurement based and linear regression approaches. A theme which was consistent with all of the proposed calculation methodologies was concern at the volume of input data required for some schemes, availability of quality data and the users interpretation of such data. Parametric sensitivity analysis provided an insight into the effect of variation of parameters that may be estimated on site. It was found that some factors had a negligible affect, however the effect of an item such as system efficiency had a more profound effect.

CHAPTER 4: STUDY OF BUILDING SIMULATION PROGRAMS

4.1 CATAGORIES OF BUILDING SIMULATION PROGRAMS

In order to calculate and evaluate building energy performance, many different methodologies may be applied. Calculation methodologies may be considered under 2 distinct headings.

- Simple methods
- Complex Dynamic Methods

Simple methods average variables over a long period of time and do not consider the time related fabric and systems integrated response whereas complex dynamic methods average variables over shorter time steps and do consider the response of fabric and systems.

The complex dynamic methodologies described above involve complex and iterative calculations, a methodology may therefore be described as a calculation engine used to solve the heat and energy transfer processes within a building. Such a calculation engine is usually used in conjunction with calculation software. Calculation software may therefore be described as the vehicle that enables the methodology to be applied. Just as there are many methodologies or calculation engines for the calculation of building energy performance, many calculation tools exist as an interface to apply the various methodologies. Hong et al [2000] has defined all such calculation tools as *Building Simulation Programs*, which may be grouped into 2 categories, Design Tools and Detailed Simulation Programs.

Hong et al state that design tools are generally steady state and are used in the earlier design phases of a project; they require relatively simple and less input data than more complex tools. Detailed simulation programs, however, incorporate computation techniques such as finite difference, finite element, state space and transfer functions for building load and energy calculations. Because of the dynamic interactions of the building plant and the building envelope, detailed simulation programs are capable of performing calculations on an hour by hour or a minute by minute and a zone by zone basis. This process enables optimum design of a building and its facilities.

4.2 STUDY OF BUILDING SIMULATION PROGRAMS

The Building Simulation Programs used in building design range in complexity from the aforementioned Design Tools to Detailed Simulation Programs.
In order to evaluate the possible calculation methodologies that satisfy the requirements of the EPBD, it was necessary to investigate the various calculation tools used to apply the many methodologies. A large number of building simulation tools have been developed over the last few decades. The most comprehensive list of calculation tools available has been generated by the US Department of Energy [US DOE 2004], which list tools from research grade software to commercial products.

An analysis of all these tools was not possible in the scope of this research. For the purpose of this research, the tools that are applicable to the calculation of building energy performance were selected for analysis. Calculation tools were divided into different categories, based on their complexity, as follows:

- Detailed Simulation Programs
- EU projects
- Simplified Simulation Programs

4.3 DETAILED SIMULATION PROGRAMS

The Detailed Simulation programs selected for analysis were:

1. EnergyPlus
2. ESPr
3. TRNSYS
4. TAS
5. IES <VE>

These tools were selected as they are the leading end of the detailed simulation programs for dynamic thermal modelling. All tools are used either as research grade software or as design software used by building professionals.

The EPBD provides a general framework for a calculation methodology to comply with the EPBD [European parliament 2003]. The framework consists of a list of items that the calculation methodology must include. Although the programs studied in this section all have the ability to deal with most items, it is how well that they are dealt with that is at question.

This section will investigate the ability and extent that each methodology deals with each item of the general framework for a methodology.

4.3.1 Brief Description

EnergyPlus:

EnergyPlus is a public domain software program developed by The United States Department of Energy in cooperation with the U.S. Army Construction Engineering Research Laboratory [Crawley et al 2004]. EnergyPlus is a building energy simulation program which uses the best features of its predecessors, BLAST (Building Systems Laboratory, University of Illinois) and DOE-2 (Lawrence Berkley National Laboratory).

EnergyPlus is essentially a simulation engine around which a user interface can be wrapped, the main purpose of which is to provide an accurate simulation for temperature and comfort prediction. Heating and cooling loads are calculated by a heat balance engine at a user specified time step; these loads are sent to the building systems simulation module at the same time step. The energy systems simulation module calculates heating and cooling systems, plant and electrical system response.

EnergyPlus, therefore has 2 basic components as illustrated in Figure 4.1. [Laurence Berkley National Laboratory 2004]

- Heat and mass balance simulation module
- Building systems simulation module

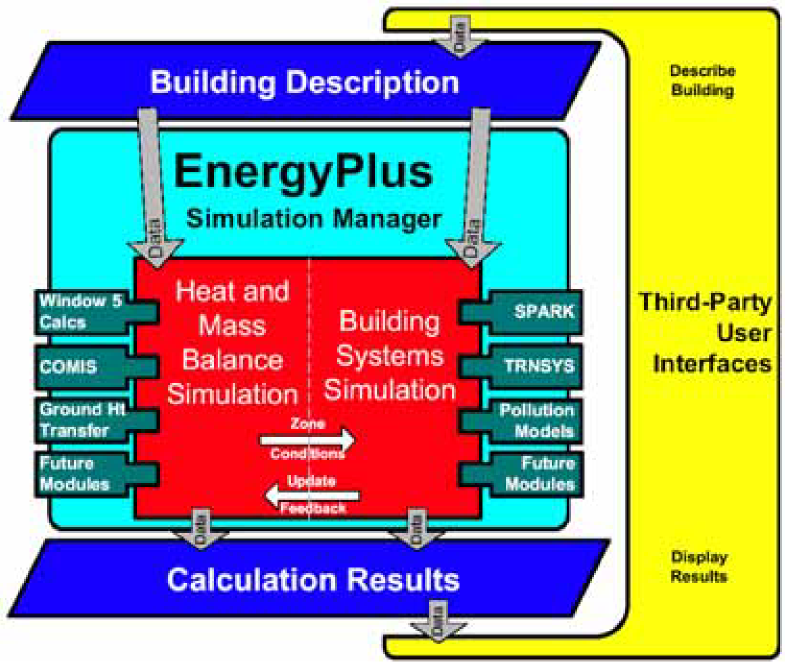

Figure 4.1: EnergyPlus Program Schematic

The building systems communication manager handles communication between the heat balance engine and the various HVAC modules and loops. The user can configure heating and cooling equipment components to give the flexibility in matching the simulation to the actual system configuration. HVAC air and water loops mimic pipework and ductwork found in an actual system.

The heat and mass balance module manages the surface and air heat balance modules and acts as the interface between the heat balance and the building systems simulation manager.

As stated previously, EnergyPlus is essentially a simulation engine, and therefore is not supplied with a user friendly interface, the input is generated via a text file, and the output generated in a similar manner. Although the data can be then exported to spreadsheet programs for analysis, EnergyPlus relies on third parties for interface development.

(Environmental Systems Performance) ESPr:

ESPr was developed by the Energy Systems Research Unit (ESRU) at The University of Strathclyde in Glasgow and is in continual development since 1974 [Clarke 2001]. ESP-r is a building energy simulation program capable of energy simulation and calculation of environmental performance of buildings. ESPr has a central project manager around which support databases, a simulation engine, performance assessment tools and various third party applications are arranged. Therefore ESPr is basically a suite of tools; a project manager controls the development of modules and gains computational services from other modules as well as a suite of third party tools.

The ESPr calculation procedure is illustrated in Figure 4.2. [Clarke 2001]

The basis of each simulation model is a zone that is attributed with data for construction, internal heat gain and idealised ventilation and infiltration. Basic input data such as this can yield a wide range of information on items such as; overheating, summer comfort assessment, evaluation of impact of mass, embodied energy, acoustics, daylight factors, visual comfort and glare studies.

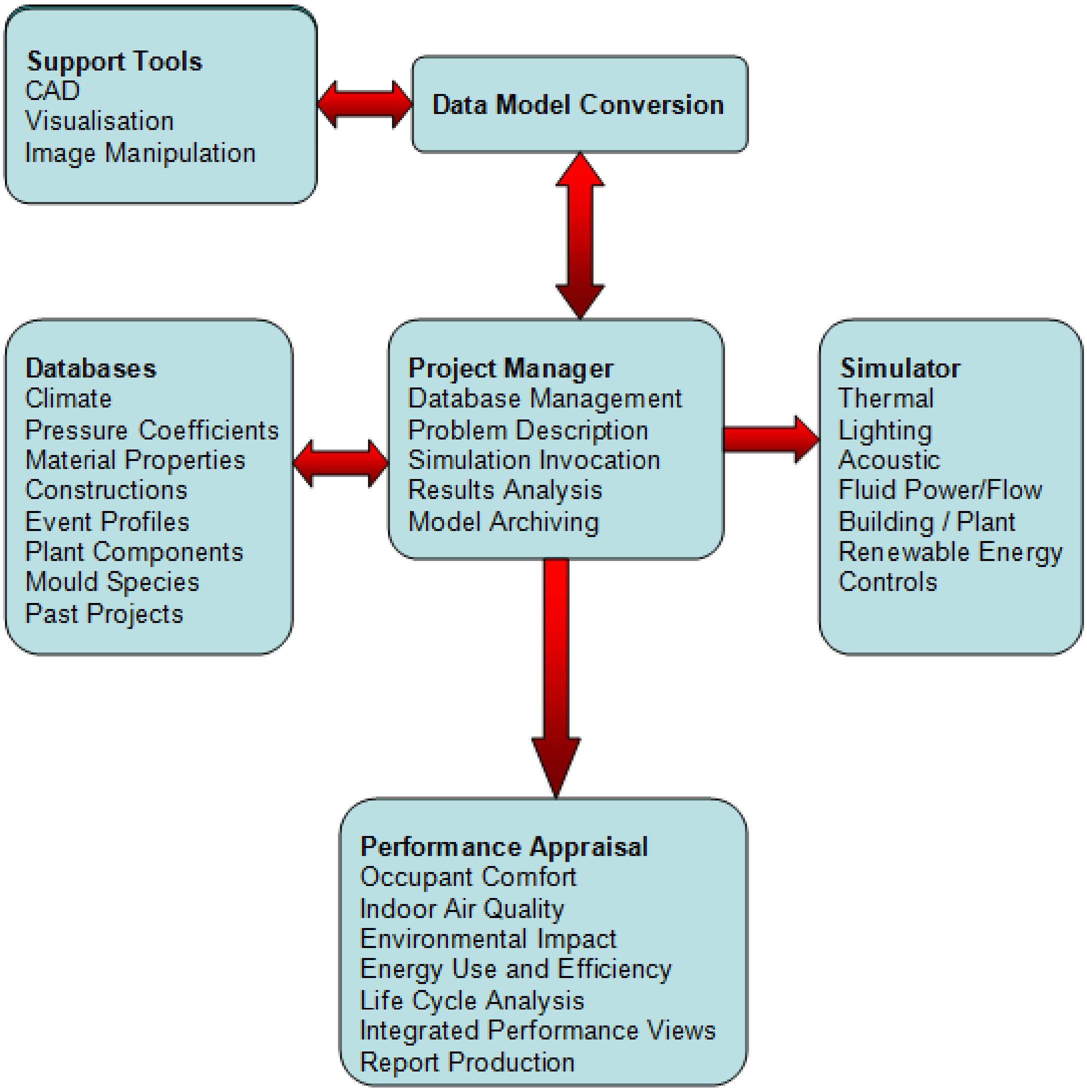

Figure 4.2: The ESPr System

If the design process requires more detailed results, additional components may be integrated into the model, (e.g. an air flow network rather than idealised ventilation and infiltration). Morbitzer [2003] states that the skills required for various simulation assessments differ from including a solar obstruction element into a thermal model to extending the model to also carry out a CFD analysis. More complex applications require the user to have an understanding of the physical processes that are to be simulated. A weakness of ESPr is that it is a general purpose tool and the extent of the options and level of detail slows the learning process. Specialist features require knowledge of the particular subject. Although robust and used for consulting engineering practice by some groups, ESPr is still mainly used in research [US DOE 2004].

ESPr is public domain software available from the University of Strathclyde under an open source licence. It is also freely available for research and development by third parties.

(TRaNsient SYstem Simulation Program) TRNSYS:

TRNSYS; was developed by the Solar Energy Laboratory (SEL) at the University of Wisconsin. TRNSYS is a commercial software product available at a cost from the University of Wisconsin. TRNSYS is capable of energy simulation, calculation of loads and building energy performance [University of Wisconsin 2006] [US DOE 2004].

The program includes a graphical interface, a simulation engine, a library of building models and standard HVAC equipment. TRNSYS is a transient system simulation program with a modular structure designed to solve complex energy system problems by breaking them down into smaller component problems. The program is configured into a fully integrated visual interface known as the TRNSYS simulation studio and building input data is inputted through a dedicated visual interface [US DOE 2004].

The simulation engine solves the algorithms that represent the whole system. All HVAC system components are solved simultaneously with the building envelope thermal balance and the air network at each time step. TRNSYS includes an extensive database of renewable energy components such as photovoltaic systems, solar thermal systems, cogeneration systems [Klein et al 2004]. The US DOE [2004] stated that as TRNSYS makes no assumptions of the building or systems, the user must establish detailed information to enter into the TRNSYS interface, which may be a potential source of error.

TAS:

TAS was originally developed by the Cranfield Institute in the UK and has been commercially developed by Environmental Design Solutions Limited (EDSL) since 1984 [EDSL 2004] [US DOE 2004]. TAS is a software package for thermal analysis of buildings. It is capable of dynamic thermal simulation and Computational Fluid Dynamics (CFD). Essentially, TAS is a suite of software products. Building envelope and natural and forced airflow calculations are carried out by the module ‘TAS building designer’. HVAC systems and controls calculations are carried out by the module ‘TAS systems’. which may be directly coupled with the building simulator, this performs automatic airflow and plant sizing calculations. The third module, TAS Ambiens, is a CFD package and produces a cross-section of microclimate variation in a space.

Within the calculation procedure, simulation data such as shading and surface information is taken from the 3 dimensional building designer model. The dynamic thermal simulation of the building and systems are combined with natural ventilation calculations. TAS also has the ability to simulate scheduled aperture openings and mixed mode systems.

TAS is a commercial software product; a user licence may be purchased from EDSL [EDSL 2004].

(IES <Virtual Environment>) IES <VE>:

IES <VE> was developed by Integrated Environmental Solutions (IES) Ltd [IES 2004]. IES <VE> consists of a system of integrated building performance analysis tools. It is capable of calculating heating and cooling loads and providing an energy analysis. IES <VE> provides a 3 dimensional geometric representation of the building to which data pertaining to the building elements and zones can be attached. The main simulation engine is ApacheSim, a dynamic thermal simulation tool which provides the mathematical modelling of the heat transfer processes. ApacheSim can be linked dynamically to MacroFlo for dynamic simulation of natural ventilation and Apache HVAC which provides dynamic simulation of HVAC systems and components. Simulations may be carried out in a variety of time steps. A detailed shading and solar penetration analysis can be carried out via SunCast. IES <VE> is a commercial software product; a user licence must be purchased from IES [IES 2004].

All of the aforementioned detailed simulation programs will be analysed under the following headings:

- Thermal characteristics and air tightness
- Heating installation and hot water supply
- Air-conditioning installation
- Built-in lighting installation
- Position, orientation and outdoor climate

- Passive solar systems and solar protection
- Natural ventilation
- Indoor climatic conditions
- Active solar and renewable energy systems
- Electricity produced by CHP
- Natural lighting
- Validation

4.3.2 Thermal characteristics and air tightness

Dynamic thermal simulation programs use an electrical analogy of conductance, resistance and capacitance to deal with building heat transfer processes. Although in most cases a program will define a construction envelope element in terms of its' thermal transmittance, this figure is irrelevant in the case of a dynamic thermal simulation program as heat transfer processes are solved as heat diffusion and storage in or through a building element related to the density and specific heat capacity of each component. Table 4.1 illustrates the modelling capabilities of each program in terms of thermal characteristics and air tightness.

	EnergyPlus	ESPr	IES<VE>	TAS	TRNSYS
Conduction Solution Method					
• Admittance method			X		
• Transfer function	X			X	X
• Finite difference		X	X		
Internal heat capacity	X	X	X	X	X
Internal Convection coefficient					
• Temperature dependant	X	X	X	X	X
• Air flow dependant		X	X	X	
• CFD based			X		
• User defined	X	X	X	X	X
Exterior convection coefficient					
• User defined	X	X	X	X	X
• Wind speed dependant	X	X	X	X	X
Shortwave radiation	X	X	X	X	X
Longwave radiation	X	X	X	X	X
Infiltration	X	X	X	X	X
Calculation of wind pressure coefficients			X	X	

Table 4.1: DSP thermal and air tightness modelling capability

4.3.3 Heating installation and hot water supply

Heating Installation

Dynamic thermal simulation programs generally deal with heating installations by two methods. Heating installations may be modelled as an idealised system or modelled as individual system components connected to simulate a specific heating system. Each programs capability is illustrated in Table 4.2. All the dynamic thermal simulation programs in this study, with the exception of TAS can model heating installations as idealised systems.

	EnergyPlus	ESPr	IES<VE>	TAS	TRNSYS
Heating Plant					
• Boiler (solid, liquid, gas)	X	X	X	X	X
• Ground source heat pump			X	X	X
Distribution System					
• Water based (pipework)	X	X	X	X	X
• Air based (ductwork)	X	X	X	X	X
• Pumping power		X			
Heating Emitters					
• Radiators	X	X	X	X	X
• Low Temperature Radiant (gas and electric)	X	X	X	X	X
• Heating Coils	X	X	X	X	X
• Fan Coil Units	X	X	X	X	X
• High temperature radiant	X	X	X	X	X
Control					
• Zone thermostats	X	X	X	X	X
• Supply air set points	X	X	X	X	X
• Outside air control	X	X	X	X	X
• Load control	X	X	X	X	X
• Economizer control	X	X	X	X	X
• User defined control strategies					X
Automatic Sizing					
• Heating Plant	X		X	X	
• Air Systems	X		X	X	
• Water Systems	X		X	X	

Table 4.2: DSP heating installation modelling capability

In order to calculate the energy performance of an idealised heating installation, the program calculates the delivered energy required for space heating as a function of the building fabric, infiltration and ventilation heat losses, applied to a coefficient of system performance to simulate the heating system efficiency. Control options can be specified in terms of time, temperature or both on a zoned basis. Primary energy is calculated on the basis of a conversion factor for the fuel used.

Hot Water Supply

In the dynamic simulation programs applicable to this study, the energy consumption associated with the domestic hot water system is modelled as a component network, although the capability differs in each program. The associated modelling capability is illustrated in Table 4.3.

	EnergyPlus	ESPr	IES<VE>	TAS	TRNSYS
Domestic Hot Water Plant	X		X	X	X
Distribution System		X			X
Domestic Hot Water Usage	X				X
Automatic Plant Sizing	X		X	X	

Table 4.3: DSP hot water supply modelling capability

4.3.4 Air-conditioning installation

Dynamic thermal simulation programs generally deal with air conditioning and cooling installations in a similar manner to that as described for heating installations. Cooling may be modelled as an idealised system or modelled as individual system components connected to model a specific system. Each programs capability is illustrated in Table 4.4. All the dynamic thermal simulation programs in this study with the exception of two have the capability to model cooling / air conditioning systems as both idealised systems and specific systems. TAS, however, does not have the ability to model idealised systems.

	EnergyPlus	ESPr	IES<VE>	TAS	TRNSYS
Cooling Plant					
• Electric Chiller	X	X	X	X	X
• Absorption Chiller	X				X
• Free cooling chiller	X			X	X
• Air to water heat pump chiller				X	X
• Water to water Heat Pump Chiller	X			X	X
Condensing Plant					
• Cooling Tower	X	X			X
• Air Cooled Condenser	X	X			X
• Evaporative Condensers	X				X
• DX Cooling Coil Evaporative Condensers	X				X
Distribution System					
• Water based (pipework)	X	X	X	X	X
• Air based (ductwork)	X	X	X	X	X
• Pumping power		X			
Zonal distribution					
• Constant Volume	X	X	X	X	
• Variable air volume	X	X	X	X	
• Dual Duct (VAV & CAV)	X	X	X		
• Fan Coil Units	X	X	X	X	X
• Cooling Coils	X	X	X	X	X
• DX Systems	X	X	X	X	
Humidification					
• Electricity consumption	X	X	X	X	X
• Water Consumption	X	X	X		X
Control					
• Zone thermostats	X	X	X	X	X
• Supply air set points	X	X	X	X	X
• Outside air control	X	X	X	X	X
• Load control	X		X	X	X
• Night time ventilation	X	X	X		X
• Humidity	X		X	X	
• User defined control strategies			X		X
Automatic Sizing					
• Cooling Plant	X		X	X	
• Air Systems	X		X	X	
• Water Systems	X		X	X	

Table 4.4: DSP air conditioning installation modelling capability

The calculation of the energy performance of an idealised cooling installation is carried out in a similar manner to that described for the idealised heating installation. Calculation of the energy required to offset the heating and cooling loads is applied to a coefficient of system performance to simulate the cooling system efficiency and control options specified in terms of time or temperature or both on a zoned basis. This calculates the delivered energy. Primary energy is calculated on the basis of a conversion factor for the fuel used.

4.3.5 Built-in lighting installation

Table 4.5 illustrates that all programs have the ability to model the built in lighting installation energy consumption.

	EnergyPlus	ESPr	IES<VE>	TAS	TRNSYS
Lighting Power Load	X	X	X	X	X

Table 4.5: DSP built in lighting installation modelling capability

4.3.6 Position, orientation and outdoor climate

Table 4.6 illustrates that all programs have the ability to model building orientation and outdoor climatic conditions. All programs exhibit a capability to accept a wide range of climatic data.

	EnergyPlus	ESPr	IES<VE>	TAS	TRNSYS
Orientation and Site Position	X	X	X	X	X
Outdoor Climate data	X	X	X	X	X

Table 4.6: DSP orientation and outdoor climate capability

4.3.7 Passive solar systems and solar protection

Table 4.7 illustrates each programs ability to model passive solar systems and solar protection. All programs can apply user defined shading control, all programs except ESPr can schedule shading devices.

	EnergyPlus	ESPr	IES<VE>	TAS	TRNSYS
User defined shading devices					
Shading device scheduling	X		X	X	X
User specified shading control	X	X	X	X	X

Table 4.7: DSP passive solar systems and solar protection capability

4.3.8 Natural ventilation

Table 4.8 illustrates the programs ability to model natural ventilation. All programs can model natural ventilation. Mixed mode systems can only be modelled by IES<VE>, TAS and TRNSYS. All programs capable of natural ventilation calculations have the ability to schedule openings based on internal or external conditions.

	EnergyPlus	ESPr	IES<VE>	TAS	TRNSYS
Natural ventilation	X	X	X	X	X
Mixed mode			X	X	X
Controllable openings based on internal on external conditions	X	X	X	X	X

Table 4.8: DSP natural ventilation capability

4.3.9 Indoor climatic conditions

Table 4.9 illustrates the programs ability to model indoor climatic conditions. All programs can model indoor temperature, either based on the loads and systems heating and cooling input or a floating temperature with no control. Also all can model indoor relative humidity and thermal comfort using at least one model of thermal comfort. ESPr, IES<VE> and TRNSYS have the ability to model concentrations of CO_2 in a zone.

	EnergyPlus	ESPr	IES<VE>	TAS	TRNSYS
Indoor temperature	X	X	X	X	X
Floating temperature – no control	X	X	X	X	X
Temp based on loads sys feedback	X	X	X	X	X
Indoor relative humidity	X	X	X	X	X
Thermal comfort	X	X	X	X	X
Zone concentrations of CO_2		X	X		X

Table 4.9: DSP indoor climatic conditions capability

4.3.10 Active solar and renewable energy systems

Table 4.10 illustrates the programs ability to model active solar and other renewable systems providing heating or electricity. All programs have the ability to model glazed flat plate solar collectors. All programs except TAS have the ability to model photovoltaic collectors. Both ESPr and TRNSYS are capable of modelling wind power. TRNSYS is capable of modelling a wide range of renewable systems.

	EnergyPlus	ESPr	IES<VE>	TAS	TRNSYS
Wind power		X			X
Glazed Flat Plate Collectors	X	X	X	X	X
Evacuated tube collectors					X
Photovoltaic Collectors	X	X	X		X
User defined Solar Storage systems					X
Hydrogen systems		X			X

Table 4.10: DSP active solar and renewable energy capability

4.3.11 Electricity produced by CHP

Table 4.11 illustrates that only ESPr and TRNSYS have the ability to model combined heat and power (CHP).

	EnergyPlus	ESPr	IES<VE>	TAS	TRNSYS
CHP		X			X

Table 4.11: DSP CHP capability

4.3.12 Natural lighting

Table 4.12 illustrates that all programs with the exception of TRNSYS provide modelling of natural lighting. All with the exception of EnergyPlus and TAS provide a choice of sky model.

	EnergyPlus	ESPr	IES<VE>	TAS	TRNSYS
Interior illumination from windows etc.	X	X	X	X	
Stepped or dimming lighting controls	X	X	X	X	X
Sky model					
• Isotropic		X	X	X	X
• Anisotropic	X	X	X		X
• User selectable		X	X		X
Daylight Illuminance Maps	X	X	X	X	

Table 4.12: DSP natural lighting capability

4.3.13 Validation

Validation is one of the most important aspects of a dynamic thermal simulation calculation program. Crawley et al [2005] considered simulation programs in terms of their validation; the table from Crawleys' study is reproduced in Table 4.13 to illustrate the validation exercises undertaken with the programs pertinent to this study.

Validation procedures are set out by, Oscar Faber & Partners [1980], U.S. Department of Energy [1981], Strachan [2000], Bloomfield [1989], Lebrun et al [1988], Judkoff et al [1995a, 1995b], ASHRAE [2001], Lomas et al [1994], Neymark et al [2002], ASHRAE [2004], Neymark et al [2004], Spitler et al [2001], Bland [1993], Bloomfield et al [1995], Jensen [1993], McDonald et al [2004] and ISO TC163/SC2 [2004].

	EnergyPlus	ESPr	IES<VE>	TAS	TRNSYS
IEA ECBS Annex 1		X			X
IEA ECBS Annex 4		X			X
IEA SHC Task 8		X			X
IEA ECBS Annex 10		X			X
IEA SHC Task 12					
• Envelope BESTEST	X	X	X	X	X
• Empirical		X		X	X
IEA SHC Task 22					
• HVAC BESTEST Vol. 1	X	X			X
• HVAC BESTEST Vol. 2	X	X			X
• Furnace BESTEST	X	X			
• RADTEST		X			X
IEA ECBS Annex 41					
HERS BESTEST					
ASHRAE 1052-RP	X				
BEPAC Conduction Tests	X	X			
BRE/EDF validation project		X			
PASSYS project		X			
CIBSE TM33		X	X	X	
ISO 13791		X		X	

Table 4.13: Summary of validation procedures

[Crawley, 2005]

Of the validation options, Crawley et al [2005] analysed this item under 19 headings, in his analysis ESPr performs best, validated by 22 of a possible 19 validation suites. The remainder in order of performance: TRNSYS (9), EnergyPlus (6), TAS (4) and IES <VE> (4).

4.4 EU PROJECTS

A number of EU projects have been commissioned under the SAVE programme [EU 2005] to investigate possible methodologies and calculation tools capable of certifying the annual energy performance of a building. This section provides a review of two projects, as follows:

1. Europrosper
2. BESTCert

4.4.1 Europrosper

The European Programme for Occupant Satisfaction, Productivity and Environmental Rating of buildings or, "*Europrosper*", is a method of achieving certification of energy performance of an existing building; it is generally suited to office type buildings and is typically used post occupancy.

The Europrosper project was funded by the EU SAVE programme [EU 2005] with co-funding from the UK carbon trust and began in April 2002. The aim of the project was to develop a methodology could be customised for any EU country while retaining a pan European harmonisation [Cohen 2004]. The project was participated by 7 EU countries; Belgium, Denmark, Greece, UK, Netherlands, Sweden and Ireland; Ireland was represented in the project by the Energy Research Group (ERG) at University College Dublin (UCD).

The project developed a methodology and associated software training package. The energy performance calculation methodology is based on meter readings of the energy supply sources. It provides comparison of building CO_2 emissions with typical and good practice benchmarks for a building with a similar specification and use.

The Europrosper calculation framework consists of 7 items, as follows [Cohen 2004]:

1. Collection of information on building type, construction, servicing, equipment, control and use.
2. Collection of information on external factors, such as degree days.
3. Calculation, collection or prediction of the buildings energy use by fuel.
4. Reporting on items 1-3 in a consistent manner.
5. Identifying appropriate yardsticks against which to assess the building.
6. Creation of a certificate identifying the results of the assessment with a headline grading.
7. Assisting in the recommendation of measures.

The calculation framework is comprehensive, combining information on the constructed building, its' services, equipment and information on fuel use. The use of degree day information provides a reasonably accurate method of establishing the heating energy consumption. The comparison to benchmark data for the certification aspect of the procedure is pertinent to establishing a comparison of the building against the national building stock.

Once the information has been gathered on items 1-3 above, the method has the following main steps.

Step 1. Calculation of the buildings energy intensity

Step 2. Calculation of benchmarks appropriate to the specific building and its use.

Step 3. Comparison of the energy use intensity with benchmarks to determine the energy efficiency grade

Step 4. Determination of the energy supplied by end use.

Step 5. Analysis and prioritisation of energy efficiency measures for cost effectiveness and calculation of potential improvement in the energy efficiency grade.

Step 6. Production of an energy certificate, reporting on the above.

The building type, floor area, accredited annual energy consumption of each fuel together with CO_2 and primary energy factors must be established in order to calculate the energy intensity of the building. This will yield an output of the annual energy consumption of each fuel, converted into CO_2 or primary energy normalised for floor area.

Europrosper calculates a specific reference value (benchmark) for each individual building. The reference value is created by calculation of the annual energy requirement based on building specific parameters. Two reference benchmark figures are calculated, a good practice and typical benchmark. The approach by Europrosper is shown using a tree diagram illustrated in Figure 4.3 [Cohen 2004].

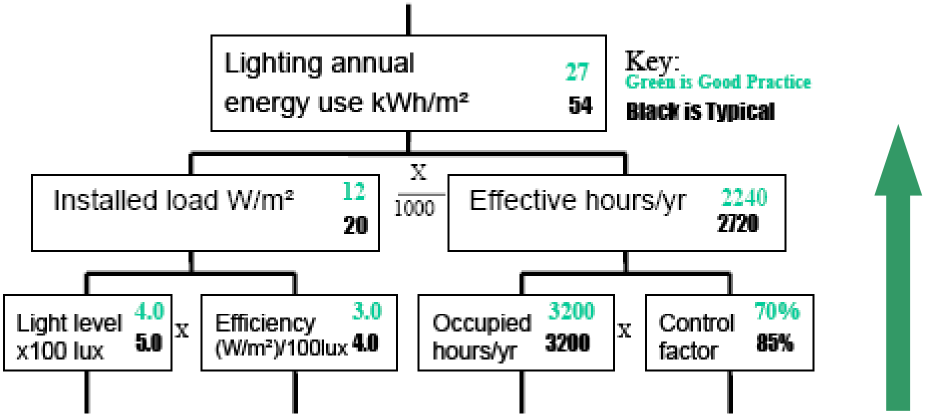

Figure 4.3: Europrosper tree diagram for lighting energy consumption

Using this approach, Figure 4.3 illustrates the calculation of a benchmark for lighting energy consumption. The light level and efficiency are fixed benchmarks for the office sector. The inputs of the good practice and typical figures at the lower end of the tree will yield a tailored benchmark for both good practice and typical energy consumption normalised for floor area. The benchmarks for good practice and typical energy performance are expanded to produce a grading scale to compare actual energy consumption against good practice and typical energy consumption. Based on this grading scale, one can identify the actual performance of the building against the tailored benchmarks.

The actual energy end use breakdown is determined using the same tree diagram model as was used to create the tailored benchmarks. In this case the actual values for efficiencies and control are inserted in place of the good practice and typical values as used in the benchmarking exercise.

Potential energy efficiency measures are analysed utilizing the tree diagram model. The assessor inserts figures to represent control and efficiency measures already present. Figures are inserted into the model to represent the potential for increasing these measures. The calculation software calculates the impact of each measure via the tree diagrams. This process is illustrated in Figure 4.4. [Cohen 2004]

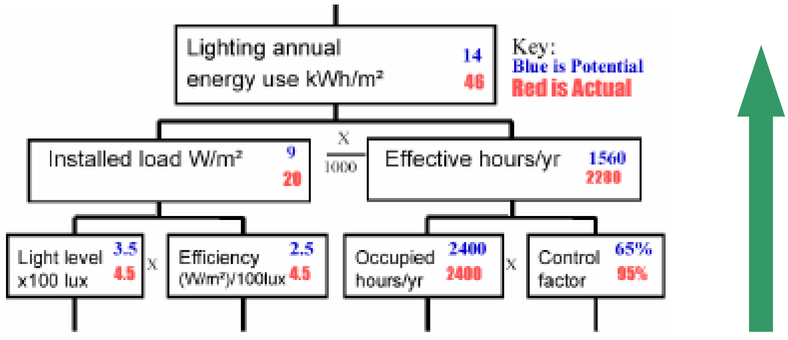

Figure 4.4: Europrosper tree diagram lighting energy and potential savings

The example in Figure 4.4 illustrates the factors affecting the annual lighting energy use in a hierarchical fashion. In this example, there is potential to improve the illuminance, efficiency and control factor. However, there is no potential to reduce the occupied hours of use as this is determined by the function of the building. Reduced illuminance and improved efficiency yield an improved installed load and similarly an improved control factor reduces the effective hours of operation. Both the improved installed load and effective hours yield an improved annual energy use.

The Europrosper software produces an energy certificate which reports on the results of the above analysis. The building energy benchmarks are interpolated and extrapolated to range from 75% of the good practice benchmark to 150% of the typical benchmark figures. The grading scheme of the certificate is based on the actual – good practice – typical (AGT) factor; the actual energy use is compared to these figures and plotted on the certificate.

The Europrosper project has produced a methodology and calculation tool for the calculation of energy performance for buildings in use i.e. a methodology for an operational rating. This calculation tool also provides a grading system against tailored benchmarks based on the ECON 19. Although this calculation tool allows analysis for improvement of building energy use, it focuses on HVAC and electrical systems and therefore does not consider the renovation of existing buildings i.e. to change the building façade to gain improvement.

4.4.2 BESTCert

Building Energy Standards Tool for Certification or "*BESTCert*" is a European funded project funded by the EU SAVE programme [EU 2005] which commenced in January 2003. The main objective of the BESTCert project was to improve the energy efficiency of buildings through the development and testing of an energy certification procedure by investigating pilot methodologies for certifying the energy performance of buildings to comply with the EPBD [Lillicrap et al 2005].

The project was carried out by a number of project partners as follows;

- Building Research Establishment (BRE), UK – project coordinator
- Centre Scientifique et Technique du Bâtiment (CSTB), France
- Association pour la Recherche et le Development des Méthodes et Processus Industriels (ARMINES-CENERG), France
- Consiglio Nazionale delle Ricerche (CNR), Italy
- Cenergia Energy Consultants (Cenergia) , Denmark
- National University of Ireland, Dublin (NUI/UCD)

Each project partner was required to investigate a methodology for the certification of the energy performance of buildings. Each methodology was required to provide the following:

- Calculation of an asset rating
- Calculation of reference values to current legal standards
- Calculation of benchmarks to enable comparison of the energy performance of a building
- Generation of an energy rating certificate.

The project was organised into 5 phases, as follows [BESTCert 2004]:

Phase 1 – Establish Energy Standards

Phase 2 – Establish building specific benchmarks

Phase 3 – Develop certification tool

Phase 4 – Test and compare experiences and case studies

Phase 5 – Dissemination

The project required each project partner to deliver the following:

- Energy Standards for 2 building types
- Building specific benchmarks for 2 building types
- Certification tool
- Case studies

Lillicrap [2005] states that each project partner collected information on several building types; including, schools, offices, university buildings, public buildings and social housing. This data was used to draw up standard occupancy schedules and to define typical and good practice standard for building fabric and HVAC performance in each country. The typical and good practice standards were used with the appropriate tool in each country to calculate building specific benchmarks. Two types of reference benchmarks were created by each methodology:

- Benchmarks for energy performance regulation i.e. a limit value expected of new buildings.
- Building Stock Reference benchmark i.e. the value that would be expected to be achieved by 50% of the national building stock at the time.

The calculation tools used by the project partners in the research exercise were as follows:

- UK – DesignBuilder / EnergyPlus
- Ireland - DesignBuilder / EnergyPlus
- Italy - DesignBuilder / EnergyPlus
- UK – SBEM
- France – COMFIE
- France – DPE Method
- Denmark – Be06

DesignBuilder / EnergyPlus is a calculation tool which uses EnergyPlus as a calculation engine and DesignBuilder as a user interface with a constrained dataset from EnergyPlus.

SBEM is the UK National Calculation Methodology (NCM) for the EPBD; SBEM shall be evaluated in Section 4.7 of this thesis.

COMFIE is a French simulation tool that performs hourly simulations of buildings. It is used by mechanical, energy and architectural engineers or architects and uses a finite volume method of calculation. The output comprises the yearly and hourly heating loads, hourly and mean temperatures in the thermal zones [US DOE 2004].

Be06 is the Danish method of compliance with the EPBD. Be06 calculations are performed in accordance with the mandatory calculation procedure set out in the Danish building regulations. The expected energy demand is calculated to operate the heating and climate conditioning systems in all types of buildings. Be06 calculates the required energy supply to a building for space heating, ventilation, cooling, hot water and artificial lighting. The US DOE [2004] state that while this method provides calculation of the energy demand for building operation it is not appropriate for design and sizing of systems.

The appropriate calculation procedure was applied to a common building for the conditions and regulations appropriate to each participant country. Table 4.14 illustrates the results obtained.

Table 4.14 shows absolute values in kg CO_2 m^{-2}, these values being; an asset rating (EP), a regulation reference (benchmark) value (R_r) and a building stock reference value (R_s). Table 4.14 also shows ratios of asset rating to regulation reference value (EP/ R_r) and asset rating to building stock reference value (EP/ R_s). The ratios were used to provide numerical reference to performance against current standards and current building stock.

Tool / Country	EP kg CO_2 m^{-2}	R_r kg CO_2 m^{-2}	R_s kg CO_2 m^{-2}	EP/ R_r	EP/ R_s	C= 1+ EP/R_s	Rating A-G
Designbuilder/ EnergyPlus UK	29.42	13.32	24.90	2.21	1.18	2.18	E
Designbuilder/ EnergyPlus Ireland	26.61	14.53	19.04	1.83	1.40	2.40	E
Designbuilder/ EnergyPlus Italy	24.72	15.36	18.81	1.61	1.31	2.31	E
COMFIE France	55.00	18.00	28.00	3.06	1.96	2.96	F
DPE Method France	61.88	27.02	31.36	2.29	1.97	2.97	F
Be06 Denmark	349.10	40.90	41.80	8.54	8.35	9.35	G
SBEM UK	117.90	43.6		2.7			

Table 4.14: Energy performance and ratings for BESTCert study

[BESTCert 2004b]

The results of the study illustrate a difference in results obtained by the same methodology and different methodologies, although in different local conditions. But the results also illustrate differences in results obtained by different methodologies in the same climate.

The common building applied to each methodology was a school; the school was studied using the same methodology (DesignBuilder / EnergyPlus) in Ireland, UK and Italy. A difference in asset rating was obtained between Ireland and UK. Although local conditions are similar and building standards are better in the UK, the relative poor performance of the building in the UK in comparison to the building in Ireland may be due to the shorter school holidays and therefore longer operation hours. A difference in asset rating was obtained between both the UK and Ireland and Italy. The better performance of the school in Italy may be due to the warmer climate in Italy. Hence, the results obtained by this methodology would appear to be in the range as to what would be expected in the respective climatic and operational conditions. The same methodology was applied to the same building in different climatic regions. This illustrates that the same methodology will generate different energy performance data under different conditions and is particularly sensitive to building operation.

The study was applied to the same school building in France using two different methodologies (COMFIE and DPE Method), the asset ratings from each methodology differ from that of the other countries in the study, also the asset rating differs between methodologies applied to the same building in the same climatic location i.e. France. Cohen states that the difference in asset rating between the methodologies applied in each country may be due to several items, as follows:

- Auxiliary electrical power for fans and pumps is included in the calculated electrical consumption in COMFIE and DPE Method whereas these are treated separately in other tools.
- EnergyPlus/DesignBuilder assumes efficient management of lighting. This assumes that electrical lighting is switched off where daylight can provide 300 lux, other methods may assume less efficient management and therefore yield a higher asset rating.

BESTCert [2004] state that the difference in asset rating between the methodologies applied in France may be attributed to the way domestic hot water (DHW) is dealt with between COMFIE and DPE.

The study was applied to the same school building in the UK using two different methodologies, SBEM and EnergyPlus/DesignBuilder. There is a significant difference in the asset ratings obtained, which is not commented on by BESTCert in the study. However, SBEM estimates DHW and ventilation energy consumption based on occupancy and therefore assumes that ideal DHW provision and ventilation rates are being achieved. This is represented differently in other methodologies and therefore would account for the difference.

An overall rating was derived from the ratio of the asset rating to the building stock reference value, although there was a significant difference between asset rating in each case, all buildings (except Denmark) achieved the same rating after the normalisation of the result using the asset rating / building stock reference ratio. This is particularly illustrated with the asset rating generated by SBEM and EnergyPlus/DesignBuilder in the UK, although SBEM did not have a building stock reference value applied to it, the ratio between the regulation reference value ratio for SBEM in UK and EnergyPlus/DesignBuilder in the UK, for a 75% difference in asset rating between the methodologies, there is only a difference of 18.1% between the ratios. One can see from the results obtained that it is extremely important that the calculation tool used for certification is also used as the tool to generate the reference (benchmark) value.

BESTCert is therefore not a calculation methodology in its own right, but a harmonisation of calculation tools to apply the rating process to buildings. It is best suited to asset rating of new buildings, although reference is made by

Cohen to the BESTCert tools application to operational ratings of existing buildings. Difficulty arises in this area as benchmark data is calculated from a standardised set of data based on a standardised use, but an operational rating is as a result of actual use. Therefore to enable comparison and certification of a building against reference values some adjustment is required to standardise the operational data or to adjust the reference data to actual occupancy and operation.

4.5 SIMPLIFIED SIMULATION PROGRAMS

The Simple Simulation models selected for the scoping study were:

1. BREEAM
2. Dutch Simplified Method NEN 2916
3. LT Method
4. SBEM

4.5.1 BREEAM:

The BRE Environmental Assessment Method or "*BREEAM"* was developed by the building research establishment (BRE) and has been in operation since 1998. BREEAM is a simple tool for specifying and evaluating the environmental performance of new, refurbished and existing buildings. Baldwin et al [1998] states the main objective of BREEAM is to distinguish buildings of reduced environmental impact in the market place while encouraging best environmental practice in building design, operation, management and maintenance.

BREEAM awards an environmental label after a building is assessed against a range of environmental issues. The BREEAM certification is based on a system of awarding credits [Prior 1993]. Where buildings have attained or exceeded various benchmarks of performance, an appropriate number of credits are awarded. The number of credits attained is interpreted in the form of an overall rating of Excellent, Very Good, Good and Pass.

Credits are awarded under 3 categories, as follows:

- Core performance credits
- Design and procurement credits
- Management and operation credits

Within the above categories are subcategories under which specific credit requirements are grouped. These are as follows:

- Management - Overall policy and procedural issues
- Health and Comfort - Indoor and external issues
- Energy - Operational energy and CO_2 issues
- Transport - Transport related CO_2 and locational issues
- Water - Consumption and leakage related issues
- Materials - Environmental implications of materials selection
- Land Use - Greenfield and brown field site issues
- Site ecology - Ecological value of the site issues
- Pollution - Air and water pollution issues (excl CO_2)

In the credit based structure, the assessor must recognise the level of achievement in attainment of the credits in terms of; achievement of basic levels at statutory levels, at best practice levels, leading edge levels and exemplar levels.

BREEAM is essentially a method of rewarding the environmental performance of a building, but in does not give an absolute value of the energy performance of the building, although the % improvement in CO_2 emissions above the Part L improvements must be quantified as part of the assessment. The BREEAM rating system awards a building for its overall environmental ethos i.e. the provision of bicycle racks and the lack of parking spaces are rewarded as a deterrent to drive to the building.

Therefore, within the BREEAM rating, an energy assessment is required. But the BREEAM rating is not an absolute rating of the actual building energy performance.

4.5.2 Dutch Simplified Method NEN 2916

NEN 2916 is a national standard published by The Dutch Standardisation Institute to describe and calculate energy performance in residential and office buildings [Netherlands standardization institute 1999]. The method of calculation allows the calculation of the energy consumption associated with space heating, water heating, ventilation, lighting, comfort cooling, pumps and humidification. In addition, the method defines ways of handling the contributions of district heating, solar energy and CHP systems. The calculation may be carried out manually, but a software program is also provided. The standard expresses energy consumption in terms of primary energy.

Heating

The heating and cooling energy consumption is calculated using a monthly heat balance. The heating energy consumption is calculated using monthly mean outdoor temperatures, fixed mean indoor temperatures and mean heat gains modified by utilisation factors for the positive effects of internal and solar heat gains. The cooling energy consumption includes the solar gains through the fabric as well as gains through windows. The impact of heat gains is modified by applying a utilisation factor to the heat losses, the factor itself depending on the loss/gain ratio and the building thermal capacity. Net losses and gains are converted into energy requirements using system efficiencies.

The Dutch standard is unique in Europe as a simple method for calculation of building energy performance as it is the only simple method that quantifies cooling energy consumption.

This program, although in essence is steady state but may be regarded as a quasi-steady state, as the dynamic effect of the internal heat capacity is quantified by a heat gain or heat loss utilisation factor based on the building time constant.

4.5.3 LT Method

The Lighting and Thermal or “*LT Method”* is a simple design tool that predicts energy performance for lighting, heating and cooling and ventilation of non domestic buildings. The method is designed for use with data available early in the development of the design. It takes account of the interaction and response to architectural variables such as built form, façade design and relationship to adjacent buildings. The method was developed at Cambridge University and was originally a paper based method but has evolved into a software based method [Baker et al 1996].

The LT method is primarily based around the glazing ratio of a façade. A direct relationship is considered between glazing ratio, heat loss, solar gain and daylight provision. The LT method uses the concept of passive and non passive zones. Passive zones, which are located on the perimeter of the building can be daylight, naturally ventilated and make use of passive solar gains for heating. A passive zone may suffer overheating in summer and is also susceptible to conduction and infiltration heat losses in winter. The non-passive zones, which are located inside the passive zones require artificial lighting and mechanical ventilation and are cooled to prevent overheating due to internal gains.

The main basis of the LT method is a set of graphs or curves, which give the total primary energy consumption on a floor area basis depending on façade orientation and glazing ratio. Individual curves are available for cooling, lighting, and heating; a total energy curve combining all of these is also provided. Correction factors are applied for external obstructions, atria and thermal mass.

The LT method is essentially a tool developed by architects for use by architects and therefore cannot be regarded as an accurate energy model for a building. The LT method should be used to test the relative performance of a number of design options. A very limited number of design parameters are required for input. A much larger number of parameters have already been given assumed values, which in some cases already represent good practice in low energy design. The method predicts the potential performance of the building, assuming that both systems and occupants function optimally.

4.5.4 SBEM (Simplified Building Energy Method)

SBEM is the calculation tool for the UK National Calculation Methodology (NCM) used to demonstrate compliance with the EPBD in the UK. The UK NCM was commissioned by the UK Office of the Deputy Prime Minster (ODPM). SBEM [ODPM 2005] is used to produce an evaluation of energy use in non domestic buildings. SBEM consists of a calculation methodology together with a compliance checking module which is utilised in the calculation.

The model is used to calculate the heating, cooling, ventilation and lighting energy requirements of a building. The calculation procedure is based on the draft European standard prEN13790 [CEN 2005]. SBEM may be described as a quasi-steady state calculation methodology, as although it carries out a monthly energy balance. The calculation takes into account the dynamic interactions of the building fabric using heating and cooling utilisation factors.

SBEM provides a standardised calculation of the energy use of a building. The program consists of a database of a number of different building types, within each building type is a database of different spaces, for each space there is standard parameters associated such as internal temperatures, casual gains, occupancy, and occupancy pattern. The program also has standard databases for typical heating, cooling and ventilation plant, which can be associated with the different zones in the building.

SBEM is used to demonstrate compliance with the limitation of CO_2 requirements of the UK Building Regulations Part L [DETR 2002] as well as performing the function of an annual energy performance calculation tool. Compliance with the minimum performance standards is based on a comparison with a notional building for which a calculation is carried out for simultaneously. The notional building has the same dimensions as the existing building, but fabric elements are at the standard Part L compliance elemental values. Although SBEM is a compliance tool, its' methodology of calculation is an annual energy performance calculation methodology, prEN 13790.

4.6 ANALYSIS

The following provides a summary of the capability of the detailed simulation programs, the EU projects and the Simplified Simulation programs in terms of their suitability for use with the EPBD.

4.6.1 Detailed Simulation Programs

The investigation of the detailed simulation programs against a variety of parameters illustrates that individual programs yield different abilities to model different aspects of a buildings energy performance.

- IES<VE> carries out the most comprehensive analysis of thermal characteristics and air tightness; it offers 2 conduction solution methods and a range of internal and external convection coefficient options.

- Both IES<VE> and TAS carry out the most comprehensive heating installation analysis. Both are capable of simulating a heat pump as a heat source. Although these calculation tools do not simulate pumping power, they do provide automatic sizing of plant and systems.
- Both EnergyPlus and TRNSYS perform the most comprehensive domestic hot water analysis. TRNSYS performs a detailed analysis of plant, distribution system and usage, but does not perform plant sizing. EnergyPlus, however, does perform plant sizing but does not model the distribution system.
- EnergyPlus demonstrated the best capability to model building cooling systems, in terms of cooling plant, condensing plant, zonal distribution, terminal distribution, system control and plant and system sizing. IES follows in terms of performance, but lacks the same ability as EnergyPlus to model chillers.
- All the dynamic calculation tools studied have similar ability to model built in lighting installations and position and orientation, as would be expected of a dynamic calculation.
- IES<VE>, TAS and TRNSYS demonstrate the best ability to model natural ventilation.
- ESPr, IES<VE> and TRNSYS demonstrate the best ability to model indoor climatic conditions.
- TRNSYS, by far has the best ability to model active solar and renewable systems
- ESPr and IES<VE> have the best ability to model natural lighting.

The simulation program ECOTECT [Marsh 1996] was identified during this research as a possible detailed simulation program. ECOTECT is designed by architects and intended for use by architects. The aim of the program is to provide designers with a holistic approach of the building design process with focus on feedback at the conceptual building design stages. However, although ECOTECT is capable of making a wide range of internal calculations, models are exported to other simulation programs such as, EnergyPlus, ESPr, HTB-2 and radiance for calculation. Results are imported back to ECOTECT for display and analysis. Although ECOTECT may be considered as a dynamic simulation tool in its own right, the dynamic calculation is taking place outside the tool itself, as a result it is not a validated tool. Therefore it was excluded from this study. It was identified that ECOTECT performs well in modelling of passive solar systems, solar protection and daylight analysis.

A study was carried out by Crawley et al [2005] with the aim of comparing and contrasting the capabilities of 22 widely used simulation programs, included in this research was the programs selected for this scoping study. The simulation programs were compared under a number of functions and capabilities.

From analysis of the parameters investigated in Crawleys’ study, one could surmise that:

IES is the best simulation program in terms of:

- Calculation of zone loads
- Infiltration, ventilation and airflow calculations
- HVAC systems calculations

- Results reporting

In addition, IES <VE>, also performs well in terms of reporting of environmental emissions and energy and life cycle costing.

TRNSYS is the best simulation program in terms of:

- Renewable energy systems modelling
- Electrical systems and equipment modelling
- HVAC equipment modelling

In addition, TRNSYS performs well in infiltration, ventilation and airflow calculations, results reporting and its completed validation procedures.

ESPr is the best simulation program in terms of:

- General modelling features
- Most extensively validated

Although ESPr still performs well in terms of, calculation of zone loads, modelling of renewable energy systems and modelling of electrical systems and equipment.

EnergyPlus is the best simulation program in terms of:

- Climatic data availability
- Reporting of environmental emissions

And still performs well in terms of general modelling features, building envelope, daylight and solar calculations, HVAC systems and equipment calculations, energy and life cycle cost reporting and results reporting.

TAS performed similarly to IES<VE> in terms of infiltration, ventilation and airflow calculations.

In terms of a methodology appropriate for use with the EPBD, based on the analysis of Hitchin [2003], a calculation methodology may be considered for its suitability for the EPBD under a number if headings i.e. credibility, repeatability and transparency.

Credibility of a program is determined by the extent of validation procedures performed on the individual programs, as all programs are validated, one could surmise that results generated are credible. In terms of repeatability and transparency, all of the dynamic simulation programs in this study require a wide range of input variables in order to generate an output, in this sense, multiple users would need to make exactly the same assumptions in order to get the same result, in terms of transparency, the range of data input required does not always lend itself to transparency.

The UK EPBD methodology review group [2003] established that the implementation of a methodology also depends on a number of criteria, follows:

(a) Deliverable within the timescale
(b) Available in the public domain
(c) Capable of addressing issues pertaining to a number of different building types
(d) Repeatable results
(e) Accurate and credible results

(f) Adaptable for future advancements in calculation and construction technology

(g) Auditable

(h) Low production timescale

Any existing methodology satisfies requirement (a), but only EnergyPlus and ESPr satisfy requirement (b), all dynamic methodologies would comply with criteria (c), (e) and (f) but in terms of items (d), (g) and (h) a dynamic methodology may not score well due to the range of input data required.

4.6.2 EU projects

Both projects funded under the SAVE programme evaluated a calculation methodology. Europrosper developed and evaluated a methodology for the operational rating of existing buildings. BESTCert evaluated several existing calculation methodologies as pilot tools for that would be appropriate for asset rating of new buildings.

The Europrosper methodology, although complies with the EPBD in terms of producing an energy rating certificate, does not encompass the items covered in the general framework for the calculation of energy performance of buildings as illustrated in Table 4.15. It does provide a comprehensive methodology for the provision of benchmarks and standards of existing buildings.

The pilot tools evaluated under BESTCert do encompass the items in the aforementioned annex to the EPBD; however these tools are more appropriate to new buildings due to the anomalies in providing a representative benchmark for existing buildings.

	Europrosper	BESTCert
Thermal characteristics	X	X
Air-tightness	X	X
Heating installation		X
Hot water supply		X
Insulation of Heating and DHWS	X	X
Air-conditioning installation		X
Ventilation		X
Built-in lighting installation		X
Position and orientation	X	X
Outdoor climate	X	X
Passive solar systems		X
solar protection		X
Natural ventilation		X
Indoor climatic conditions	X	X
The Designed indoor climate	X	X

Table 4.15: European Projects comparison to EPBD Annex

4.6.3 Simplified Simulation Programs

Table 4.16 illustrates a comparison of the capability of each simplified simulation program in terms of the Annex to the EPBD.

	BREEAM	Nen 2916	LT-Method	SBEM
Thermal characteristics	X	X		X
Air-tightness	X	X		X
Heating installation	X	X		X
Hot water supply	X	X		X
Insulation of Heating and DHWS				X
Air-conditioning installation	X	X		X
Ventilation	X	X		X
Built-in lighting installation	X	X	X	X
Position and orientation	X	X	X	X
Outdoor climate	X	X	X	X
Passive solar systems	X	X	X	X
solar protection	X	X	X	X
Natural ventilation	X	X		X
Indoor climatic conditions	X	X		X
The Designed indoor climate	X	X		X

Table 4.16: Simplified Methods comparison to EPBD Annex

Although BREEAM provides a building energy label it does not provide a measure of the absolute energy performance of a building. The building is rewarded for environmentally sustainable items that are not necessarily pertinent to the energy performance to the building as an asset. BREEAM does consider the whole cycle of building from construction in terms of embodied energy, through to the users of the building in terms of travel requirements.

The LT method does not give an accurate calculation of the energy performance of a building, it does however allow architects to investigate the relative improvements of design options in terms of heating, cooling ventilation and lighting in a very simplistic manner.

The calculation methodology behind NEN 2916 provided much of the methodology for the European Standard prEN 13790 on which SBEM is based. Both NEN 2916 and SBEM satisfy the requirements of the EPBD as they calculate the energy use associated with all of the energy consuming services in a building, although in a standardised manner.

Therefore, in order to proceed with the investigation of a calculation methodology suitable for use with the EPBD, two tools were chosen to be used in a number a comparisons in the following chapter. A detailed simulation program or a dynamic methodology – IES<VE> and a simplified simulation program SBEM.

CHAPTER 5: APPLICATION OF METHODS

5.1 APPLICATION

In order to evaluate a calculation methodology that may be applicable to calculate the annual energy performance of a building in the context of the EPBD, a dynamic calculation methodology and a simplified calculation methodology were applied to a building for comparison purposes.

In order to achieve the objectives of this thesis, the following was carried out:

- Comparison of the ability of a dynamic and steady state calculation methodology to calculate heating and cooling plant size
- Investigation of the ability of a dynamic and quasi-steady state calculation methodology to improve annual energy performance by the application of natural ventilation to the model
- Analysis of the ability of both methodologies to investigate key design parameters to generate an improvement in annual energy performance
- Analysis of sensitivity of both methodologies to the variation of key design parameters

The choice of an arbitrary building is justified in this case as the aim of the research was the comparison of calculation methodologies and not to validate against measured data. Extensive validation procedures against measured data have been carried out on both IES <VE> [Crawley et al 2005] and prEN13790 [Corrado 2007].

The choice of a particular building type is justified as Rey et al [2007] carried out a comparison between a steady state and dynamic methodology by application to a healthcare building. Karlsson et al [2007] carried out a comparison between measured data and a dynamic methodology by application to low energy housing. Kokogiannakis carried out a study of a dynamic methodology to encompass the requirements of the EPBD using a singular arbitrary office building. Burke et al [2005] carried out a comparison between a dynamic methodology and measured data on school buildings. In each of the above applications, particularly the work by Rey et al and Karlsson et al, the research was undertaken specifically to compare the methodologies but in no particular context. Work by Burke et al carried out a study in the context of the EPBD. Focus was on the certification procedure and the sensitivity of the variation of parameters to the certification grading scale. Work by Kokogiannakis, although in the context of the EPBD, studied the suitability of a single methodology to the requirements of the EPBD. Methods proposed by Richalet et al, Lee et al and de Santoli et al all involved application to multiple sets of buildings, but all required significant data collection for the creation of multiple regression models.

The original research work set out in this thesis, is the comparison of dynamic and quasi-steady state calculation methodologies in the context of the EPBD and investigation of the underlying calculation algorithms of both methodologies in order to investigate the difference in data generated. Research in the past has focused on comparison of calculation methodologies against other methodologies and measured data. Few have been carried out in the context of the EPBD.

The key aspects of a buildings design chosen for analysis were;

- Heating plant size
- Cooling plant size
- Suitability for natural ventilation
- Variation of thermal mass of the building envelope and internal elements
- Variation of solar properties of glazing
- Use of solar shading
- Variation in glazing ratio

These key aspects were chosen as they represent the items with the greatest effect on a buildings energy performance as identified by Corrado et al [2007].

The comparison of heating and cooling plant size was used as a reflection on how the methodology deals with the thermal properties of the building in terms of heat loss and gain. This was carried out by comparison of a dynamic and steady state load calculation application.

The suitability for natural ventilation was used as a reflection on how the methodology captures the effects of natural ventilation in the building. This was carried out as an application of the dynamic airflow analysis application within IES <VE> in order to quantify the need for mechanical cooling and ultimately to utilise a mixed mode solution.

5.2 THE BUILDING

The model used is a standard office block with a ground, first and second floor. The office block had a mixture of open plan and cellular office spaces located around a central atrium. A diagram of the ground floor is provided in Figure 5.1. Plan layouts of ground, first and second floors are provided in Appendix A. The building has a total floor area of 1663 m^2 and is orientated with the entrance facing east and the main exposed facades on the south and north.

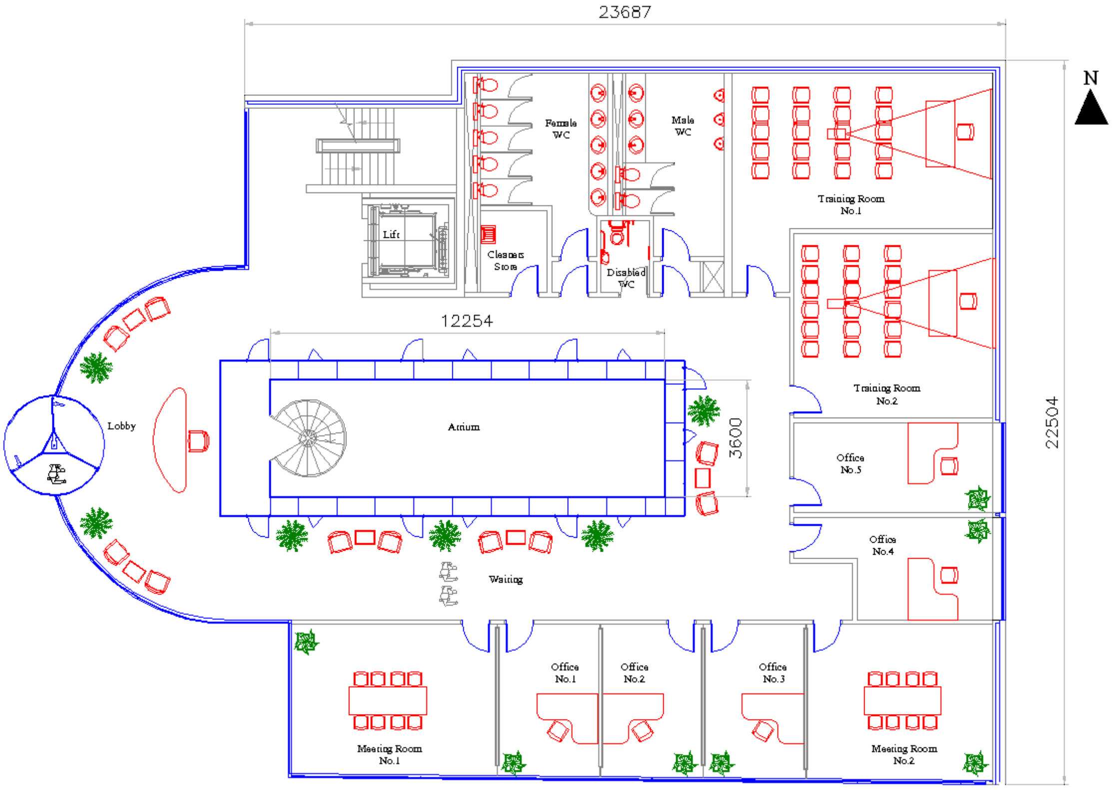

Figure 5.1: Standard Office Block Ground Floor Layout

5.2.1 Thermal Properties of Fabric Elements

The building envelope and internal fabric elements chosen for use in the initial calculations were those with thermal transmittance coefficients in compliance with the building regulations TGD L 1997 [DELG 1997] maximum elemental values. TGD L 2007 was chosen as a comparison was to be applied to ECON

19 [DETR 2000] for benchmarking purposes as carried out by Rey [2007]. These values are comparable to the values used in compiling ECON 19.

In addition to thermal transmittance, the elements were defined with standard admittance, decrement factor, surface factor, decrement factor time lag and internal heat capacity. The properties and makeup of the elements are detailed in Appendix B.

5.2.2 Set-Point Temperatures

The set point temperatures used are those as recommended by CIBSE Guide A [CIBSE 2006] and are detailed in Table 5.1.

Area	**Summer setpoint Temp.**	**Winter setpoint Temp.**
	°C	**°C**
Office	23	21
Foyer	23	19
Meeting Rooms	23	21
Training Rooms	23	21
Toilets	23 (no cooling)	19
Circulation	23	19
Canteen	24	22

Table 5.1: Design setpoint temperatures

5.2.3 Casual Gains

The casual gains for people, lighting and equipment used are those as recommended by CIBSE Guide A [CIBSE 2006] with standard occupancy levels and are detailed in Table 5.2.

Area	**Occupancy Density**	**Equipment Gain**	**Lighting gain**
		W m^{-2}	**W m^{-2}**
Office	9 m^2 per P	15	15
Meeting Rooms 1 2	 8 8	12	12
Training Rooms 1 2	 19 21	15	12
Toilets	5 each		12
Circulation	12 m^2 per person		6
Canteen	48	0	12

Table 5.2: Casual Gains

5.2.4 Ventilation Air Exchanges

Ventilation air exchanges were applied for mechanical ventilation, and infiltration. The rates applied for mechanical ventilation were those as recommended by CIBSE Guide B2 [CIBSE 2001]. Occupied spaces were applied a mechanical ventilation rate in l s^{-1} per person, whereas intermittently occupied spaces were applied a rate in AC h^{-1}. The rates applied are detailed in Table 5.3. These values were applied to represent values typical of current building design practice.

Area	**Ventilation Rate**	**Ventilation Rate**	**Infiltration Rate**
	l s^{-1} p^{-1}	**AC h^{-1}**	**AC h^{-1}**
Office	8	-	1.0
Meeting Rooms 1 2	8	-	1.0
Training Rooms 1 2	8	-	1.0
Toilets	-	10	1.0
Circulation	8	-	0.5
Canteen	8	-	1.0

Table 5.3: Ventilation Air Exchanges

5.2.5 Weather Data

For the dynamic simulation a Test Reference Year (TRY) climate file for Dublin was used. This information was used to model external weather conditions and solar data. The climate file contains hourly information on parameters such as, dry bulb temperature, wet bulb temperature, direct radiation, diffuse radiation, wind speed, wind direction, cloud cover, relative humidity, solar altitude, solar azimuth, etc. Sample data from the weather file and shading calculations are included in Appendix C.

For the steady state calculations within IES <VE> the location used was Dublin with a winter design temperature of –3°C and summer maximum dry bulb and wet bulb temperatures of 26.7°C and 20.5°C respectively. The design conditions comply with CIBSE recommendations and are currently used by building services engineers in the design of buildings.

5.3 MODELLING OF THE BUILDING IN IES<VE>

IES <VE> has the ability to import the plan drawing of each floor in a drawing exchange format (*.dxf*) this is attributed with a story height within the program.

Using the "*ModelIT"* component program within IES <VE> the *.dxf* file can be drawn over using a series of 3-dimensional polygons to represent each zone. The greater the number of zones applied to a space the more detailed the information extracted from the space

The program automatically recognises zones interconnected to other zones either by internal partition, floor or ceiling. Also external elements are recognised as external wall, exposed floor or roof. Elements such as external glazing may be applied to the chosen façade (or roof) either as a % of the façade area or inserted manually.

In order to provide internal openings within the space, either on the vertical plane (to join zones in the same room) or on the horizontal plane (to join zones vertically connected) holes may be inserted in the perimeter of a zone polygon. Using the thermal component program "*Apache*" within IES <VE> each fabric element may be assigned thermal properties. A designer may select a predefined fabric element from the internal database or create a specific element from the standard component library. The thermal parameters for the fabric element such as thermal transmittance, admittance, surface factor, decrement factor, decrement factor time lag etc, are automatically calculated for each fabric element. This process was used to define the fabric elements described in Section 5.2.1.

Each zone created may be assigned to a specific function i.e. *office space* or *circulation space*. Each function area may be assigned a set of properties in terms of occupancy, casual gains, lighting, heating, cooling and ventilation air exchanges. Within a function area, a zone may be assigned different parameters to the other zones if required. Each of the above properties may be assigned a schedule of operation, which may be based on time or temperature.

Using the *MacroFlo* component within IES <VE> natural ventilation may be simulated. Openings can be selected as permanent openings or scheduled to open on time or an internal or external threshold temperature. In this case the natural ventilation openings were calculated using the procedure set out in CIBSE AM 10 [CIBSE 1997]. The window and stack opening sizes required to allow a ventilation rate of 6 air changes per hour was calculated using guidance in CIBSE AM 10. The opening area required on each floor was divided between the assigned natural ventilation inlets on each floor. The natural ventilation inlets were scheduled to open at a threshold inside temperature of 23℃, so as to avoid hunting in the heating system. The louvers at the top of the atrium were assigned as a natural ventilation outlet for which the opening area required was also calculated using CIBSE AM 10 and also scheduled to open at a threshold temperature of 25℃.

A building must be assigned a climate file for its specific geographical location prior to the simulation, as described in section 5.2.5. A range of geographical locations are provided in the internal databases. A shading analysis was carried out using the *Suncast* component within IES <VE>, to calculate the external and internal areas subject to direct and diffuse solar radiation for the annual period. Samples of the climatic data and shading information are provided in Appendix C.

At this stage, a building is fully defined within IES <VE> in terms of its’ external envelope, internal fabric, ventilation air exchanges (mechanical, infiltration and natural), heating, cooling, climate, occupancy schedule and control schedule.

A full dynamic simulation may be carried out using the *ApacheSim* module within IES <VE>. The user has the option to select if the calculation will be carried out with or without natural ventilation and also the user has the option to select from a range of internal and external convection coefficients. In addition IES <VE> has the ability to carry out steady state calculations using CIBSE or ASHRAE steady state procedures.

Results generated from the dynamic simulation may be assessed in the *Vista* component of the program. Results are available for a variety of parameters at both building level and zone level. At building level, loads are available for heating and cooling plant, room loads and energy consumption and carbon dioxide emissions associated with plant. At zone level, information is provided for parameters such as, air temperatures, operative temperature, mean radiant temperature, PPD, PMV, internal gains and external gains.

The standard office building was modelled using the dynamic thermal simulation facility and also using the CIBSE and ASHRAE steady state procedures within IES <VE>. This information was used initially to investigate the first of the key aspects, the peak heating and cooling loads. The dynamic simulation results for the initial building were also used to establish a base case benchmark from which the other key aspects could be measured against.

5.4 HEATING AND COOLING PLANT SIZE

The peak heating and cooling loads obtained using the dynamic and steady state calculation methodologies were compared. Over sizing of heating and cooling plant is a problem, as shown by Crozier [2000] who found that, in a sample of buildings, 80% of the heating plant, 88% of the ventilation plant and 100% of the chiller plant had capacity that exceeded their design requirements. More realistic peak loads can be obtained using a dynamic methodology in comparison to a steady state methodology and hence a heating and air conditioning system chosen is more representative of the actual loads.

This aspect of the calculation of heating and cooling plant size is important in terms of the EPBD, as Article 8 requires for the regular inspection of boilers with a rated output greater than 100kW and Article 9 requires for the regular inspection of air conditioning systems with a rated output greater than 12kW. Article 9 also states that “the inspection shall include an assessment of the air conditioning efficiency and sizing compared to the cooling requirements of the building.” [European Parliament 2003 pp L1-69] Therefore, an accurate means of load calculation and plant sizing is required for buildings. Table 5.4 illustrates the comparison between the CIBSE steady state peak loads and the dynamic peak loads. The results for both the dynamic and steady state calculations are included in Appendix D.

Methodology	Peak Heating Load	Peak Cooling Load
	KW	kW
Steady State CIBSE	294.01	103.13
Dynamic	375.01	83.24

Table 5.4: Comparison of Steady State and Dynamic Plant Loads

Table 5.5 illustrates the difference between steady state procedures, in this case the CIBSE steady state procedure and the ASHRAE heat balance method [ASHRAE 2001a pp20-20].

Methodology	Peak Heating Load	Peak Cooling Load
	KW	KW
Steady State CIBSE	183.17	113.43
Steady State ASHRAE	192.89	112.16

Table 5.5: Comparison of CIBSE and ASHRAE Steady State Plant Loads

As can be seen in Table 5.4, the CIBSE steady state heating load represents 294.01 kW and the CIBSE steady state cooling load represents 103.13 kW. The dynamic peak heating load was calculated at 375.01 kW which was 27.5% higher then the steady state heating load. The dynamic peak cooling load was calculated at 83.62 kW which was 19.3% lower then the steady state cooling load.

5.4.1 Peak Heating Load

Figure 5.2 illustrates the occurrence of the peak heating load, which takes place at 6.30am on Monday 15th February following shutdown over a weekend period. The peak load corresponds to an outside temperature of -1.0℃, which was the minimum temperature over the weekend period. Figure 5.2 provides a comparison of the peak heating load on Monday 15th February and Tuesday 16th February. In each case the heating systems were activated at 6.30am and the load increases to the peak value in order to provide the required occupancy temperature. In both cases the heating load reduces as the occupancy temperature of the building is achieved and the internal and external heat gains are providing a heat input into the space.

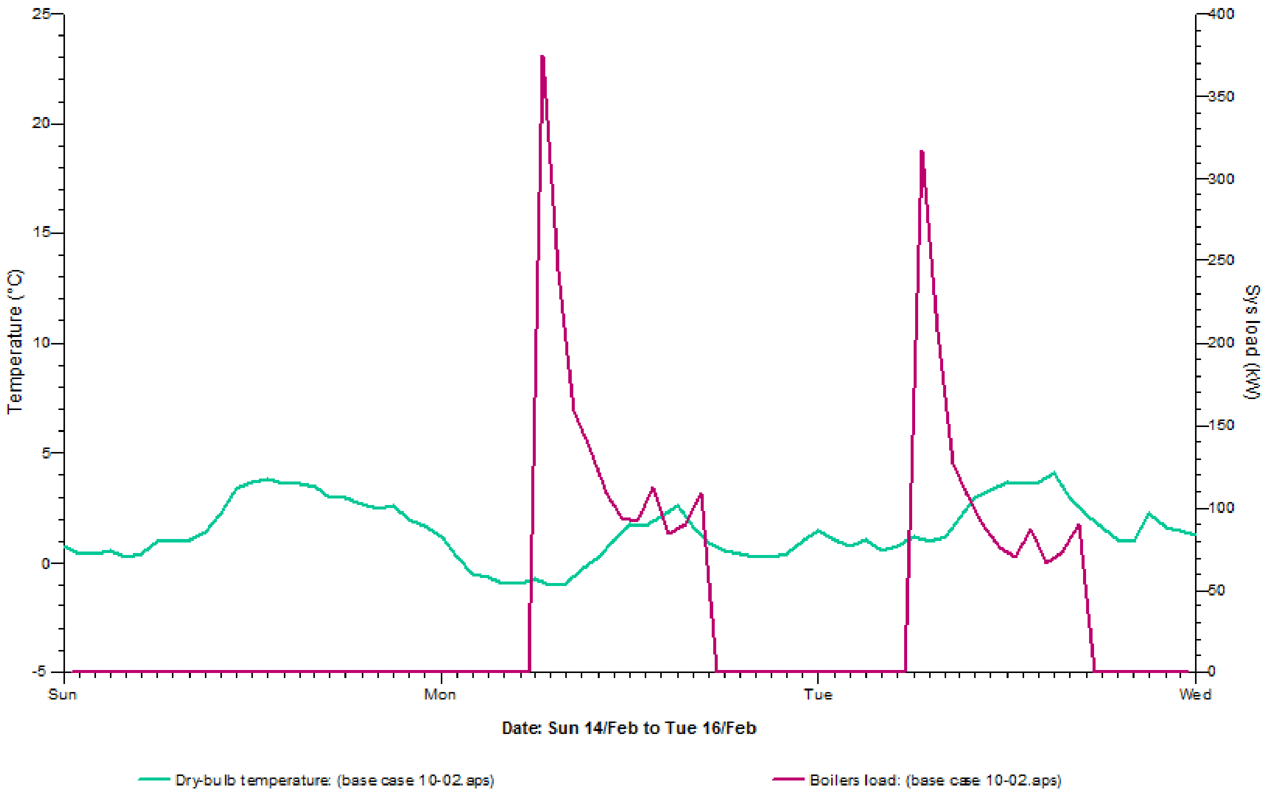

Figure 5.2: Peak Heating load and external dry bulb temperature

A steady state condition was reached with some peaks following the lunch breaks where the space was unoccupied. The difference between Monday 15th and Tuesday 16th may be attributed to the respective external temperatures.

Over the annual period the minimum outside temperature was – 4.2 °C at 5.00am Wednesday 20th January; the minimum temperature during heat-up period was – 4 °C at 7.00am on Thursday 18th January with a heating load of 217.23 kW; the minimum temperature during an occupied period was –2.9 °C on Wednesday 20th January with a heating load of 128.39 kW, as can be seen in Appendix C. This comparison illustrates that the minimum external temperature does not correspond with the peak heating load.

In order to gain a greater insight as to the external influencing parameters on the heat transfer properties of the building, Figure 5.3 and 5.4 compare wind speed and cloud cover respectively to boiler load. The comparison to wind speed indicates a relative high wind speed over the weekend period, which may have increased the convective heat transfer from the building. The comparison to cloud cover indicates relatively high levels of cover over the weekend period, and low at the time of the peak load, useful direct solar gain would have been excluded from the building over the weekend period and at the time of the peak heating load the buildings radiant heat transfer properties would have been at a maximum.

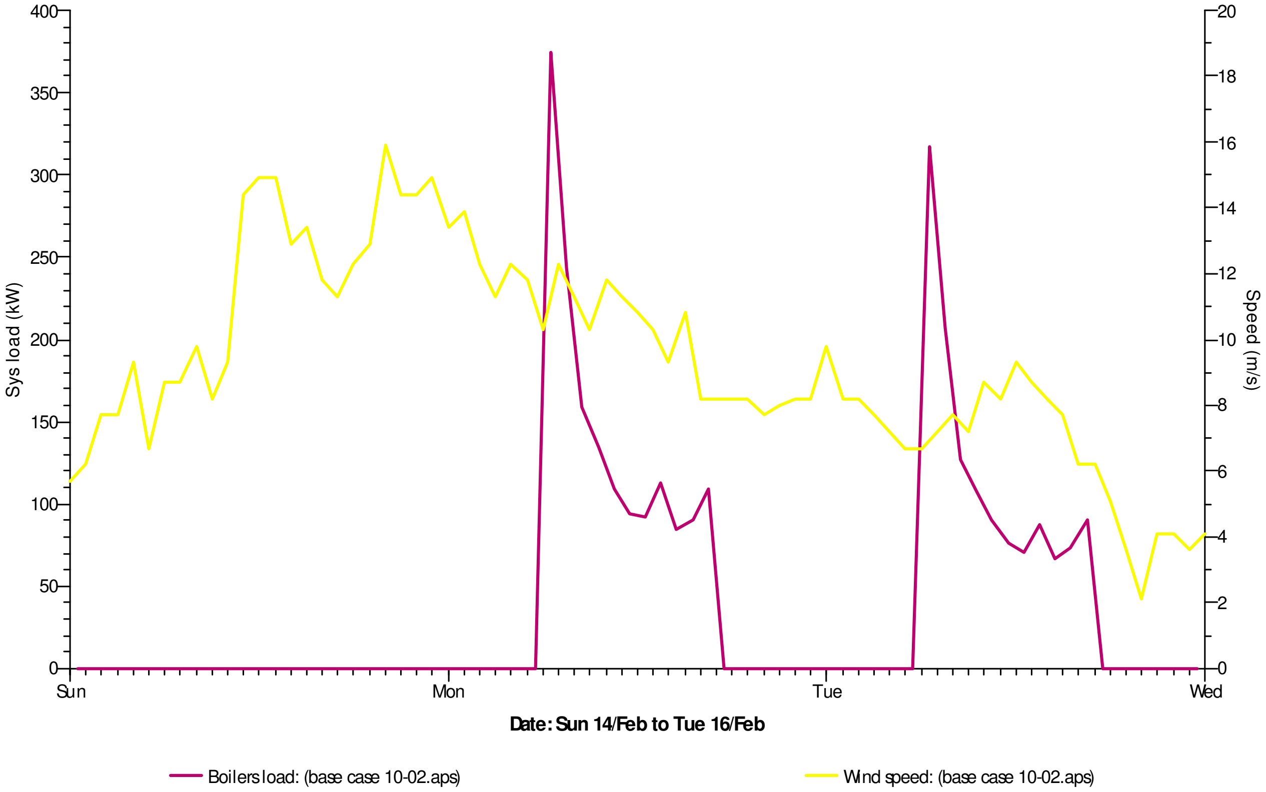

Figure 5.3: Peak Heating load and external wind speed

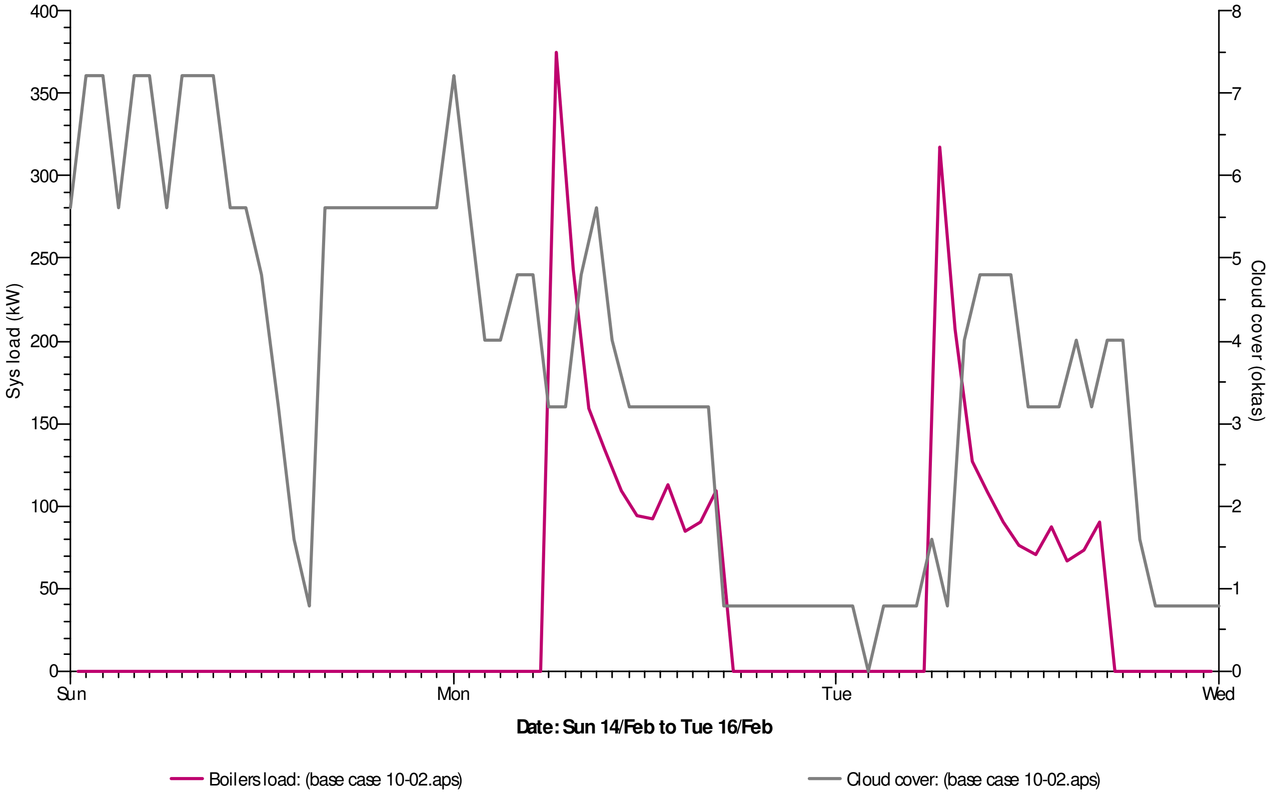

Figure 5.4: Peak Heating load and external cloud cover

When comparing this to the steady state design outside temperature of –3.0℃ one can see that the peak loads do not correspond to the minimum outside temperature but are a function of the stored heat in the fabric of the building. This comparison illustrates that the results obtained using simulation are significantly more realistic than the steady state methods, as an actual weather file is used for the appropriate area and the appropriate outside conditions, whereas the steady state calculation does not take these factors into account. It is therefore pertinent that a methodology can model thermal mass effectively.

5.4.2 Peak Cooling Load

The peak cooling load of 83.24 kW occurs on 15.30 on 5th July. Figure 5.5 illustrates the correspondence of the peak cooling load with direct solar radiation and external dry bulb temperature.

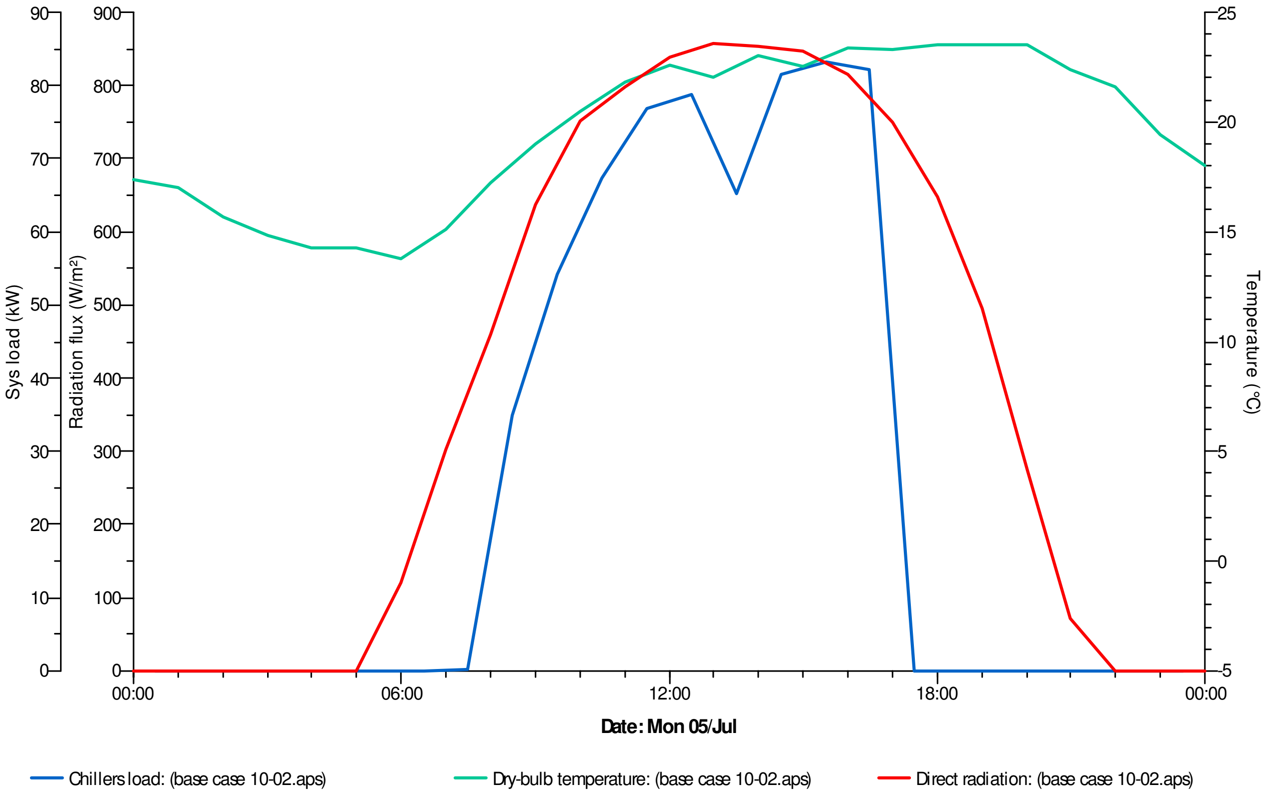

Figure 5.5: Peak cooling load analysis

This load corresponds to an external dry bulb temperature of 22.5°C and direct solar radiation of 847 W m^{-2}. The maximum direct solar radiation occurred at 13.00 on Monday 5th July and the maximum external dry bulb temperature occurred at 17.00 on Saturday 10th July. Therefore the peak solar radiation is transferred to the space after a time lag of approximately 3.5 hours and represented as a peak cooling load inside the building. The dynamic calculation methodology has accounted for the thermal capacitance in the building fabric, whereas the CIBSE steady state calculation has used the admittance method.

In terms of the energy performance of a building, the dynamic cooling load yields a significantly smaller size of cooling plant then the steady state calculation, which is satisfactory in terms of capital and running costs. But the dynamic heating load is significantly higher than the steady state heating load, with a corresponding larger boiler plant for the building.

5.5 SUITABILITY FOR NATURAL VENTILATION

The second of the key aspects for investigation is the suitability of a building for natural ventilation. The aim of this comparison was to investigate the use of a dynamic methodology as an early design step, to establish if all rooms in the building will require mechanical cooling or can these requirements be fulfilled by natural ventilation. This can be identified using a dynamic calculation methodology capable of bulk airflow analysis but cannot be performed by steady state means. If the effects of natural ventilation in a space can be quantified accurately, it can represent substantial energy savings for the building in terms of fan power and cooling loads.

CIBSE recommends that if dry resultant temperature in a space is greater than 25°C for more than 5% of the time, cooling is required in the space [CIBSE 1999 pp1-2]. Spaces which fall outside these criteria do not require mechanical cooling. If air is introduced into a space by natural means, the heat gains may be offset while also providing the fresh air requirement.

The base case building was simulated initially in a free floating condition i.e. mechanical cooling and ventilation turned off. A range test was carried out to quantify the rooms with dry resultant temperatures exceeding 5°C for more than 5% of the occupied time. The results are illustrated in Appendix D (Table D2). Dry resultant temperature exceeded 25°C for more than 5% of the time in 76% of the building (22 No. rooms) and was not exceeded in 24% of the building (7 No. rooms). Therefore, 76% of the building (22 No. rooms) required mechanical ventilation and cooling.

In order to quantify the improvement if natural ventilation was added to the space, the building was simulated using bulk airflow analysis. To simulate natural ventilation a portion of the external windows were assigned as natural ventilation openings. The window and stack opening sizes required to allow a ventilation rate of 6 air changes per hour was calculated using guidance in CIBSE AM 10 [CIBSE 1997] as described in Section 5.3.

Results were obtained and the dry resultant temperatures during the occupied period were analysed using the range test facility in IES <VE>. The comparison is illustrated in Appendix D (Table D2).

For the fully naturally ventilated building, the dry resultant temperature exceeded 25°C for more than 5% of the time in 62% of the building (18 No. rooms) and was not exceeded in 38% of the building (11 No. rooms), hence a reduction of 14% of the building (4 rooms) requiring mechanical ventilation and cooling compared to the base case model.

By using a methodology capable of bulk airflow analysis, initially 76% of the building required mechanical cooling (a fully air conditioned building). After the application of natural ventilation, 62% of the building required mechanical cooling i.e. the application of natural ventilation to 38% of the building.

The next stage of this early design process was to use natural ventilation in the rooms in which natural ventilation could satisfy the cooling loads and ventilation requirements and use mechanical ventilation and mechanical cooling in the rooms with temperatures in excess of the aforementioned criteria, thereby reducing the need for cooling or mechanical ventilation and hence the overall energy consumption of the building. Table 5.6 illustrates the results obtained.

	Peak Cooling Load	Cooling Energy Consumption	Cooling $C0_2$ Emissions
	KW	kWh m^{-2} y^{-1}	kg m^{-2} y^{-1}
Base Case	83.24	12.34	1.57
Early Design Step	74.86	7.62	0.97
Reduction	8.38	4.72	0.60

Table 5.6: Early design step comparison

A reduction of 10.1% was achieved in terms of cooling plant size, a reduction of 38.2% was achieved in terms of both annual energy consumption and the CO_2 emissions associated with the cooling system.

The ability of a calculation methodology to apply natural ventilation is extremely important in order to achieve these energy savings.

5.6 IMPROVEMENT OF ENERGY PERFORMANCE

The remainder of the key aspects for investigation; variation of thermal mass of the building envelope and internal elements, variation of solar properties of glazing, use of solar shading and variation in glazing ratio, were investigated under the general heading of, *Improvement of energy performance*. This comparison investigated the use of a dynamic methodology at a detailed design stage to apply different design options for a building in order to gain an improvement in the buildings energy performance.

Initially the building was considered with full heating, cooling and mechanical ventilation i.e. the base case model. The base case building model was compared against the benchmark ECON 19 “Air Conditioned Standard Office”, [DETR 2000] and showed comparable energy performance results as shown in Table 5.12. Design changes were carried out and compared to this standard base case. Calculations were then applied to a number of different design option scenarios, as follows:

- High thermal mass external envelope and internal elements
- Low thermal mass external envelope and internal elements
- Reflective coat external glazing
- Absorptive coat external glazing
- Solar shading
- Reduced glazing

Each case was compared with the base case, firstly in terms of annual energy consumption for space heating and cooling and secondly in order to establish a reduction in operative temperature, solar gain and cooling load in the space. Heating load was also examined in each case in order to examine any detrimental effects. Initially the base case building consumed 140.31 MWh of boiler power and 20.52 MWh of cooling power, normalised for floor area, this corresponds to 84.38 kWh m^{-2} y^{-1} and 12.34 kWh m^{-2} y^{-1} respectively.

5.6.1 High thermal mass external envelope and internal elements

This design option modelled the base case building, with the external walls and internal partitions changed to elements with a high thermal mass, as shown in Table 5.7. The high thermal mass external wall and internal partitions used in the simulation were chosen as the admittance and decrement factor time lag was in excess of the base case external wall properties, thereby requiring more heat to raise the operative temperature of the space and delaying the heat flow from outside through the structure.

Element	U-Value	Admittance	Admittance time lead	Decrement factor	Decrement factor time lag
	W m^{-2}·K	W m^{-2}·K	Hrs	m^2 K W^{-1}	Hrs
Ext. Wall	0.36	6.59	1.59	0.26	9.00
Int. Partition	3.38	5.83	1.35	0.68	4.00

Table 5.7: High Thermal Mass Building Fabric Properties

The high thermal mass building consumed 156.21 MWh and 14.51 MWh of heating and cooling power respectively, normalised for floor area, heating - 93.93 kWh m^{-2} y^{-1} and 8.72 kWh m^{-2} y^{-1} cooling. This represented a reduction in cooling energy consumption and an increase in heating energy consumption, as would be expected of a high thermal mass building.

5.6.2 Low thermal mass external envelope and internal elements

This design option modelled the base case building, with the external walls and internal partitions changed to elements of low thermal mass, as shown in Table 5.8. The external walls and internal partitions used were chosen as the admittance and decrement factor time lag was less than that of the base case, thereby requiring less heat to raise the environmental temperature of the space and allowing fast heat flow from outside through the structure.

Element	U-Value	Admittance	Admittance time lead	Decrement factor	Decrement factor time lag
	W m^{-2}·K	W m^{-2}·K	Hrs	m^{2} K W^{-1}	Hrs
Ext. Wall	0.35	0.85	3.95	0.99	1.00
Int. Partition	1.66	1.80	1.12	0.99	1.00

Table 5.8: Low Thermal Mass Building Fabric Thermal Properties

The low thermal mass building consumed 132.23 MWh and 24.65 MWh of heating and cooling power respectively, normalised for floor area, 79.52 kWhm^{-2} y^{-1} heating and 14.82 kWh m^{-2} y^{-1} cooling. This represented a reduction in heating energy consumption and an increase in cooling energy consumption, as would be expected of a low thermal mass building.

5.6.3 Reflective coat external glazing

This design option modelled the base case building with the glazing changed to reflective coat glazing with thermal properties as illustrated in Table 5.9.

Element	U-value	Short-wave shading coefficient	Long-wave shading coefficient	Total shading coefficient
	W m^{-2}·K	W m^{-2}·K	W m^{-2}·K	W m^{-2}·K
Reflective Coat glazing	2.8	0.26	0.12	0.39

Table 5.9: Reflective Coat Glazing Thermal Properties

The reflective coat glazing had a short wave shading coefficient in excess of the base case building, long wave shading coefficient was similar and total shading coefficient was less than the base case model. The outside pane reflected 26%, absorbed 45% and transmitted 29% of the solar energy, compared to the base case with 7% reflected, 11% absorbed and 82% transmitted.

This design option consumed 154.32 MWh and 7.85 MWh of heating and cooling power respectively, normalised for floor area, 92.79 kWhm^{-2} y^{-1} of heating and 4.72 kWh m^{-2} y^{-1} of cooling. This represented a reduction in cooling energy consumption and an increase in heating energy consumption, as would be expected when reflecting the solar gain from the space.

5.6.4 Absorptive coat external glazing

This design option modelled the base case building with the glazing changed to double coat absorptive glazing with thermal properties as illustrated in Table 5.10.

Element	U-value	Short-wave shading coefficient	Long-wave shading coefficient	Total shading coefficient
	W/m²·K	W/m²·K	W/m²·K	W/m²·K
Absorptive Coat glazing	2.8	0.05	0.15	0.20

Table 5.10: Absorptive Coat Glazing Thermal Properties

The absorptive coat glazing short wave shading coefficient was less than that of the base case building, long wave shading coefficient was similar and total shading coefficient was less.

The outside pane reflected 21%, absorbed 73% and transmitted 6% of the solar energy, compared to the base case with 7% reflected, 11% absorbed and 82% transmitted.

This design option consumed 157.19 MWh and 7.03 MWh of heating and cooling power respectively, normalised for floor area, 94.52 kWhm^{-2} y^{-1} of heating and 4.22 kWh m^{-2} y^{-1} of cooling. This represented a reduction in cooling energy consumption and an increase in heating energy consumption, as would be expected when reducing the amount of solar gain entering the space.

5.6.5 Solar shading

This design option modelled the base case building with the addition of solar shading in the form of window overhangs. The window overhangs extended 2m and were positioned on the south, west and east facades so as to exclude the summer incident solar radiation but allow the useful winter incident solar radiation. An illustration is shown in Figure 5.6. This design option consumed 145.90 MWh and 11.54 MWh of heating and cooling power respectively, normalised for floor area, 87.73 kWhm^{-2} y^{-1} of heating and 6.94 kWh m^{-2} y^{-1} of cooling. This represented a reduction in cooling energy consumption and an increase in heating energy consumption, as would be expected when reducing the amount of solar gain entering the space.

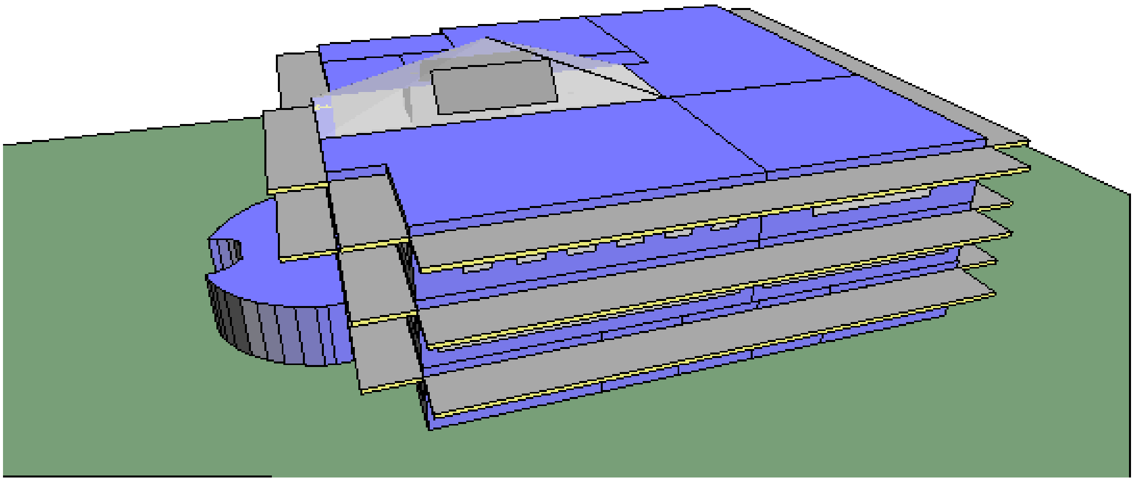

Figure 5.6: Image of Standard Office Block Model with Solar Shading

5.6.6 Reduced glazing

This design option modelled the base case building with the glazing ratio reduced by 30%. This design option consumed 136.65 MWh and 15.41 MWh of heating and cooling power respectively, normalised for floor area, 82.17 kWh m^{-2} y^{-1} of heating and 9.27 kWh m^{-2} y^{-1} of cooling. This represented a reduction in cooling energy consumption and a reduction in heating energy consumption as would be expected.

5.6.7 Reduction in solar gain

Using the data obtained, solar gains, operative temperature and cooling loads were analysed and compared in a number of occupied spaces in order to quantify a reduction. The heating load was also analysed to observe any negative effect. The results are presented in Appendix E.

Each room was analysed at its peak solar gain time. A subsequent analysis was carried out for the reduction of solar gain and operative temperature at that time, using the different design options. In the south facing rooms chosen for analysis, absorptive glazing reduced solar gain by as much as 86.7% in Level 1 Meeting Room No. 2. and 81.5% in Level 1 Office No. 1 & 2.

In the east and north east rooms analysed, solar shading showed the most substantial reduction in solar gain, although in all these cases solar absorptive glazing showed the most substantial reduction in operative temperature and cooling load.

In all cases solar absorptive glazing showed the most substantial reduction in operative temperature when compared to the base case. In most cases the dry operative temperature in the space was reduced by as much as 4℃.

A disadvantage of the solar absorptive glazing was an associated increase in heating load in the south facing spaces. This may be attributed to the lack of useful solar gain in the space.

Using this process it was established that absorptive glazing showed the most substantial reduction in solar gain and hence operative temperature and cooling load. This reduction in cooling load and associated CO_2 emissions outweigh any increase in heating load.

Sample graphs and sample data provided in Figure 5.7 and Table 5.11, illustrate the results obtained. The sample graph illustrates the effect of each design option on the solar gain reaching the space, the worst case being the base case building.

Although the high thermal mass and low thermal mass design options showed no reduction in solar gain (as would be expected), they both represented a reduction in cooling load and operative temperature.

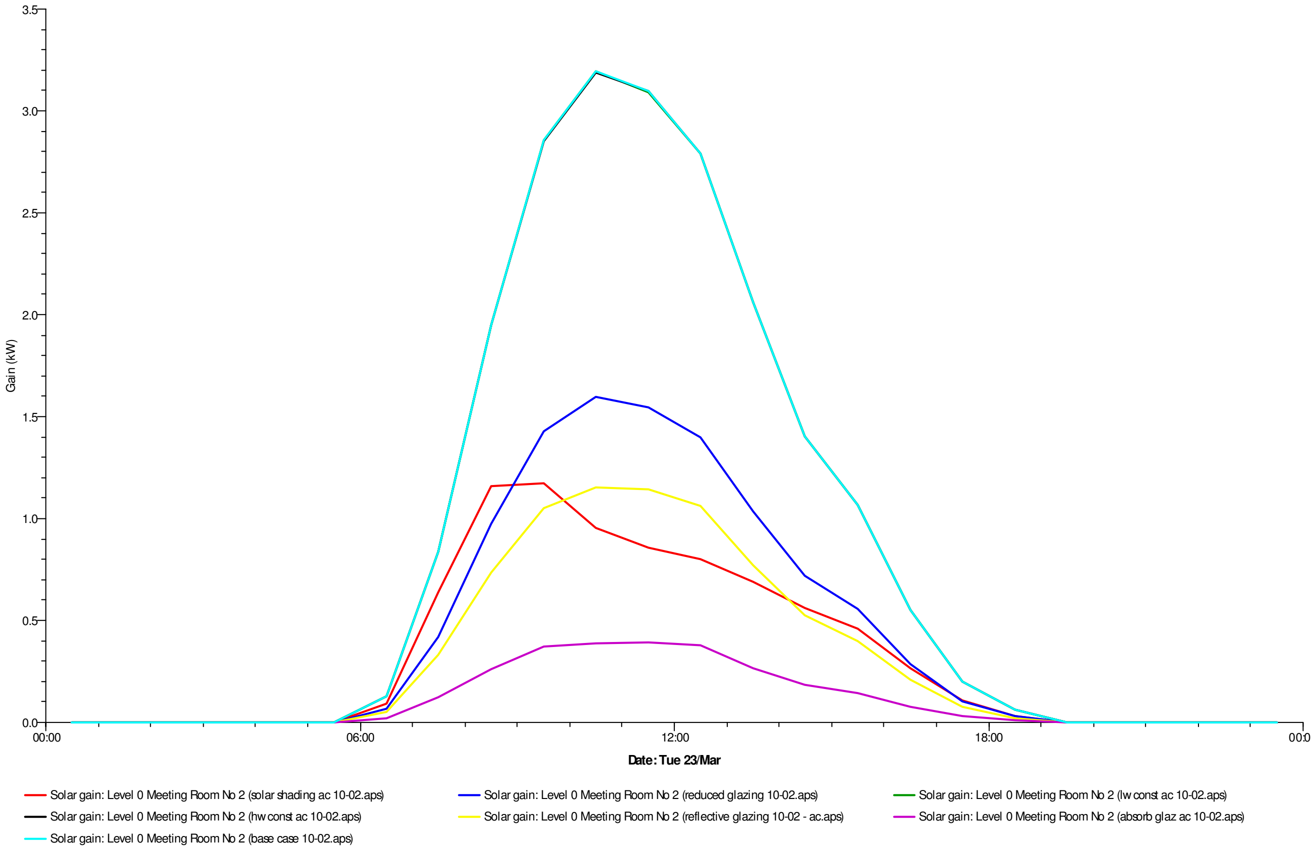

Figure 5.7: Solar Gain Meeting Room No. 2 10.30 23rd March

Design Option	Operative Temp	Heating Load	Cooling Load	Solar Gain
	℃	KW	kW	W m^{-2}
Base Case	23.97	0	16	3.067
Absorptive Glazing	20.96	1043	0	0.408
Shading	21.25	694	0	0.884
Reflective Glazing	21.36	559	0	1.152
Reduced. Glazing	21.70	98	0	1.541
Low Thermal Mass	24.55	0	380	3.068
High Thermal Mass	22.18	0	0	3.068

Table 5.11: Solar Gain Solar Meeting Room No. 2 10.30 23rd March

The sample data in Table 5.11 illustrates the reduction in operative temperature and solar gain in the space. An important point to note in the data is the increase in heating load due to the reduction in solar gain in the space, which is discussed in more detail in the following sections.

5.6.8 Annual Energy Performance

The absorptive glazed building offers the best reduction in cooling energy consumption, with a penalty in terms of heating energy consumption. Overall this design improvement offers a good reduction in overall energy consumption and CO_2 emissions compared to all the design improvements as illustrated by Figure 5.8 and 5.9.

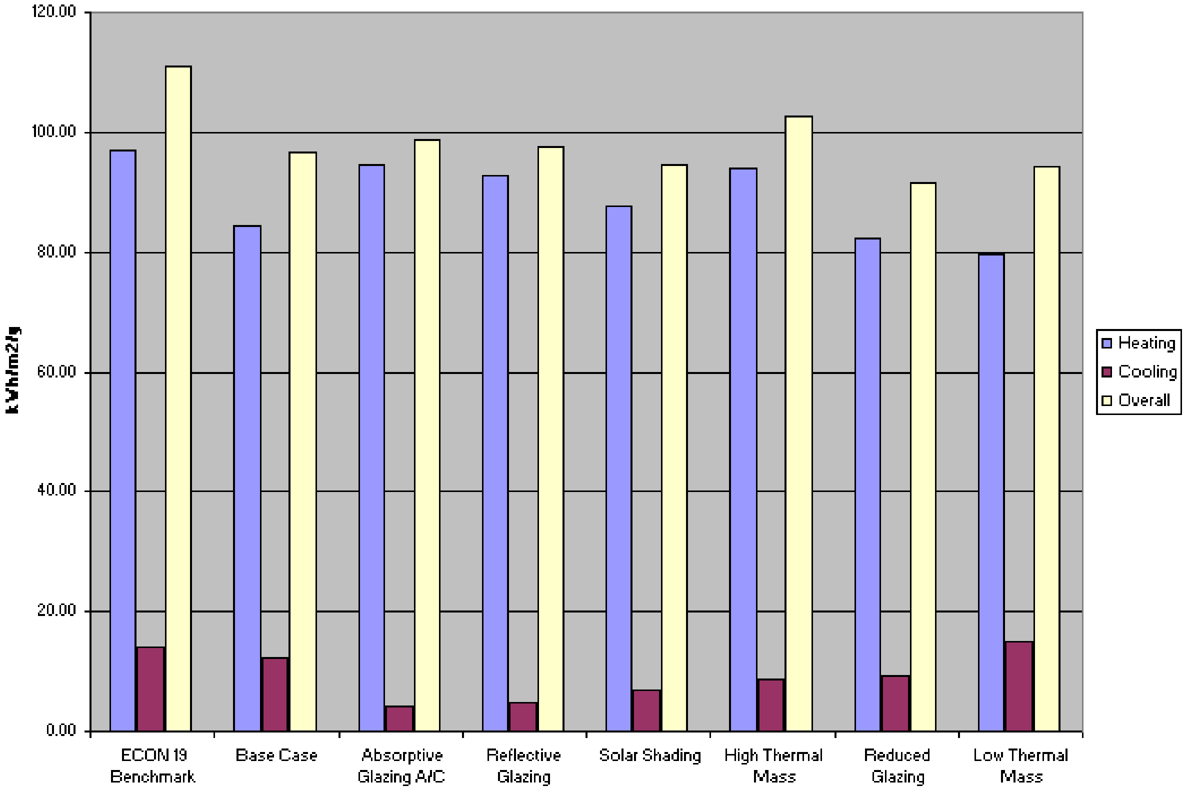

Figure 5.8: Comparison of heating, cooling and overall energy performance

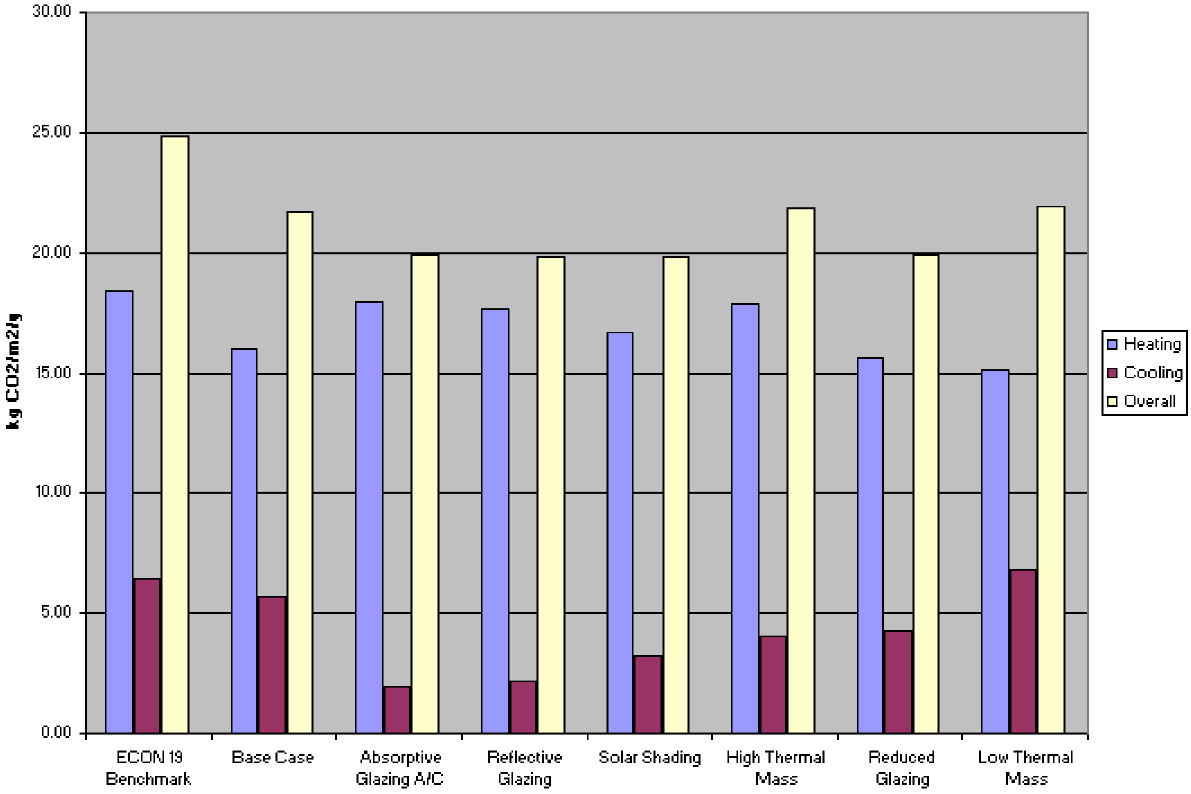

Figure 5.9: Comparison of heating, cooling and overall CO_2 emissions

The above process has established that the absorptive glazing option is the best design improvement option to go forward with. The annual energy performance and the CO_2 emissions associated with the heating and cooling systems are set out in Table 5.12 and 5.13 respectively and compared to the base case building and to the ECON 19 good practice benchmark for a Type 3, Air Conditioned Standard building.

Description	Heating Energy	Cooling Energy	Overall Energy	Improvement
	kWh m^{-2} y^{-1}	kWh m^{-2} y^{-1}	kWh m^{-2} y^{-1}	%
ECON 19 Benchmark	97.00	14.00	111.00	
Base Case	84.36	12.34	96.71	
Absorptive Glazing	94.52	4.22	98.75	+ 2.1

Table 5.12: Annual energy performance comparison a/c building

Description	Heating CO_2	Cooling CO_2	Overall CO_2	Improvement
	kg m^{-2} y^{-1}	kg m^{-2} y^{-1}	kg m^{-2} y^{-1}	%
ECON 19 Benchmark	18.43	6.44	24.87	
Base Case	16.03	5.67	21.70	
Absorptive Glazing	17.96	1.94	19.90	-8.3

Table 5.13: CO_2 emissions comparison a/c building

Table 5.12 shows initially a comparison of the base case building energy consumption with the ECON 19 benchmark building. The heating and cooling energy consumption are 13% and 12% less than the ECON 19 benchmark respectively; this can be attributed to the good thermal properties of the building.

Table 5.12 also compares the fully air-conditioned base case building with the fully air-conditioned absorptive glazed building. It can be seen that by initially applying absorptive glazing and excluding all but 6% of direct solar radiation from the occupied spaces, the cooling load is reduced by 8.12 kWh m^{-2} y^{-1} (66%). The detrimental effect of excluding the direct solar radiation is the reduction in useful solar gain and hence an increase in heating energy consumption, in this case an increase of 12%. Overall this has resulted in an increase in energy consumption of 2.1%.

In terms of CO_2 emissions, the cooling associated emissions are reduced by 3.73 kg CO_2 m^{-2} y^{-1} (65.8%), and the emissions associated with the heating system have increased by 12%, however the net overall effect is a reduction of 1.5 kg CO_2 m^{-2} y^{-1}(8.3%). Therefore any increase in heating energy consumption is outweighed by the reduction in cooling energy consumption due to the associated carbon emission factors.

The effect of this can be clearly seen in Figure 5.10. As solar gain increases between 8am and 3pm the heating load reduces in the base case building. In the absorptive glazed building the solar gain is reduced significantly and hence the heating load increases at the corresponding time.

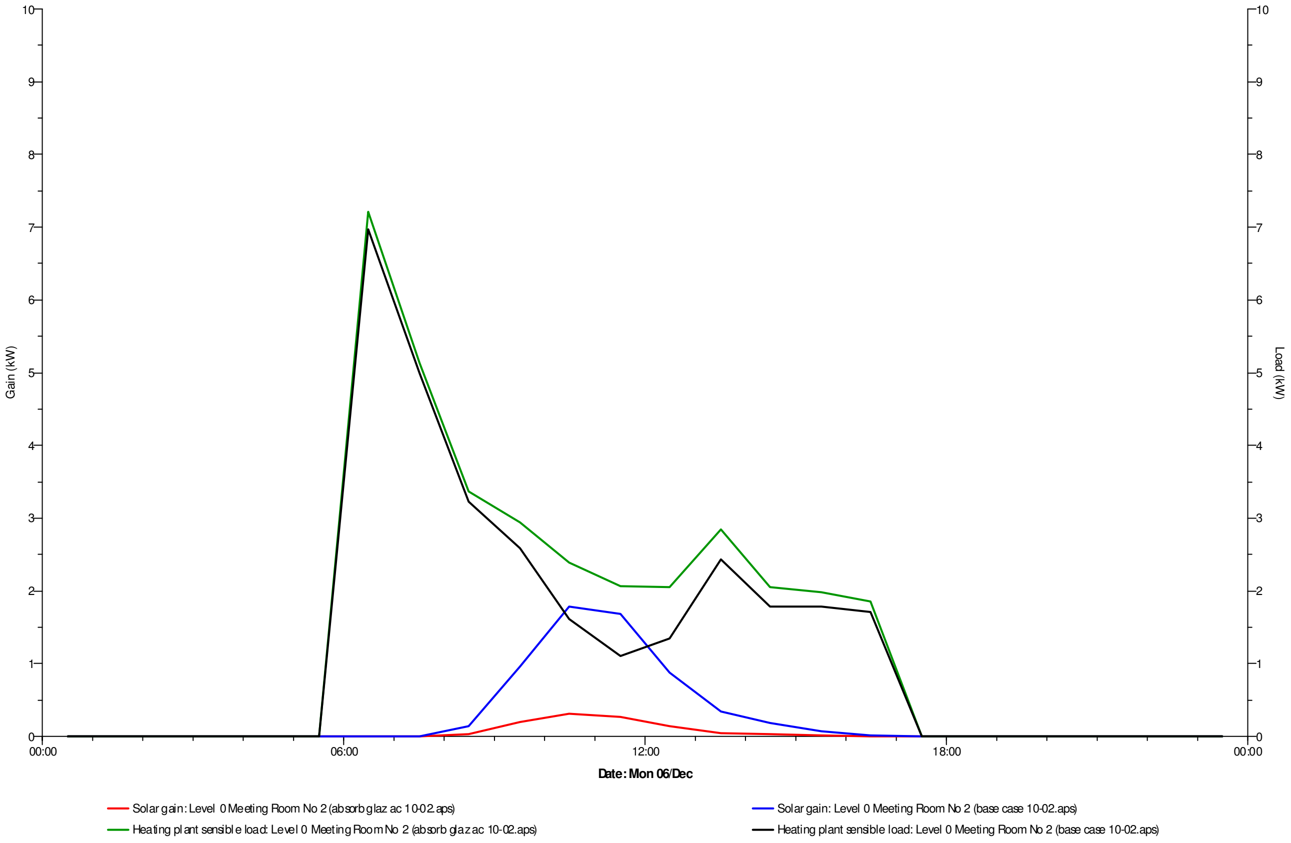

Figure 5.10: Solar Gain and Heating comparison

Using this detailed design process, the designer can apply a number of different design options to a building and interrogate and analyse the implications for other design team members. This would enable a design team to come to a well-informed decision on a design solution for a building, founded on accurate information. This process would complement a financial or an architectural / aesthetic based decision to yield a substantially reduced energy performance and associated carbon and CO_2 emissions.

5.7 MIXED MODE BUILDING

The next stage of the detailed design process was to establish a mixed mode building. A range check was again performed on the building with absorptive coat glazing in order to establish the rooms with operative temperature exceeding 5°C for more than 5% of the occupied time. In this case 35% of the building (10 No. rooms) required mechanical cooling and 65% of the building (19 No. rooms) did not require mechanical cooling. The results are provided in Appendix E.

Therefore using the step of providing solar absorptive glazing alone has reduced the number of air-conditioned rooms by 41% (12 No. rooms) when compared to the base case in the early design step.

The building was modelled using bulk airflow analysis to simulate a fully naturally ventilated building. Natural ventilation openings were designed as set out in section 5.3.2. This calculation established that the 20% (6 No. rooms) of the building required to be air conditioned rooms and 80% (23 No. rooms) naturally ventilated.

Using this information, the 6 rooms requiring mechanical cooling were assigned ventilation and mechanical cooling as set out in section 5.2. The remaining 23 rooms were assigned natural ventilation. The building was modelled using bulk airflow analysis in order to simulate a mixed mode building.

The annual energy performance associated with the heating and cooling systems are set out in Table 5.14 and the CO_2 emissions associated with the heating and cooling systems are set out in Table 5.15. In both cases the % improvement is compared to the base case building.

Description	Heating Energy	Cooling Energy	Overall Energy	Improvement
	kWh m^{-2} y^{-1}	KWh m^{-2} y^{-1}	kWh m^{-2} y^{-1}	%
ECON 19 Benchmark	97.00	14.00	111.00	
Base Case	84.36	12.34	96.71	
Absorptive Glazing AC	94.52	4.22	98.75	+2.1
Absorptive Glazing Mixed Mode	84.96	4.19	89.15	-7.8

Table 5.14: Annual energy performance comparison mixed mode building

Description	Heating CO_2	Cooling CO_2	Overall CO_2	Improvement
	kg m^{-2} y^{-1}	kg m^{-2} y^{-1}	kg m^{-2} y^{-1}	%
ECON 19 Benchmark	18.43	6.44	24.87	
Base Case	16.03	5.67	21.71	
Absorptive Glazing AC	17.96	1.94	19.90	-8.3
Absorptive Glazing Mixed Mode	16.14	1.93	18.07	-16.8

Table 5.15: CO_2 emissions comparison mixed mode building

When the mixed mode solution was applied to the building, the cooling energy consumption was reduced by 8.15 kWh m^{-2} y^{-1}(66%) in comparison to the base case building, this is due to the excluded direct solar radiation and the reduced reliance on the mechanical cooling system. The heating energy consumption increased by 0.7% when compared to the base case building, due to the additional ventilation heat loss.

In terms of CO_2 emissions, the cooling associated emissions are reduced by 1.04 kg m^{-2} y^{-1}(66%), and the emissions associated with the heating system increased by 0.7%. A net reduction in CO_2 emissions of 1.0 kg m^{-2} y^{-1}(16.9%) was achieved.

Using this detailed design process and a methodology capable of bulk airflow analysis, the designer can apply natural ventilation to a space and accurately quantify the effect on operative temperature, heating loads and cooling loads within a space. This enabled the process of establishing that a fully naturally ventilated building would not work without substantial architectural modification but a mixed mode solution would also yield substantially reduced energy consumption and associated CO_2 emissions.

5.8 MODELLING OF THE BUILDING IN SBEM

The UK national calculation methodology (SBEM) was applied to the commercial office block building described in Section 5.2. The standard office block was modelled for the base case building described previously.

Although SBEM is used as a compliance tool, the underlying methodology is for annual energy performance calculation, as set out by Roulet [2002]. In its use as a compliance tool, compliance is expressed in terms of annual CO_2 emissions which are calculated by a conversion factor applied to the calculated annual energy performance. This methodology is therefore primarily used for annual energy performance calculation. This work compares the sensitivity of the annual energy performance calculation aspect of the underlying methodology.

SBEM contains several internal databases containing standardised information on various building types, occupancy patterns, control profiles, standard temperatures, etc. This methodology is designed in such a manner so as to minimise the input required of the user and therefore contains a large amount of default data.

There are a number of stages to inputting a building into SBEM, as follows.

General Information

Information is required for the type and location of building. The input for the type of building is used to establish the default data required for the calculation.

Project Database

A database was built up of the different constructions and glazing types of the fabric elements. In this case fabric elements were assigned with similar thermal properties as those set out in Section 5.2.1. Opaque elements were defined simply by their thermal transmittance in W m^{-2} K and the effective thermal capacity (C_m) in kJ m^{-2} K. Transparent elements were defined by solar energy transmittance and the light transmittance. Details of the assigned constructions are provided in Appendix F.

Geometry

Initially orientation, height, air permeability and thermal bridging factors were applied to the building. The building was separated into a number of zones, each zone was defined by activity. Spaces of different uses were identified and an activity allocated to each. In this case open plan offices, cellular offices, toilets, canteen, atrium etc.

The envelope elements that enclose the zone were attributed to each zone. The physical elements that define a space were identified. Definitions were applied to each element for; area, orientation, conditions in the adjacent spaces and constructions.

Building Services

The space heating, ventilation and air conditioning systems and DHW (domestic hot water) systems were defined. The building was attributed with a gas fired boiler, a constant air volume ventilation system and an electrical chiller. All spaces were provided with air conditioning with the exception of the toilets and atrium.

The SBEM input works on a hierarchy of zones as illustrated in Figure 5.11 [ODPM 2006 pp7]. An envelope of internal and external elements such as walls, floor and ceiling surrounds each zone. Each zone is assigned a HVAC system and domestic hot water system as appropriate. The lighting system and ventilation characteristics of each zone are defined and assigned to the appropriate HVAC and DHW systems.

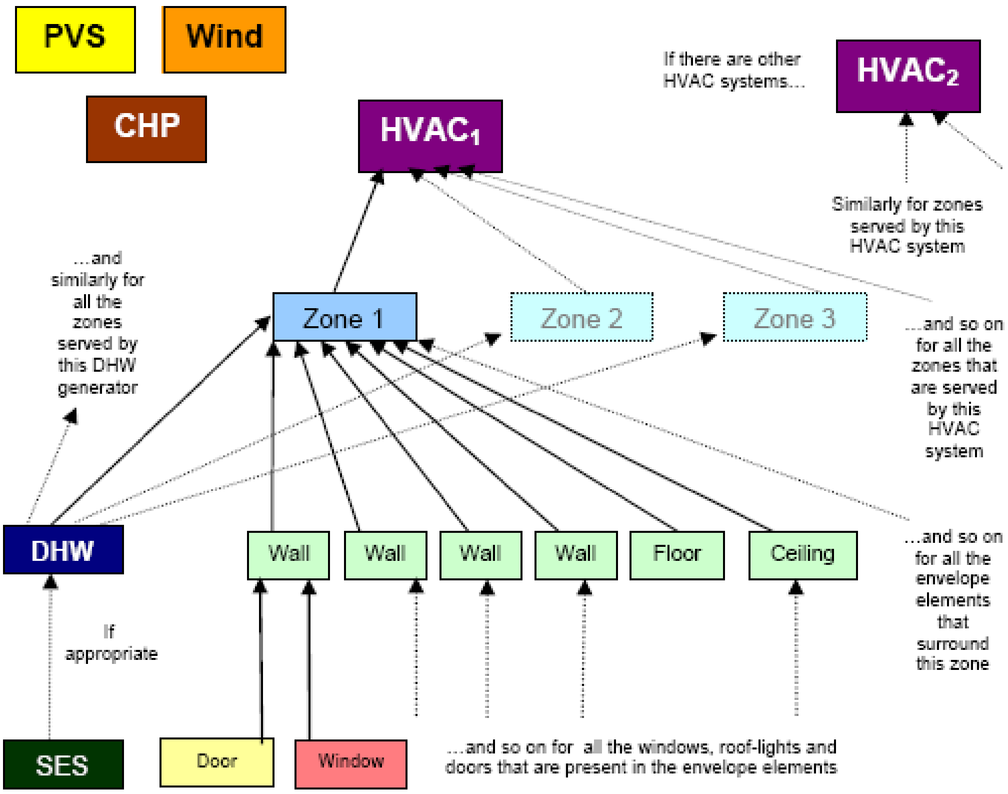

Figure 5.11: Hierarchy of SBEM Building Objects

From the outset it was obvious that comparable results would not be obtained from both calculation methodologies. Therefore the purpose of carrying out such a comparison was to investigate both the operation of SBEM and its' sensitivity to the variation of design parameters.

5.9 IMPROVEMENT OF ENERGY PERFORMANCE

Initially SBEM was applied to the base case building; results obtained are shown in Table 5.16 and compared to both the IES results for the same building and the ECON 19 benchmark.

Description	Heating Energy	Cooling Energy	Overall Energy
	KWh m^{-2} y^{-1}	KWh m^{-2} y^{-1}	kWh m^{-2} y^{-1}
ECON 19 Benchmark	97.00	14.00	111.00
Base Case IES	84.36	12.34	96.71
Base Case SBEM	51.76	32.84	84.06

Table 5.16: Annual Energy Performance IES and SBEM

The SBEM annual heating energy consumption is 38.6% less than the IES <VE> calculated annual heating energy consumption and the SBEM cooling annual energy consumption is 166% greater than the IES <VE> calculated annual cooling energy consumption. The ECON 19 heating and cooling annual energy consumption benchmark figures are shown for a guideline. The IES <VE> calculation results are within a comparable range to the benchmark figure, however although the SBEM heating energy consumption is within range the cooling energy consumption is out of range.

The next step was to quantify how SBEM facilitated the analysis of design options in order to achieve a building with an improved energy performance. The standard office building was modelled under the same criteria as set out in the previous sections and changed in terms of the following:

- High thermal mass external envelope and internal elements
- Low thermal mass external envelope and internal elements
- Reflective coat external glazing
- Absorptive coat external glazing
- Solar shading
- Reduced glazing

5.9.1 High thermal mass external envelope and internal elements

In order to change this item in SBEM, an element must be defined in terms of its' thermal transmittance (U) in W m^{-2} K and its' effective thermal capacity (Cm) in kJ m^{-2} K.

SBEM offered 3 options for defining elements

- Import from the library
- Help with inference procedures
- Introduce your own values.

In order to insert a material with a high thermal mass similar to that used in the IES modelled building, an appropriate option was not available in the project database therefore specific values had to be introduced. The effective thermal mass presented difficulty in inserting a similar thermal mass to the IES element which is quantified in terms of admittance, decrement factor and decrement factor time lag.

The effective thermal mass C_m (kJ m^{-2} K) is given by:

$$C_m = \rho \times d \times C$$

Where

ρ = Density (kg m^{-3})

d = thickness (m)

C = specific heat capacity (kJ kg^{-1} K)

In order to model a high thermal mass building, an external wall was defined with a thermal transmittance of 0.32 W m^{-2} K and an effective thermal capacity of 230 kJ kg^{-1} K, and an internal wall defined with a thermal transmittance of 3.3 W m^{-2} K and an effective thermal capacity of 230 kJ kg^{-1} K.

Results obtained for heating energy and cooling energy consumption were 54.24 kWh m^{-2} y^{-1} and 29.81 kWh m^{-2} y^{-1} respectively. This represents a 4.6% increase in heating energy consumption and a 9.2% reduction in cooling energy consumption, which is in range of what would be expected.

5.9.2 Low thermal mass external envelope and internal elements

Modelling of this design option required the same input data as to use a high thermal mass element. The external wall was defined with a thermal transmittance of 0.34 W m^{-2} K and an effective thermal capacity of 10.37 kJ kg^{-1} K, and the internal wall defined with a thermal transmittance of 1.66 W m^{-2} K and 11.97 kJ kg^{-1} K.

Results obtained for heating energy and cooling energy consumption were 47.18 kWh m^{-2} y^{-1} and 36.13 kWh m^{-2} y^{-1} respectively. This represents an 8.8% reduction in heating energy consumption and a 10.0% increase in cooling energy consumption.

5.9.3 Absorptive coat external glazing

Glazing is quantified in SBEM in terms of its thermal transmittance (U) in W m^{-2} K, solar transmittance (T-Solar) and light transmissivity (L-Solar). In IES <VE> the glazing is quantified in terms of reflectance, absorbance and transmittance of each pane of glass in addition to the long wave, short wave and total shading coefficients. SBEM proved difficult to represent the actual figures. The absorptive coat glazing was defined with a solar transmittance of 0.06 and a light transmissivity of 0.8. This represented a heating and cooling energy consumption of 55.68 kWh m^{-2} y^{-1} and 16.65 kWh m^{-2} y^{-1} respectively. This represents a 7.6% increase in heating energy consumption and a 49.3% reduction in cooling energy consumption

5.9.4 Reflective coat external glazing

The reflective coat glazing was defined with a solar transmittance of 0.29 and a light transmissivity of 0.6. This represented a heating and cooling energy consumption of 52.77 kWh m^{-2} y^{-1} and 23.37kWh m^{-2} y^{-1} respectively. This represents a 2.0% increase in heating energy consumption and a 28.8% reduction in cooling energy consumption.

5.9.5 Solar shading

Solar shading is defined in the windows menu, the user may select whether the window has user moveable external protection, automatically controlled external protection or not (all other cases). Also the user may apply a transmission factor, which is the fraction of light transmitted through the shading. The application of solar shading represented a heating and cooling energy consumption of 54.11 kWh m^{-2} y^{-1} and 20.92 kWh m^{-2} y^{-1} respectively. This represents a 4.5% increase in heating energy consumption and a 36.3% reduction in cooling energy consumption.

5.9.6 Reduced glazing

The application of reduced glazing requires the user to access each envelope element and each window and reduce dimensions to suit. Glazing area was reduced by 30%, similar to that of the IES<VE> calculation. The reduction in glazing area represented a heating and cooling energy consumption of 43.30 kWh m^{-2} y^{-1} and 31.12 kWh m^{-2} y^{-1} respectively, which represents a 16.3%

reduction in heating energy consumption and a 5.2% reduction in cooling energy consumption.

5.9.7 Naturally Ventilated Building

The application of natural ventilation in SBEM involves ticking a box. The calculation assumes that all of the ventilation needs of the building are supplied by natural means. The application of natural ventilation represented a heating consumption of 60.27 kWh m^{-2} y^{-}, which represents a 16.4% increase in heating energy consumption and a 100% reduction in cooling energy consumption.

5.9.8 Mixed Mode Building

SBEM does not have the facility to model a mixed mode building.

5.9.9 Deficiencies within SBEM

Table 5.17 highlights a number of deficiencies in the facilitation of investigation of design options for a building.

Design Option	**Ability to accurately represent**
Absorptive Glazing	Use of non-standard parameters proved difficult to represent real window
Shading	Few options available to model reality
Reflective Glazing	Use of non-standard parameters proved difficult to represent real window
Reduced. Glazing	Laborious repeat input data

Table 5.17: Deficiencies in SBEM

5.10 PARAMETRIC SENSITIVITY ANALYSIS

The annual energy performance results obtained by both SBEM and IES <VE> were analysed and compared to assess the sensitivity of both methodologies to variation of the key parameters of the buildings design. Table 5.18 illustrates the annual heating and cooling energy consumptions obtained and Table 5.19

illustrates % difference between the improvement results obtained by each methodology.

	IES		SBEM	
Design Option	**Heating**	**Cooling**	**Heating**	**Cooling**
	kWh m^{-2} y^{-1}	**kWh m^{-2} y^{-1}**	**kWh m^{-2} y^{-1}**	**kWh m^{-2} y^{-1}**
Base Case	84.36	12.34	51.76	32.84
Absorptive Glazing A/C	94.52	4.22	55.68	16.65
Solar Shading	87.73	6.94	54.11	20.92
Reflective Glazing	92.79	4.72	52.77	23.37
Reduced Glazing	82.17	9.27	43.30	31.12
High Thermal Mass	93.93	8.72	54.24	29.81
Low Thermal Mass	79.52	14.82	47.81	36.13

Table 5.18: Sensitivity Analysis Annual Energy Consumption

	IES Improvement		SBEM Improvement	
Design Option	**Heating**	**Cooling**	**Heating**	**Cooling**
	%	**%**	**%**	**%**
Absorptive Glazing A/C	-12.0	65.8	-7.6	49.3
Solar Shading	-4.0	43.8	-4.5	36.3
Reflective Glazing	-10.0	61.8	-2.0	28.8
Reduced Glazing	2.6	24.9	16.3	5.2
High Thermal Mass	-11.3	29.3	-4.8	9.2
Low Thermal Mass	5.8	-20.1	8.8	-10.0

Table 5.19: Sensitivity Analysis Percentage Difference

In both IES <VE> and SBEM, the absorptive glazed building showed the most significant improvement in cooling energy consumption and net overall improvement. IES <VE> showed an improvement of 65.8% and SBEM showed an improvement of 49.3% and both showed a heating energy consumption penalty, although SBEM only showed 7.6% against 12% in IES <VE>.

The remaining design options showed the same range of improvement, both SBEM and IES<VE> showed similar improvement and heating penalty for reduction in solar gain. However, SBEM does not model the cooling improvement or heating penalty for reflective glazing to the same level as IES <VE>.

Although quite different results were obtained in terms of annual heating and cooling energy consumption, the standard deviation between the heating and cooling energy consumption design options was 6.05 and 3.87 respectively in the case of IES <VE> and 4.36 and 7.06 respectively in the case of SBEM. However regarding the difference in results obtained by each, a standard deviation of 3.65 was achieved in the case of heating energy consumption and 3.81 in the case of cooling energy consumption. This illustrates that although there was a wide disparity between the results obtained by both methodologies, the sensitivity to design improvements were within closer range.

Although the SBEM results do not compare well with the IES <VE> results, it must be noted that SBEM is still in its infancy. Results obtained and problems the author encountered with the software were of a similar nature to those encountered in the building services engineering industry in Britain. Research carried out by Kennett [2006] reported difficulties in data entry and a lack of confidence in results and in some cases gave counter intuitive results. Stephens [2006] also reported similar difficulties. Initially unusual results were obtained for the high thermal mass design option in which SBEM calculated a 4.6% increase in cooling energy consumption and IES <VE> calculated a 29.3% improvement. Also in the reduced glazing design option SBEM calculated a 0.3% increase in cooling energy consumption whereas IES <VE> calculated a 24.9% improvement; however more recent versions have become more stable. The difference in results is mainly due to the difference in calculation methodology i.e. IES <VE> is a dynamic calculation methodology and SBEM is a quasi steady state methodology based on a monthly heat balance. The following sections analyse and compare the calculation algorithms and procedures in both methodologies.

5.11 IES <VE> CALCULATION METHODOLOGY

Within the simulation facility in IES <VE>, each element of the building fabric is modelled in terms conduction, convection and radiation heat transfer processes, this is coupled with models of room heat gains, air exchanges and plant dynamics.

In order to simulate the external environment, IES <VE> uses a Test Reference Year (TRY) weather file with hourly weather data. The weather data parameters include; dry bulb, wet bulb and external dew point temperatures; wind speed and direction; direct, diffuse and global radiation; solar altitude and azimuth; cloud cover; external relative humidity and external moisture content.

The IES <VE> calculation is carried out under the following headings:-

- Heat conduction and storage
- Convection heat transfer
- Heat transfer by air movement
- Long-wave radiation heat transfer
- Solar radiation
- Casual gains

- Thermo-physical properties of air
- Room plant & control
- Room & building heat balance

5.11.1 Heat Conduction and Storage

IES <VE> uses partial differential equations to govern conduction heat transfer and heat storage and solve the time evolution of spatial temperature distribution in a solid [IES 2005 pp 6]. The IES <VE> calculation assumes each building element to be uniform, therefore the conductivity, density and specific heat capacity of each element are considered to be uniform. In order to calculate heat diffusion, each element is divided into a finite number of discrete nodes at which the temperature is calculated. The heat diffusion equation is solved using a finite difference approach. In this equation the variation in position of conductivity, density and specific heat capacity in a multilayered element is accounted for. The heat storage and conduction equations are closed by the application of boundary conditions.

Accurate modelling of heat transfer and storage characteristics of the element is achieved by distribution of the nodes within the layer. As a result, a layer may be assigned many nodes. The time variable is descretised, using either explicit methods or implicit methods. Explicit methods use a forward difference scheme; implicit methods use a backward difference scheme. In order to improve accuracy a combination of explicit and implicit time stepping is used in the form of the Crank- Nicholson semi implicit method [Myres 1971].

Air gaps in construction are modelled as a resistance based on the surface temperature difference across the air gap and a combined radiative / convective resistance.

Heat storage in large air masses contained within the building is taken into consideration based on the product of; the specific heat capacity, density, volume and rate of change of temperature of the air in the space.

5.11.2 Convection Heat Transfer

IES has the ability to model exterior and interior convection as both forced and natural convection [IES 2005 pp9]. Heat transfer by forced convection calculated as the product of a convection coefficient and the difference between the surface temperature and the bulk air temperature. The coefficient is applied to simulate forced convection as a linear process. Natural convective heat transfer is based on the product of the difference between the surface temperature and the bulk air temperature and the convective heat transfer coefficient (h_c). IES state that 'h_c' can be modelled in a linearised form using a constant value or can be varied as a function of temperature difference. In this case an iterative process updates the value of 'h_c'. The user has control over which process can be adopted into the calculation.

Exterior Convection

Convection on the exterior envelope is mainly wind driven forced convection in this case the exterior convection coefficient is modelled using the McAdams empirical calculations which are wind speed dependant. In other cases the ASHRAE simple method is used. Variables in the simulation weather file are recorded at hourly intervals. Linear interpolation is applied between the recorded values to compute values at each simulation time-step.

Interior Convection

Inside the building convective heat transfer occurs between the internal air masses and the internal surface of building elements. In this case IES offers a number of options [IES 2005 pp10].

- Fixed convection coefficients specified by CIBSE
- Variable convection coefficients calculated according to CIBSE
- Variable convection coefficients calculated from the relations proposed by Alamdari & Hammond.
- User specified convection coefficients

(a) CIBSE Fixed Convection Coefficients

The CIBSE ‘Simple Model’ [CIBSE 2006 pp A3-7] for Heat Loss and Heat Gain calculations based on a constant (average) convection coefficient for internal surfaces

(b) CIBSE Variable Convection Coefficients

CIBSE Guide C [1998 pp C3-12] provides a procedure for calculating convection coefficients, including the effect of; surface orientation, air-surface temperature difference and mean room air velocity. These coefficients are dependent on varying air-surface temperature difference and are applied as part of an iterative calculation procedure.

(c) Alamdari & Hammond Convection Coefficients

Alamdari & Hammond [1983] provide a procedure for calculating temperature varying internal surface convection coefficients which are applied within the iterative calculation procedure.

(d) User specified convection coefficient

IES allows the user to define and specify the convection coefficients for each construction type.

5.11.3 Heat Transfer by Air Movement

The rate of heat transfer associated with a stream of air entering a space is quantified as the product of the mass flow rate, specific heat capacity and the temperature difference between room air and supply air. The equation includes the assumption that the air displaced by the supply air is at the room mean air temperature [IES 2005 pp 13].

Air movement can be modelled in a number of ways, as follows:

- Fixed air exchanges
- Air flows calculated in the bulk air flow analysis simulation component
- Air flows specified or calculated by HVAC systems simulation component

(a) Fixed air exchanges

Fixed air exchanges may be classified as infiltration, natural or mechanical ventilation and are sourced from outside air. The air exchanges may be represented by a static or a time varying temperature offset.

(b) Air flows calculated in the bulk air flow analysis simulation component

This simulation component calculates natural ventilation airflows arising from wind and buoyancy. This component runs simultaneous to the simulation and the calculations of the two programs are interdependent.

(c) Air flows specified or calculated by HVAC systems simulation component

Air flows specified or calculated by the HVAC systems simulation component which runs simultaneous with the simulation. The ducted mechanical ventilation rates are superimposed on other air flows dealt with by the main simulation.

5.11.4 Long Wave Radiation Heat Transfer

The long wave thermal radiation refers to the radiation emitted by the building surfaces. IES takes account of the emission and absorption of long wave radiation by building surfaces [IES 2005 pp15].

(a) Emission of long wave radiation

Emission of long wave radiation considers the radiation flux emitted to a small solid angle normal to the surface considered. The radiation flux emitted to the solid angle is integrated to calculate the total long wave radiation over the plane surface. The radiation flux is calculated as the product of; the surface emissivity, the Stefan-Boltzmann constant and the absolute temperature of the surface.

(b) Absorption of long wave radiation

The fraction of radiant energy absorbed by a surface is assumed equal to the surface emissivity [IES 2005 pp16]. IES state that this is an approximation and does not take into account wavelength dependence, but provides an accurate model for predicting long wave radiant exchange in buildings.

Interior Long wave radiation

Long wave radiation heat transfer between internal surfaces is modelled by integrating the radiation flux emitted by a small solid angle over the emitting area and receiving solid angle, which results in a shape factor, which is the fraction of radiation emitted by surface 1 that reached surface 2.

IES uses a model based on the CIBSE [2006 pp A5-65] mean radiant temperature model. This model is used as an approximation and introduces a single radiant node into each element, which deals with all surface radiant exchanges. The net radiant exchange between a surface and the rest of the room is the product of the surface heat transfer coefficient and the difference in temperature between the surface and mean radiant temperature.

The effect of air is included in interior radiation exchanges [IES 2005 pp 16]. Water vapour and CO_2 in the air act to absorb and emit radiation to their surroundings. IES <VE> applies an air emissivity to quantify this process. For this purpose the effect of CO_2 is negligible and therefore ignored. The effect of water vapour in the air increases with humidity and room size. IES states that a large room such as an atrium may have an air emissivity of approximately 0.3 and a small space such as an office may have an air emissivity of 0.1. The air emissivity has a significant effect on radiant temperature in the space. An air mass absorbing radiation will reduce the ability of the space surfaces from absorbing radiation and hence the radiant temperature perceived by the occupants. The model used to quantify radiant air exchange was developed by Hottel [1954]. Hottels' model expresses the emissivity of air as the product of mean beam length of the air and the partial vapour pressure of the air. This model is used in IES <VE> to modify the calculation for the effect of intersurface radiant exchange, radiant exchange between surface and air, distribution of radiant plant and casual gains to surfaces, air and mean radiant temperature.

Exterior Long Wave Radiation

Exterior building surfaces emit and receive long wave radiation. Radiation is transferred between the sky, the ground and other warmer/cooler objects. The difference in the radiation emitted and absorbed results in a net radiant gain, which may be positive or negative.

The long wave radiation gain for a surface is calculated using a CIBSE [2006] procedure. The gain is quantified by the product of the surface emissivity and the sum of direct long-wave radiation from the sky, direct long-wave radiation from the ground and the absolute temperature of the external surface.

Long wave radiation received from the ground is based on the short wave ground reflectance, total solar flux and a shape factor from the surface to the ground. For an inclined surface, long-wave radiation received directly from the sky is obtained using Cole's correlation [Cole 1979]. For a horizontal surface it is estimated from the temperature and water vapour content of the air, with a modification for cloud cover.

5.11.5 Solar Radiation

Solar radiation incident on building surfaces can be broken down into three main components:

(i) Direct radiation emanating from near to the sun's disc
(ii) Diffuse radiation from the sky vault
(iii) Radiation scattered by the ground

Surrounding buildings and landscape features have a significant effect on the direct radiation received by a building. Solar radiation entering a building through transparent surfaces is absorbed (after repeated scattering) by internal surfaces. Part of this radiation may be lost by being retransmitted out of the building through glazing. The effect of absorption and scattering by exterior surfaces (both opaque and transparent) is also significant.

IES uses real time actual recorded weather data at hourly intervals. The variables associated with solar radiation are as follows [IES 2005 pp 20]:

- Direct solar radiation measured perpendicular to the beam
- Diffuse solar radiation measured on the horizontal plane
- Solar altitude and azimuth

The solar flux incident on every external building surface is the product of solar flux measured perpendicular to the beam and the angle of incidence. The diffuse solar flux has components radiated from the sky and the ground.

Distribution of solar radiation

The radiation received by an exterior surface is calculated from the incident beam solar flux, taking account of the surface geometry and an external shading factor. For transparent surfaces the transmission and absorption of the incident solar radiation is calculated. The transmitted solar radiation is tracked through successive interactions with building surfaces. For opaque surfaces the solar radiation is partially absorbed and partially reflected using an assumed solar absorptance of 0.55. Beam radiation falling on a transparent element is transmitted, absorbed and reflected in accordance with the element’s properties.

Radiation reflected from opaque or transparent surfaces is returned to the adjacent room for later distribution as diffuse radiation. Transmitted beam radiation is tracked on further receiving surfaces. The process terminates when all components of the beam have either encountered opaque surfaces or left the building through transparent elements.

Calculation of incident diffuse solar radiation

Diffuse radiation incident on an exposed surface is the sum of components from the sky, the ground, and shading objects. Shading objects block diffuse sky solar radiation to a degree; these are determined by a *diffuse shading factor*.

Distribution of diffuse solar radiation

The diffuse component of solar radiation incident on an external glazed element is the sum of components from the sky and the ground. This is partially transmitted and partially absorbed by the element. The transmitted portion is distributed over the interior building surfaces in proportion to their areas and is repeated up to 10 times to distribute the diffuse radiation through the space. Any residual radiation at the end of the process is assigned to room surfaces in a final modified *acceptance* distribution [IES 2005 pp21]:

5.11.6 Casual Gains

IES applies casual gains for the following [IES 2005 pp28]:

- Lighting
- Equipment
- Cooking
- Computers
- People

These are user defined and may be scheduled on a time profile. Sensible gains may be divided into sensible and radiant factions. The radiant portion is added to the room surfaces and the convective portion is added to the room air. Latent gains are considered to add water vapour to the air.

5.11.7 Thermophysical Properties of Air

The standard psychrometric processes of the air are modelled as part of the calculation, and the storage of water vapour in the room air mass is represented by the product of the air density and the room air humidity ratio.

5.11.8 Room and Plant Control

Using IES room and plant control can be achieved in 2 ways [IES 2005 pp30]:

- Idealised plant control
- Mechanical System Simulation

Idealised room control is based on heating plant input when the heating setpoint is achieved and a cooling plant input when the cooling setpoint is achieved. This may be applied with or without a maximum plant capacity and may be assigned against a time or temperature profile. Mechanical system simulation control can be achieved using the HVAC add-on module within IES.

5.11.9 Room and Building Heat Balance

A thermal balance is carried out as part of the IES calculation in order to balance sensible and latent heat flows in and out of each air mass and building surface [IES 2005 pp33].

If the HVAC module or the bulk air flow part of the simulation is enabled, a thermal balance of each system is also carried out.

The room and building heat balance may be summarised under the following headings:

- Sensible air heat balance
- Thermal storage in air and furniture
- Convection from room surfaces
- Heat transfer by air movement
- Convective portion of casual gains
- Convective portion of plant input

In order to achieve a balance at the air node the sum of these components must equal zero.

An interior room surface heat balance may be summarised under the following headings:

- Heat conduction out of the building element
- Convection to the surface from the room air
- Thermal radiation exchanged with the radiant temperature node
- Solar gain absorbed by the surface
- The surface's share of the radiant portion of casual gains
- The surface's share of radiant plant input – idealised or from the HVAC simulation module.

As a mean radiant temperature model of long wave radiant heat exchange is used a further heat balance is required at the radiant temperature node to equate all the heat flows to zero.

A heat balance is also carried out at the exterior surface, under the following headings:

- Heat conduction out of the building element
- Convection to the surface from the outside air
- Thermal radiation exchanged with the external environment
- Solar gain absorbed by the surface

The heat balance equations are solved using linear algebra techniques as an iterative process.

5.12 SBEM CALCULATION METHODOLOGY

The UK Simplified Building Energy Model (SBEM) calculation tool is described briefly in Chapter 4 of this thesis. The methodology for this tool is the European (CEN) standard prEN13790, *Thermal Performance of buildings – calculation of energy use for space heating and cooling* [CEN 2005]. Figure 5.12 sets out a representation of the methodology.

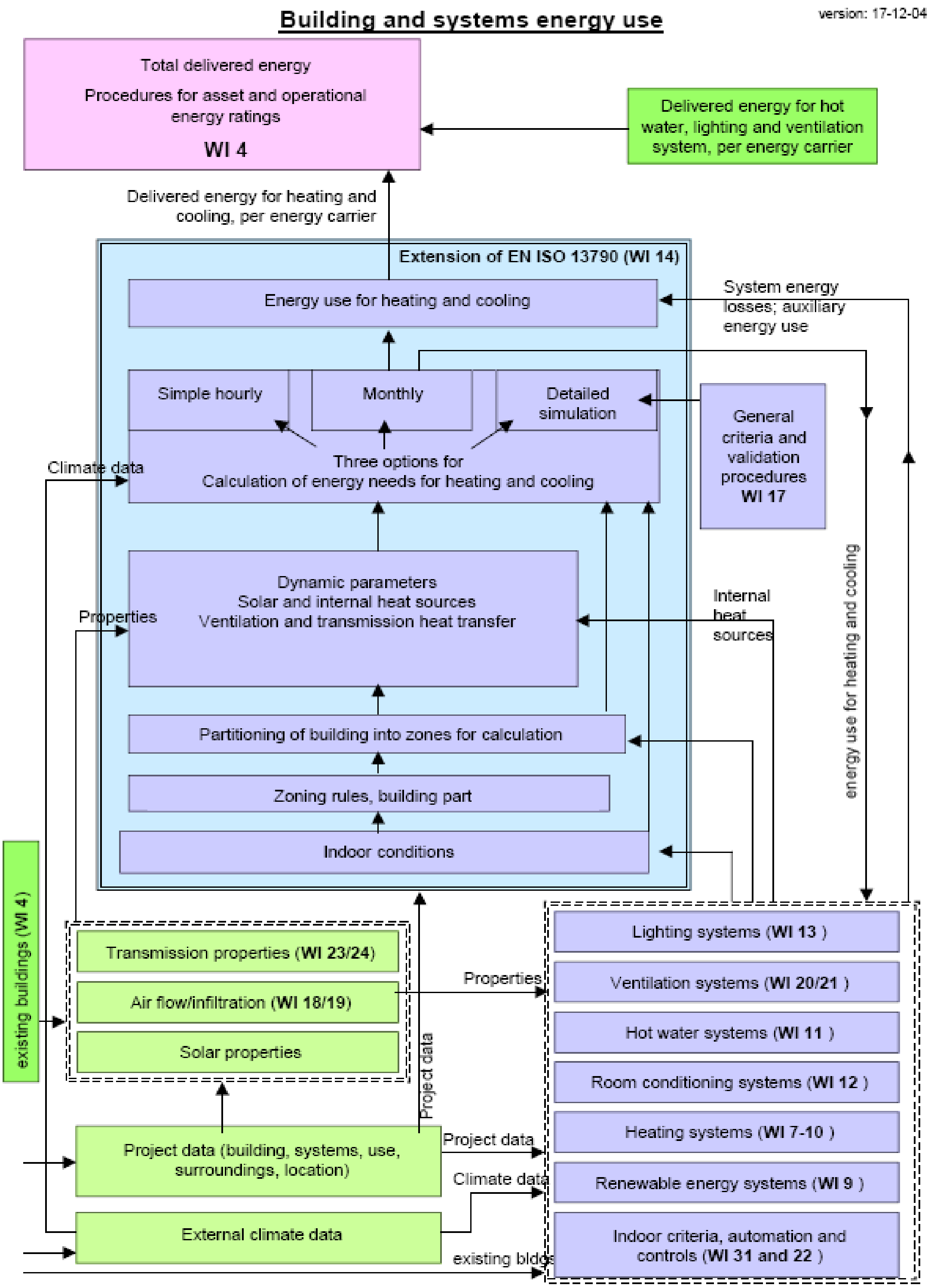

Figure 5.12: Calculation Methodology Representation

[CEN 2005 pp10]

In order to harmonise methods for the calculation of the energy performance of buildings, the European standards organisation (CEN) has updated existing standards and also created new standards. The relationship between the CEN standards and the EPBD calculation methodology is set out in the CEN Umbrella document [CEN 2004].

CEN [2005] sets out a procedure for a monthly or seasonal method and a simple hourly method.

Using the monthly or seasonal method, the building energy need for space heating is calculated as a product of the heat transfer and heat source properties of the building or building zone, coupled with and a utilization factor for the use of heat gains. The building energy need for cooling is calculated as a product of the heat source and heat transfer properties of the building or building zone, coupled with and a utilization factor for the use of the heat losses. The length of the heating or cooling operation for the monthly method is determined using heating or cooling degree days with a weighting applied for months with a large gains to loss ratio.

Using the simple hourly method the building energy need for space heating and cooling is determined using an hourly time step based on user schedules. The model uses an equivalent analogous RC circuit to represent nodes of significance. This equivalent RC circuit is illustrated in Figure 5.13.

The heating and cooling need is quantified by establishing each hour that heat needs to be supplied to or taken from the internal air node (θ_i) to maintain a set point temperature.

Heat transfer by ventilation is established as a function of the ventilation rate (H_v) and the supply air temperature ($\theta_{\sup,air}$).

Heat transfer by transmission is established as a function of the thermal transmission coefficients of the building fabric, this is divided into elements of no thermal mass (H_w), such as glazing systems and elements with thermal mass (H_{opp}).

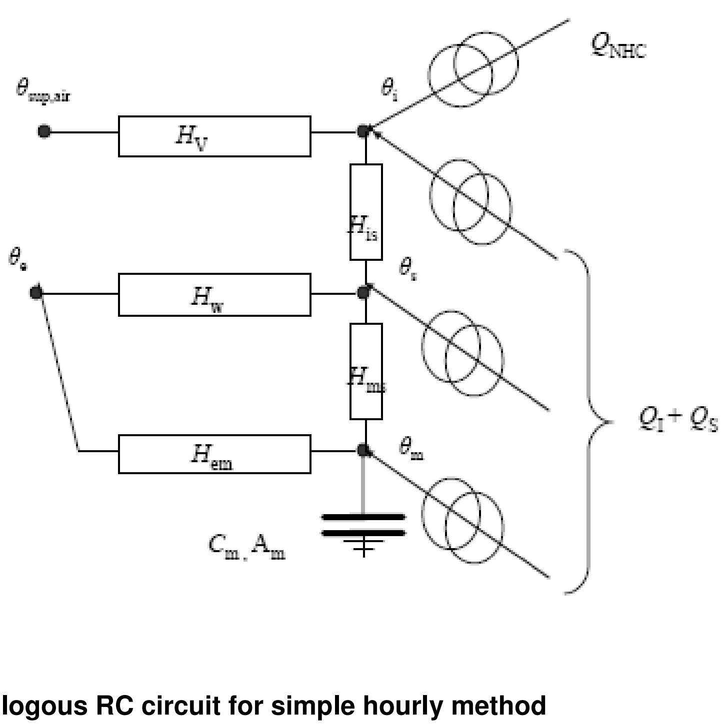

Figure 5.13: Analogous RC circuit for simple hourly method
[CEN 2005 pp24]

Heat gains, both internal and solar are applied to the air node (θ_i), the central node (θ_s) (which includes mean radiant temperature) and the node representing the thermal mass of the building (θ_m).

The coupling conductance (H_{is}) between the ventilation and transmission nodes is calculated on the basis of a fixed heat transfer coefficient between zones and the area of all facing surfaces in the space (based on a fixed ratio of internal surfaces to floor area).

The thermal mass is represented by a single thermal capacity (C_m)
The coupling conductance (H_{ms}) between the internal air node (θ_i) and the surface node (θ_s) is based on fixed heat transfer coefficient.
The length of heating and cooling seasons is determined by averaging the heating and cooling demand over the pervious four weeks.

CEN [2005] refers to the difference between this method and dynamic methods and states that the monthly method may yield correct results on an annual basis, the results for individual months close to the beginning or end of a heating or cooling season may have large relative errors. The simple hourly calculation produces hourly results which have not been validated can again have large relative errors [CEN 2005 pp12].

5.12.1 Monthly and Seasonal Method

This section describes the calculation procedure for the seasonal and monthly method, as this is the method used by the UK SBEM calculation procedure.

The calculation methodology includes the calculation of the following:

- Heat transfer by transmission or ventilation when the building is heated or cooled to a constant temperature.
- The contribution of solar or internal heat sources to the building heat balance.
- The annual energy required by the heating and cooling systems of the building for space heating and cooling, using the system characteristics in relevant national or international standards.
- Additional annual energy required by the ventilation system for provision of appropriate air flow rates and pre-heating / pre-cooling of the air.

The methodology states that the boundaries of the building must be established and the building divided into thermal zones where appropriate. The boundary may be the separation between the building and the exterior or between a zone and an adjacent zone at different conditions.

The methodology sets out that zone calculation may be carried out at three different levels [CEN 2005 pp17].

- A single zone calculation
- A multi zone calculation without thermal coupling between zones
- A multi zone calculation with thermal coupling between zones

In the case of a single zone, the internal temperature for heating and cooling are determined based on the average set point temperature in the space [CEN 2005 pp19].

The external environment is quantified by; external air temperature and global solar radiation on the horizontal plane (including the parameters required to convert solar radiation on the horizontal plane into incident solar radiation on the building surfaces). The quantity of data required depends on the calculation procedure adopted i.e. simple hourly, seasonal or monthly method.

The procedure for calculation of the building energy need for space heating and cooling set out in prEN 13790 is as follows [CEN 2005 pp20]:

- Calculation of heat transfer by transmission
- Calculation of heat transfer by ventilation
- Calculation of internal heat sources
- Calculation of solar heat sources
- Calculation of dynamic parameters
- Calculation of building energy need for heating and calculation of building energy need for cooling.

5.12.2 Calculation of heat transfer by transmission

The methodology in prEN 13790 sets out the procedure for calculation of the total heat transfer by transmission as illustrated in Figure 5.14. The total heat transfer by transmission is the product of the transmission heat loss coefficient, temperature difference between zone and adjacent zone/exterior and the calculation period [CEN 2005 pp26].

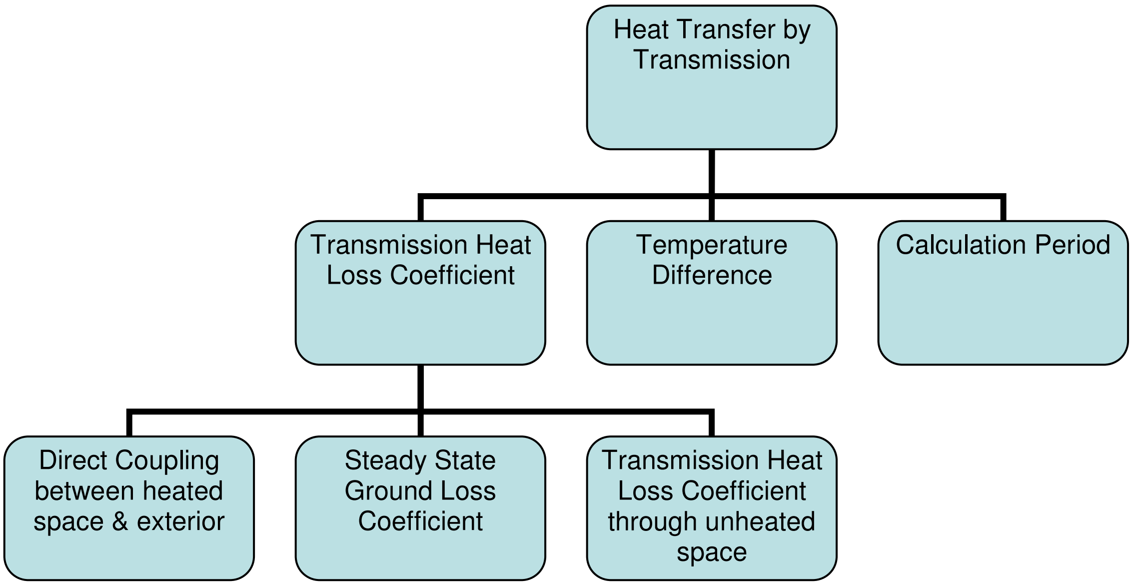

Figure 5.14: Calculation of heat transfer by transmission

Transmission heat loss coefficient

The transmission heat loss coefficient is established using the procedure set out in the European standard transmission heat loss coefficient calculation method, EN 13789. This is the sum of the direct coupling coefficient between the heated space and exterior, the steady state ground heat loss coefficient and the transmission heat loss coefficient through an adjacent unheated space.

The direct coupling coefficient between the heated space and exterior is calculated from the sum of the products of; element area and thermal transmittance, length of thermal bridge and linear thermal transmittance and point thermal transmittance [CEN 1999].

The steady state ground heat loss coefficient is calculated from a procedure set out in the European standard for heat loss calculation through the ground [CEN 1998].

Temperature Difference

The temperature difference is the difference between the internal temperature and the temperature of adjacent space or environment. The internal temperature is based on useful floor area and set point temperature. The external environment temperature is the average hourly or average monthly temperature of the adjacent space or environment.

Calculation period

The calculation period is also dependant on the calculation method adopted i.e. hourly or monthly.

5.12.3 Calculation of heat transfer by ventilation

The methodology sets out the procedure for the calculation of the total heat transfer by ventilation as illustrated in Figure 5.15. The total heat transfer by ventilation is the product of the ventilation heat transfer coefficient, the temperature difference between room air and supply air and the calculation period [CEN 2005 pp30].

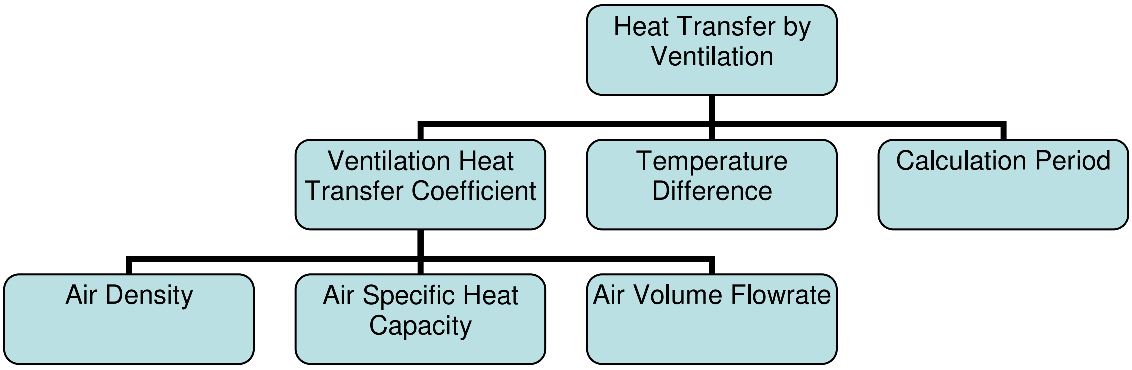

Figure 5.15: Calculation of heat transfer by ventilation

Ventilation heat transfer coefficient

The ventilation heat transfer coefficient is calculated as set out in prEN 13790 [CEN 2005 pp31]. This is the product of the density, specific heat capacity and volume flowrate of the air.

Temperature Difference

The temperature difference is the difference between the internal temperature and the supply air temperature. The supply air temperature of the air flow element entering the building or building zone is dependant on the source of the air i.e. external or from an adjacent space or from a mechanical ventilation system.

5.12.4 Calculation of internal heat sources

The internal gains taken into account by the methodology include heat generated in the space by sources other than the space heating system, cold sources are also included i.e. those with a negative contribution.

The standard sets out the following as internal heat sources [CEN 2005 pp 34]:

- Metabolic heat from occupants
- Dissipated heat from appliances
- Dissipated heat from lighting devices
- Heat dissipated from or absorbed by hot and mains water sewage systems
- Heat dissipated from or absorbed by heating, cooling and ventilation systems
- Heat to or from processes and goods

The methodology sets out the expression to calculate the energy contribution of internal heat sources as the time averaged sum of internal heat sources. Internal heat sources in adjacent spaces are also included in the calculation, reduced by application of a reduction factor defined in EN ISO 13789 [CEN 1999, 2005 pp 35].

In order to establish the energy generated by internal heat sources the heat flow rate in watts from internal heat sources must be established. The expression set out in prEN 13790 is the sum of the aforementioned internal heat sources.

5.12.5 Calculation of solar heat sources

The calculation of total solar heat sources includes the solar heat sources in the zone itself and the solar heat sources from adjacent zones with a reduction factor applied. The solar heat sources are calculated in accordance with the procedures set out in prEN 13790 [CEN 2005 pp 40]. The calculation process is illustrated in Figure 5.16.

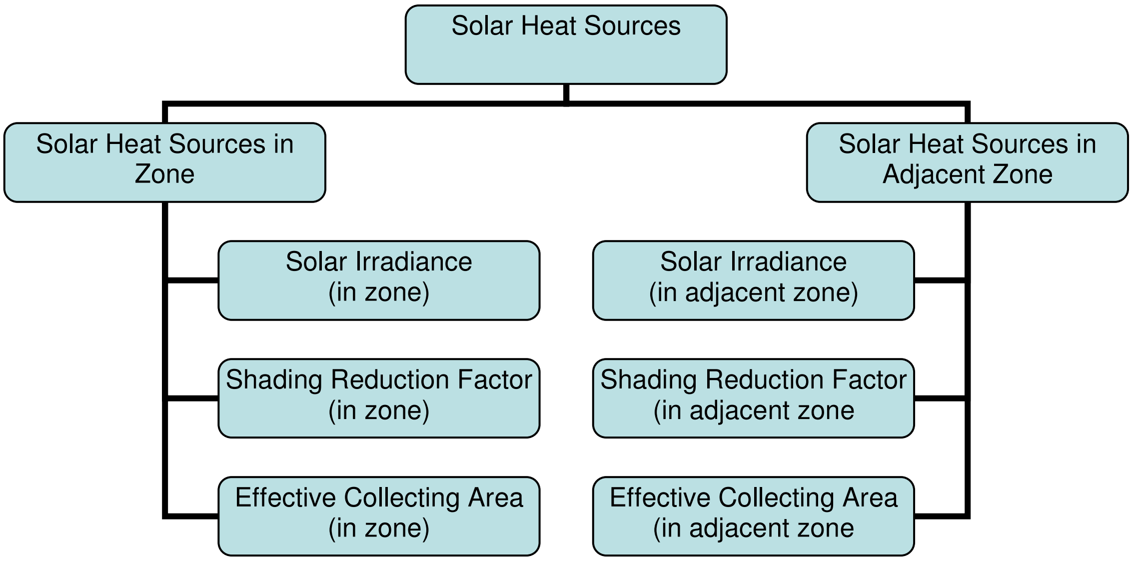

Figure 5.16: Calculation of solar heat sources

The solar irradiance is the total solar energy during the calculation period per m^2 of a surface with a given orientation and tilt angle.

The shading reduction factor is a factor applied for the shading provided by external obstacles.

In order to calculate the effect of solar radiation on a building a procedure is given for the calculation of effective solar collecting areas depending on whether the surface is opaque or glazed. An illustration of the calculation of effective collection area of glazed elements is provided in Figure 5.17.

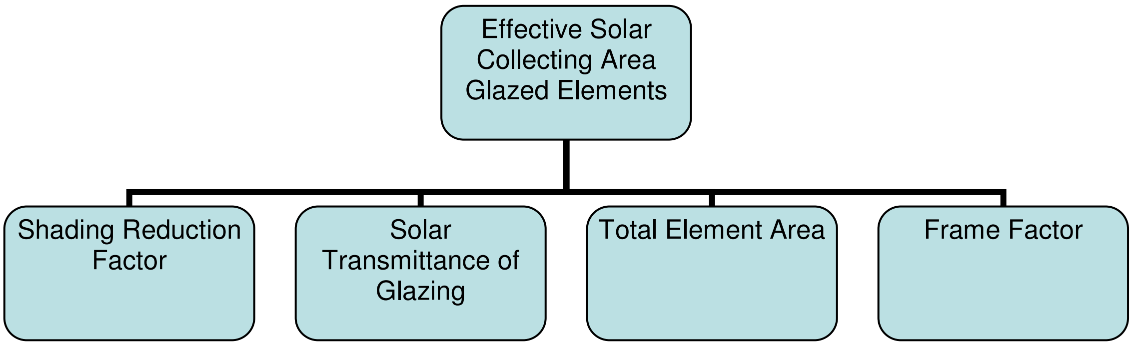

Figure 5.17: Calculation of glazed elements effective solar collecting area

The shading reduction factor is to account for movable shading provisions. The factor is based on the weighted fraction of time with solar shading as a function of the intensity of solar radiation this is given by CEN [2005 pp 43].

The calculation of the solar energy transmittance of glazing is given by EN 13363-2, however for hourly and monthly calculations an averaged value is required, therefore a correction factor is used.

The frame factor is the ratio of transparent surface to opaque surface for the glazing element. The frame factor is applied to the total element area to determine the transparent portion.

An illustration of the calculation of effective collection area of opaque elements is provided in Figure 5.18.

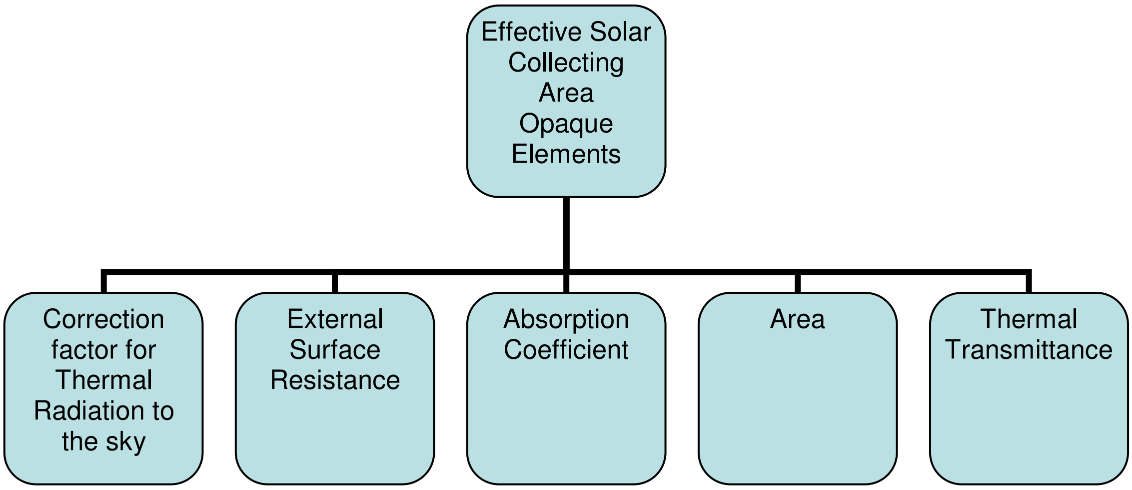

Figure 5.18: Calculation of opaque elements effective solar collecting area

CEN provides an expression [CEN 2006 pp 41] which establishes the collecting area as the product of; a correction factor for thermal radiation to the sky, external surface resistance, an absorption coefficient for solar radiation in the opaque part, the surface area and the thermal transmittance of the opaque element.

The correction factor for thermal radiation to the sky is given in by CEN [2005 pp 42], an illustration is provided in Figure 5.19.

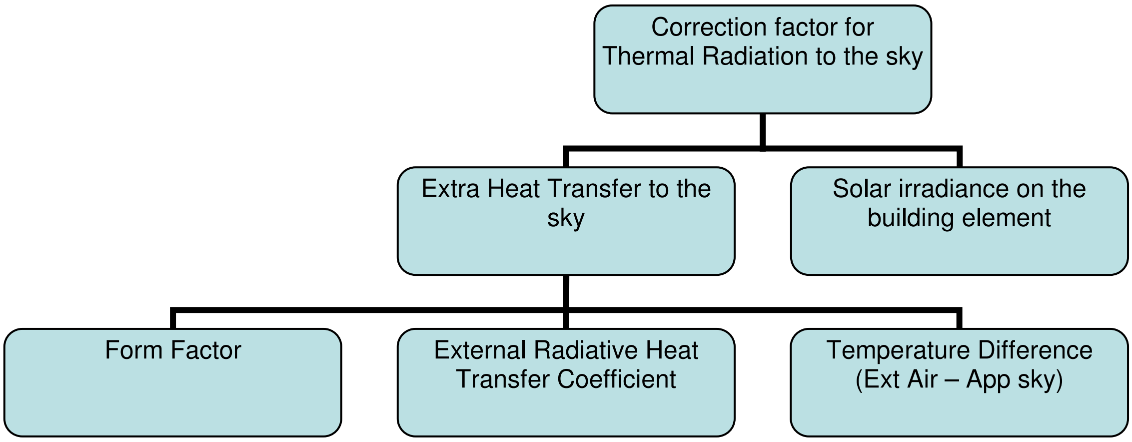

Figure 5.19: Calculation of opaque elements effective solar collecting area

This is a ratio of the solar radiation absorbed to the extra heat transfer by thermal radiation to the sky. The absorbed solar radiation is the product of the solar irradiance on the building element and the absorption coefficient of the surface concerned. The extra heat transfer by thermal radiation to the sky is given by CEN [2006 p 44] as the product of a form factor between the element and the sky, external radiative heat transfer coefficient and the average difference between the external air temperature and apparent sky temperature.

5.12.6 Calculation of Dynamic Parameters

The simply hourly and monthly methods within the methodology use a gain utilization factor for heating and a loss utilization factor for cooling in order to take into account the thermal capacity of the building [CEN 2005 pp45].

The effect of thermal inertia in the case of intermittent heating is taken into account by an adjusted set point temperature to correct the calculated heat need.

Gain utilization factor for heating

The gain utilization factor for heating is given as a ratio of heat losses to heat gains during the heating season and includes the effect of a numerical parameter related to the building time constant (a_H). An illustration is provided in Figure 5.20.

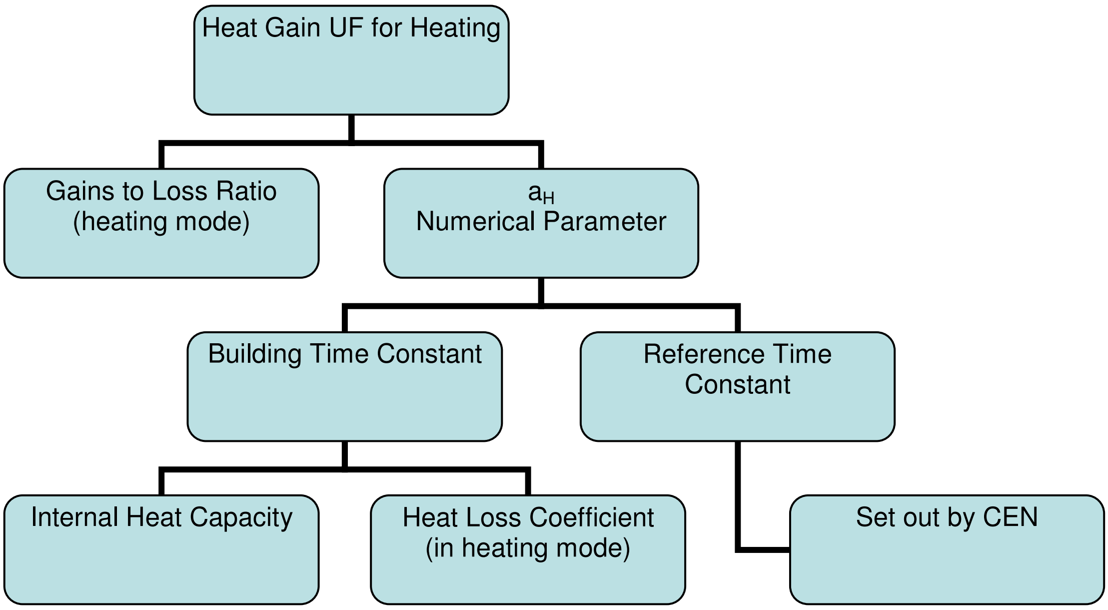

Figure 5.20: Calculation of gain utilization factor for heating

The numerical parameter (a_H) which is a ratio of the building time constant to a reference time constant added to a dimensionless reference parameter ($a_{0,H}$) [CEN 2005 pp46]

The reference time constant and reference parameter are tabulated figures related to the type and use of the building [CEN 2005 pp 46].

The building time constant in heating mode is calculated by dividing the internal heat capacity of the building by the heat loss coefficient of the building in heating mode.

Loss utilization factor for cooling

The loss utilization factor for cooling is given as a ratio of heat loss to heat gains during the cooling periods and includes the effect of a numerical parameter related to the building time constant (a_C) [CEN 2005 pp 47]. An illustration of the process is provided in Figure 5.21.

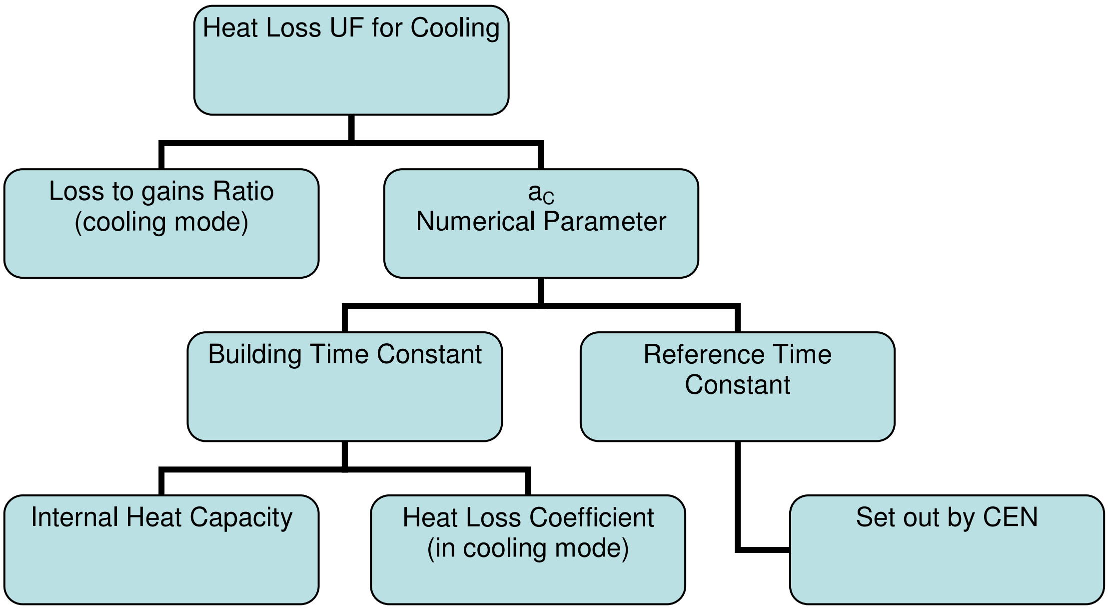

Figure 5.21: Calculation of loss utilization factor for cooling

In cooling mode, the numerical parameter (a_C) is a ratio of the building time constant to a reference time constant added to a dimensionless reference parameter ($a_{0,C}$) [CEN 2005 pp46].

The building time constant in cooling mode is calculated by dividing the internal heat capacity of the building by the heat loss coefficient of the building in cooling mode.

The internal heat capacity of the building calculated for each type of element as the product of; area, density, specific heat capacity and thickness of each layer.

5.12.7 Calculation energy need for space heating and cooling

The calculation of the energy need for space heating and cooling is carried out as a monthly or seasonal calculation per zone.

(i) Space Heating

The monthly or seasonal calculation of the energy need for space heating per zone is calculated as the product of the gains utilization factor and total heat sources subtracted from the total heat transfer in heating mode.

(ii) Cooling

The monthly or seasonal calculation of the energy need for cooling per zone is calculated as the product of the loss utilization factor and the total heat transfer in cooling mode subtracted from the total heat sources in cooling mode.

The total heat transfer in heating mode or cooling mode is given by the sum of the transmission and ventilation heat transfer from the building or zone [CEN 2005 pp 22].

(ii) Total Heat Sources

The total heat sources in heating mode or cooling mode are the sum of the internal heat sources and solar heat sources over the given period [CEN 2005 pp23].

Control Corrections for Intermittent Heating

For the calculation of the heating energy use using intermittent heating, prEN13790 uses an equivalent internal temperature instead of a set point temperature to take into account alternating or reduced heating periods [CEN

2005 pp 51]. The methodology uses three relevant modes of intermittency, as follows [CEN 2005 pp 52]:

(O) Where set point temperature variations between normal and reduced heating periods are less than 3K. In this case a time averaged set point temperature may be used.

(A) Where the time constant of the building is greater than 3 times the duration of the longest reduced period. In this case the normal set point temperature may be used for all cases.

(B) Where the time constant is less than 0.2 times the duration of the shortest reduced heating period. In this case time averaged set point temperatures may be used

Control Corrections for Intermittent Cooling

prEN 13790 states that the basis for the intermittency correction for the monthly cooling calculation is that a thermostat set back or switch off will have a smaller effect on the energy need for cooling than for heating due to diurnal variations in weather and the effect of the thermal inertia of the building [CEN 2005 pp 53].

The expression given in prEN 13790 for the energy need for cooling with intermittent cooling [CEN 2005 pp53] takes into account the energy need for cooling for the normal cooling period, the energy need for cooling for the intermittency period and a correction factor for intermittent cooling, based on the building time constant for the cooling mode and the loss/gain ratio for the building in cooling mode.

The annual energy need for space heating and cooling for the given building or building zone is calculated by summing the energy need per period [CEN 2005 pp55].

5.12.8 Calculation of Building Delivered Energy

Regarding the total system energy use, prEN 13790 prescribes the calculation for the annual system energy use for heating and annual system energy use for cooling including system losses [CEN 2005 pp 56]. The methodology specifies three possible methods of calculation:

Option (a)

Total energy use of the heating system and cooling system per energy carrier.

Option (b)

As energy loss and auxiliary energy of the system, i.e. heating system loss and auxiliary heating, cooling system loss and auxiliary cooling. The methodology states that these losses and auxiliary energy comprise of the generation, transport, control, storage and emission.

Option (c)

The system heat losses indicated by an overall system efficiency, where the energy use for the heating including system losses is calculated by dividing the building energy need for heating by the overall system efficiency for the heating system or where the energy use for the cooling system including system losses is calculated by dividing the building energy need for cooling by an overall system efficiency for the heating or cooling system.

The methodology states that the system efficiency for the heating and cooling system includes generation, electronics, storage, distribution and emission losses [CEN 2005 pp 56].

5.13 COMPARISON OF CALCULATION METHODOLOGIES

In order to compare both methodologies for the calculation of the energy performance of buildings, an analysis may be performed under the following headings:

- Internal environment
- External environment
- Heat transfer by transmission
- Heat transfer by ventilation
- Internal heat gains
- Solar heat gains
- Dynamic parameters
- Control

5.13.1 Internal Environment

In the IES calculation methodology, each zone in a building may be assigned a heating and a cooling setpoint temperature and relative humidity or alternatively, dynamic simulation can establish internal conditions and comfort criteria achieved during a heating or cooling cycle.

However in the CEN methodology, the design internal temperatures in heating or cooling mode are calculated based on the relationship between the setpoint temperature and the useful floor area, the SBEM calculation has opted to use generic setpoint temperatures for specific types of space in specific types of building, as a result the user does not have control of the chosen setpoint temperature or relative humidity for the space.

5.13.2 External Environment

In order to simulate the external environment, the IES calculation methodology uses a real time weather data for the particular geographical location. However, depending on the CEN calculation procedure used, hourly climatic data, monthly or seasonal average weather data may be used. The SBEM procedure has chosen to use standard data for 3 UK locations, this does have an effect on the accuracy of the calculation and also may underestimate or overestimate the use of energy saving devices on the building.

5.13.3 Heat Transfer by Transmission

In both calculation methodologies transmission heat transfer is dealt with differently. In the CEN methodology a specific calculation is carried out for heat transfer by transmission. In the IES calculation methodology, calculations are carried out which simultaneously deal with heat transfer heat storage and heat diffusion. In order to have a more pragmatic comparison, heat transfer by transmission may be analysed under the following headings:

- Conduction heat transfer
- Convection heart transfer
- Radiation heat transfer

Conduction heat transfer

Heat transfer by conduction is dealt with dynamically in the IES calculation methodology, by partial differential equations. Temperature and heat flow at nodes in each fabric element are solved using a finite differencing approach. Whereas conduction is modelled using the fabric elements' conductivities in the CEN methodology, to yield the thermal transmission coefficient and ultimately the transmission heat transfer coefficient.

Convection heat transfer

In the IES calculation methodology various internal and external convection coefficients may be used, some of which are time and temperature varying, this calculation is carried out as an iterative process.

In the CEN methodology and SBEM calculation fixed internal and external convection coefficients area used.

Radiation Heat Transfer (Long Wave Radiation)

In the IES calculation methodology long wave radiation emission and absorption are both considered as is the radiant fraction of internal (casual) heat gains.

In the CEN methodology and SBEM calculation, internal and external surface resistances included in the thermal transmission coefficient together with an absorption coefficient take account of radiation properties.

Heat Storage

In the IES calculation methodology, heat storage and nodal temperature distribution are considered in the partial differential equations, which simultaneously solve the heat transfer, heat diffusion and heat storage properties of fabric elements.

In the CEN calculation methodology heat storage in fabric elements is taken into account of by the building time constant and the thermal capacity of fabric elements based on their thickness, density and specific heat capacity.

5.13.4 Heat Transfer by Ventilation

The heat transfer associated with air masses entering or leaving the space is quantified based on the mass flow rate, specific heat capacity and supply air temperature in both cases. The CEN calculation methodology deals primarily with the heat lost or gained by ventilation with the supply air temperature as a fixed value depending on the time step of the calculation and the geographical position. However the IES calculation methodology also takes account of the heat storage properties of air masses, the supply air temperature is associated with the geographical position and varies with time. In addition, IES has the ability to analyse fixed air changes, dynamic natural ventilation and dynamic mechanical ventilation. The volume of air entering the space and associated temperatures of the space and entering air can be established using IES based on buoyancy and wind driving forces.

In terms of convection coefficients, IES uses exterior convection coefficients that vary with wind speed and various internal convection coefficients may be used that vary with air speed and temperature, the calculation is therefore carried out as an iterative process, in comparison, convection coefficients used in the CEN methodology are fixed.

5.13.5 Internal Heat Sources

The CEN calculation methodologies use the sum of the casual sensible heat gains in the space in order to quantify the internal heat sources, which may be scheduled against time. However in IES, latent heat gains are also considered and sensible gains are broken down into their convective and radiative components, as a result an elements long wave emissions, absorptions, re emissions and re absorptions are all considered in an iterative process.

5.13.6 Solar Heat Sources

Solar radiation in IES is divided into three components, direct, diffuse and scattered solar radiation. The magnitude of the direct solar radiation is established using the real time weather data associated with the geographical area. The solar altitude and azimuth are used to calculate an angle of incidence to calculate the solar irradiation on the building surfaces.
The solar irradiation absorbed and reflected from the opaque building surfaces' are quantified using a standard absorption coefficient, the reflected portion is later considered as scattered radiation.

The solar irradiation incident on transparent building surfaces' transmission, absorption and reflection are quantified using the glazing elements thermal properties. The transmitted solar radiation goes through a number of iterations until all elements have been absorbed or left the space.

However in the CEN calculation methodology the magnitude of the solar irradiation incident on the collecting surface is based on standard data, the time step is dependant again on the calculation time step. The quantity of solar radiation absorbed by opaque elements is considered, again, using a standard absorption coefficient. The solar radiation transmitted, absorbed and reflected depends on the transparent elements' thermal properties. The CEN calculation, however, is primarily concerned with the portion transmitted to the space. Both methodologies allow external fixed or moveable shading to be modelled, however IES models the path of the sun and calculates the solar radiation emitted to the space using shading, the CEN methodology uses only a correction factor.

5.13.7 Dynamic Parameters

IES is a dynamic thermal simulation program, calculation of transmission, ventilation, solar and internal heat transfer all consider the prevailing outside conditions as they vary against time and their effect on conditions inside the building against time, after buffers such as the building envelope are considered. However, the CEN calculation methodology is not a dynamic process, as stated in prEN 13790, it may be described as a quasi-steady state method. Therefore the effect of some of the dynamic properties of the building are taken into account. As stated previously gain and loss utilization factors are employed for this process. As stated in the previous sections, the utilization factor is determined using a building time constant based on the internal heat capacity of the building. So although the calculation is not dynamic, it does try to establish the heat storage available in a building, although the calculated building time constant is related to a reference time constant depending on the type of building.

5.13.8 Control

In the IES calculation methodology, plant and system control can be idealised of profiled against time. In the CEN calculation methodology, control is modelled as a change in set point temperature, in order to model intermittent heating / cooling or heating / cooling with a reduced set back temperature. The cooling control correction does include the building time constant in order to account for the effect of the thermal inertia in it's' response.

CHAPTER 6: DISCUSSION OF FINDINGS

6.1 MODELLING OF THE BUILDING

The application of the dynamic calculation methodology, IES<VE> to the building was applied with relative ease due to the program user interface and the graphical representation of the building. The number of input parameters required by IES <VE> is significant. This is necessary to ensure accuracy but is a potential source of error and involves considerable time input. The results produced by IES<VE> can be interpreted on a room, zone, building, energy flowpath or comfort basis.

The application of the quasi-steady state methodology, SBEM to the building, was applied with difficulty. SBEM has the ability to function as a design tool but does not do so easily, due to the lack of a graphical user interface and graphical representation of the building. The limited input parameters required by SBEM provided a reduction in both the time requirement for a calculation and the potential for error. The results produced by SBEM do not allow interrogation of heating or cooling requirements on a room or zone basis, also it was not possible to gain data on comfort conditions. Inputting similar constructional information in both tools was also difficult; Karlsson et al [2007] reported similar findings.

6.2 HEATING AND COOLING PLANT SIZE

The comparison of the calculation of heating and cooling plant size illustrated the accuracy provided by a dynamic method in comparison to a steady state method. The dynamically calculated plant size takes account of the external fluctuations and the integrated response of the building, whereas the steady state method only considers static conditions.

6.3 APPLICATION OF NATURAL VENTILATION

The application of natural ventilation to the dynamic method as an *early design step* reduced annual energy consumption and CO_2 emissions significantly. The buildings' requirement for mechanically cooled rooms reduced by 14% which was reflected in plant size reduction of 10% and annual cooling energy consumption and CO_2 emission reduction of 38.2%.

This process allowed the application of a mixed mode solution. In this case, the buildings' requirement for mechanically cooled rooms reduced by 41%. This was reflected in a reduction in annual cooling energy consumption and CO_2 emission reduction of 66%.

These reductions in annual energy consumption and CO_2 emissions were achieved due to the ability to analyse each room's requirement for mechanical ventilation and cooling. The quasi-steady state methodology could not carry out this function as optimum ventilation rates in each zone are assumed.

6.4 INVESTIGATION OF DESIGN CHANGES

It was established that a dynamic methodology has the ability to investigate a number of key aspects of a building in terms of energy performance. The effect of the design changes to achieve a reduction in operative temperature and solar gain in individual spaces was investigated. Using this process, the solar absorptive glazing design option performed best. However, it was observed that as the operative temperature in a space reduced, there was a corresponding increase in heating load, resulting in an overall increase in annual energy consumption but a net overall reduction in CO_2 emissions. This illustrates that the effect of a particular design option on overall annual energy consumption is not fully representative. It is necessary to have the ability to interrogate the results for a building in order to achieve the optimum solution.

It was established that the quasi-steady state methodology has the ability to investigate a number of key parameters of a buildings design in order to achieve an improvement in annual energy performance. Although an overall heating or cooling energy consumption result was obtained for each case, it was not possible to investigate the effect of the variation of solar gain and operative temperature in individual spaces.

The sensitivity of both the dynamic and quasi-steady state methodology was compared to variation of design parameters and their effect in terms of the annual energy performance calculation. Both generated results in range of what would be expected for the respective design options. IES <VE> was more sensitive to the design changes in most cases. Solar shading was the only parameter to show a similar improvement in both methodologies with a 0.5 % difference in heating and 7.5% difference in cooling. This was unusual as different methods are used in both methodologies to model solar shading.

There was a large difference between both methodologies sensitivity terms of cooling energy consumption, but the sensitivity of design changes reflected in heating energy consumption were within closer range. The change in thermal capacity had the largest disparity across both methodologies. This indicates difficulty with storage and attenuation of heat gains. Similar findings were reported by Roulet [2007] and Corrado et al [2002] in terms of difficulty with dynamic parameters.

The magnitude of the improvement was greater in IES <VE>, from which one could state that SBEM understates the advantageous or disadvantageous effect of a particular optimisation to reduce energy consumption. The design option with the greatest improvement was the same as that found by the dynamic methodology.

6.5 INVESTIGATION OF CALCULATION METHODS

The difference in the ability of a dynamic and a quasi-steady state methodology to reward energy saving measures was established by investigation of the underlying calculation process. Significant differences exist between algorithms in both calculation methodologies, as would be expected between a dynamic methodology and a methodology based on a monthly heat balance.

The dynamic calculation methodology yields more credible results and act as a useful design tool in order to arrive at the best possible solution for a building. The quasi-steady state methodology is useful as a compliance tool but it does not fully represent some of the energy saving devices that may be employed in buildings. Significant improvements were employed in the case study building in order to arrive at a mixed mode building with solar absorptive glazing. The quasi-steady state methodology was not able to model such a solution.

CHAPTER 7: CONCLUSION

The main objectives of this research were to:

- To establish the ability of currently used calculation methodologies to capture the requirements of a calculation methodology as set out in Article 3 of the EPBD.
- To compare the ability of both a dynamic and quasi-steady state calculation methodology to capture the effects of variation of key parameters of a buildings design.
- To quantify the difference in the ability of a dynamic and simplified methodology to reward energy saving measures, by investigation of the underlying calculation process.

This research has established the ability of a range of dynamic simulation programs, EU projects and simplified simulation programs to calculate annual energy performance under the requirements of the EPBD framework. IES<VE> was found to be the most appropriate dynamic simulation program. It was also demonstrated that different dynamic thermal simulation programs provide better analysis over certain specific areas; similar findings were proposed by Crawley et al [2005]. The quasi-steady state methodology SBEM was found to be the most appropriate simplified simulation program.

The ability of a dynamic methodology (IES <VE>) and a quasi-steady state methodology (SBEM) to capture the effects of design changes was established by a parametric sensitivity analysis. Both programs illustrated a capability to investigate the key parameters but application and interrogation of results were facilitated with greater ease in IES <VE>. Both programs generated an improvement in annual energy performance and rewarded the same design changes as the greatest improvement although IES <VE> rewarded improvement with greater magnitude. The ability within IES <VE> to interrogate operative temperature, heating loads and cooling loads at peak times in individual rooms provided the ability to achieve a substantial reduction in annual energy performance.

The findings illustrate that although it is possible to use SBEM as a design tool at the early stages in order to predict annual energy consumption and to investigate design improvements, there are limitations in its application. Also, a particular disadvantage of SBEM is the absence of a graphical representation of the building and an inability to interrogate results for individual rooms.

The difference in the ability of both the dynamic and quasi-steady state methodologies to reward energy saving measures was established by investigation of the underlying calculation process.

Differences in generated results were as a result of differences in calculation procedure. Particular differences were noted in terms of the following:

- Calculation time steps
- External and Internal conditions
- Transmission heat transfer
- Storage of heat in fabric elements

- Ventilation heat transfer
- Internal and solar heat gains
- System control

The main findings of this research are as follows:
The energy performance of a building depends on the integrated performance of both, building fabric and systems. Calculation of the energy performance capabilities of such integrated systems requires the application of an integrated calculation methodology.

A quasi-steady state methodology such as SBEM has the ability to investigate the energy performance of simple buildings i.e. those provided with heating only, mechanical ventilation and simple cooling systems. The use of a heat gain and heat loss utilization factor, although not an accurate method of modelling in the true sense of simulation, captures the effects of thermal mass and its effects on heating and cooling systems.

A dynamic methodology, such as IES <VE> has the capability to assess the energy performance of even the most complex building types, particularly those optimised to use passive measures. In this case the ability to accurately calculate natural ventilation, thermal mass and control is of paramount importance. However the data input required for such calculations is onerous in terms of the time input and the many variables and coefficients that may be chosen.

The optimum solution is a dynamic methodology with a constrained data set utilising default convection coefficients, internal conditions and external environments. This would provide transparency and repeatability to while still allowing the user to investigate the resultant internal conditions in the space.

7.1 FURTHER WORK

This research has identified the following areas of future research.

A benchmarking study of non residential building stock in Ireland

There is a distinct lack of information on building energy benchmarks applicable to Ireland, and hence significant scope for a benchmarking and indexing project for the non residential building stock.

A review of buildings in use in Ireland

There is significant scope for research on the comfort conditions, plant size and operational energy performance of Irish non residential building stock.

The integration of a constrained data dynamic thermal simulation program interface model into a building services practice

The uptake by Irish practitioners of dynamic thermal simulation, although growing, is minimal. There is scope for research and development of a dynamic thermal simulation program interface to enable easier data input and monitoring the effectiveness of such a tool in practice.

The impact of the EPBD on domestic building performance

As the requirement for energy certification of buildings is new, there is significant scope for research on the impact of the implementation of the EPBD on building energy consumption across all sectors of buildings.

The effect if variation of parameters such as internal and external convection coefficient on the calculation of energy performance

As dynamic thermal simulation programs offer a wide range of variables and coefficients for a particular simulation, there is scope for research on the effect of these parameters on the calculation of annual energy performance.

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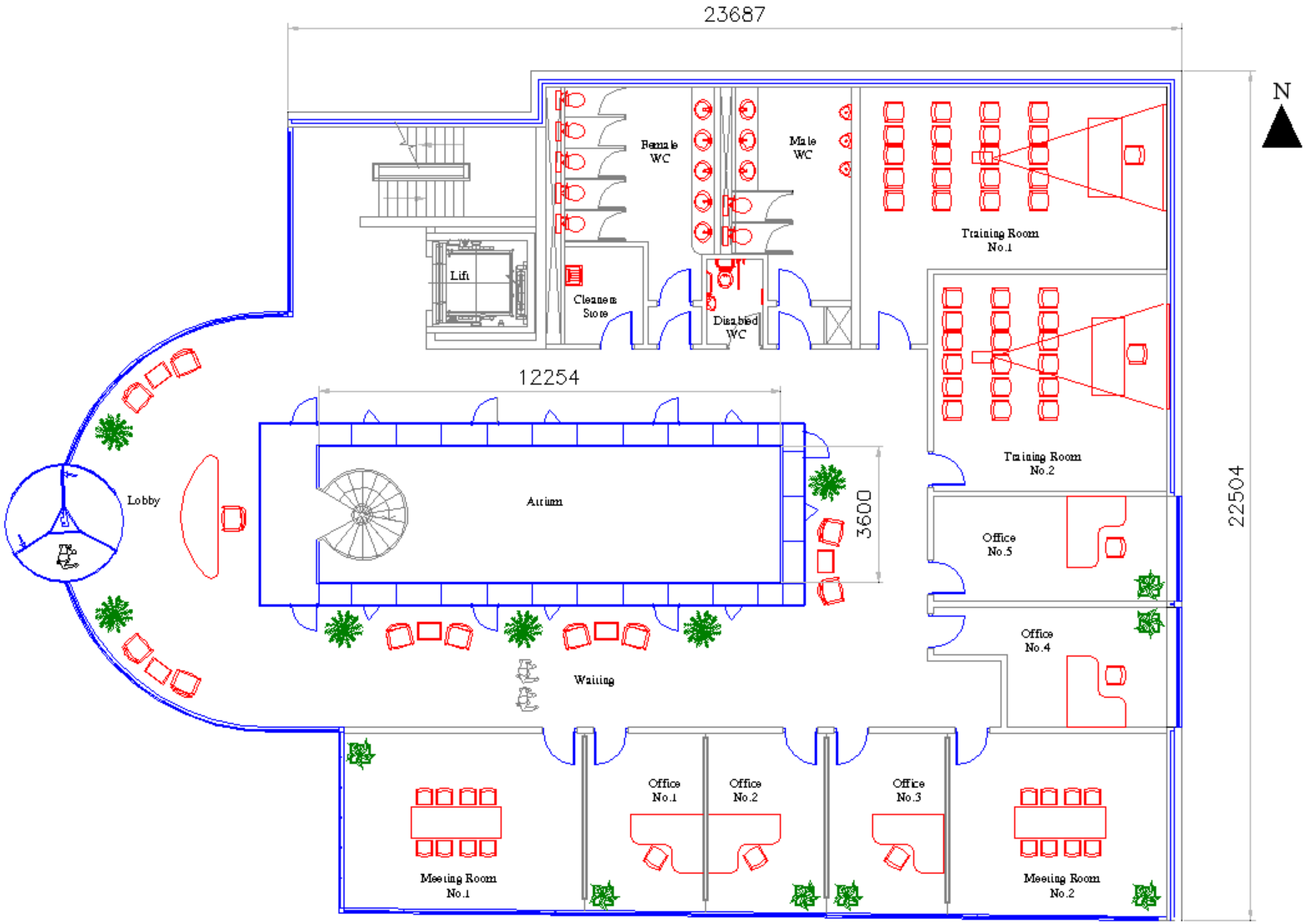
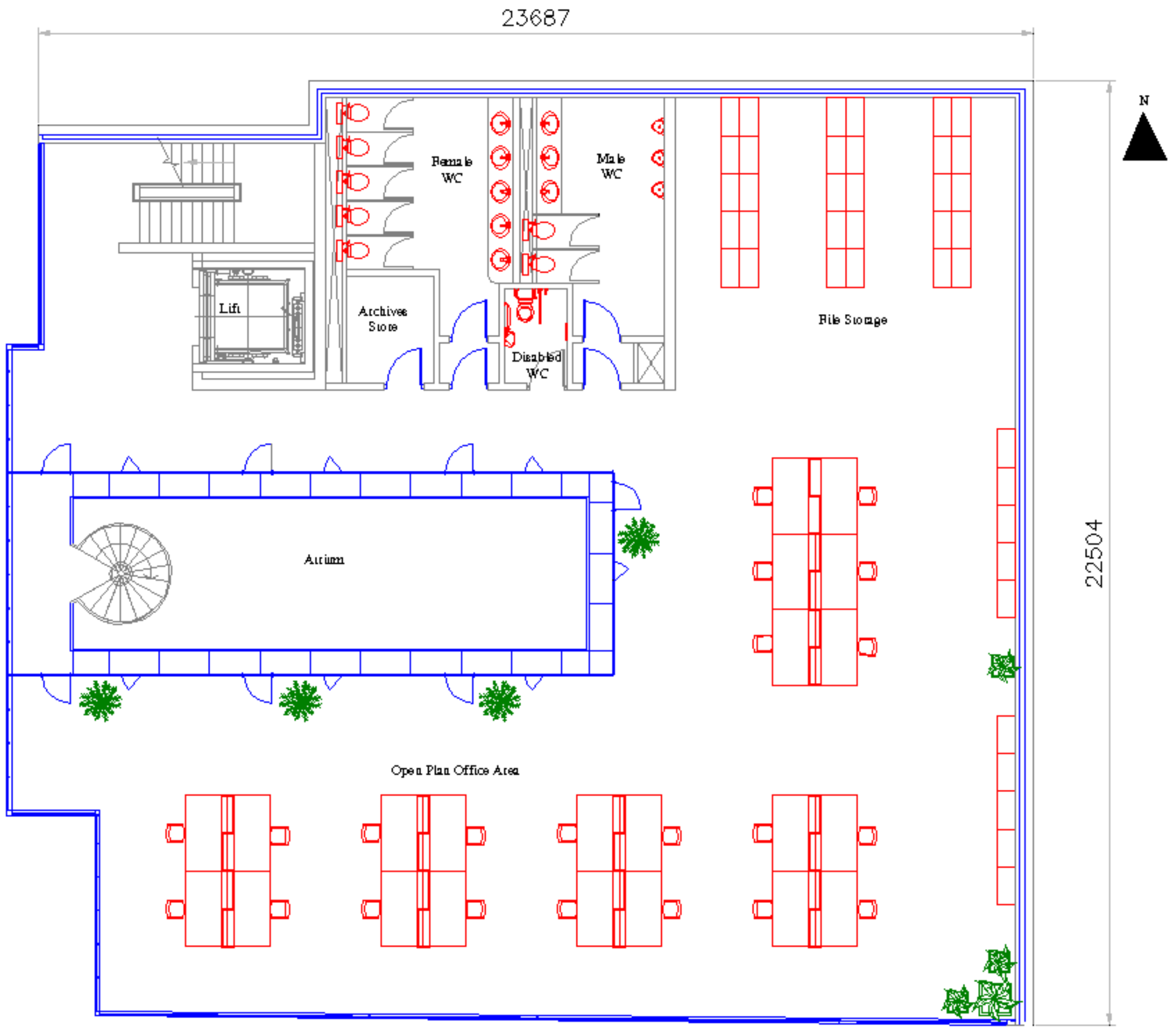
APPENDICES

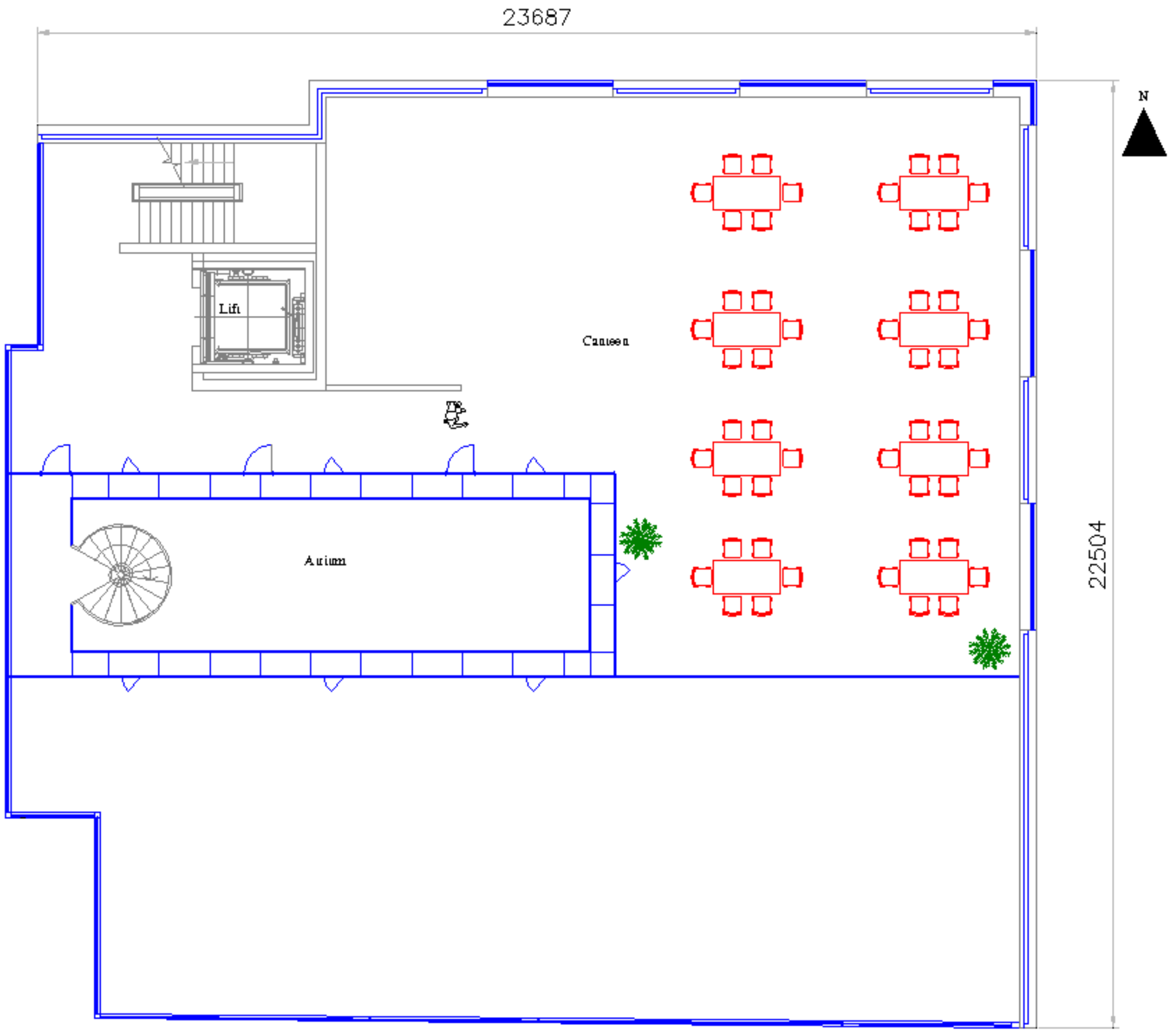
Appendix A Standard Office Building Layout



Ground Floor


23687
22504
N
Female WC
Male WC
File Storage
Lift
Archives Store
Disabled WC
Atrium
Open Plan Office Area

First Floor



Second Floor

Appendix B Standard office building thermal properties

This appendix contains the thermal properties of the base case standard office building modelled in IES <VE>

Element	Description	Makeup
External Wall	Type 1 Brick- Block Cavity Wall	200mm Brick 100mm Air Gap 70mm Insulation 100mm Conc. Block 13mm Plasterboard
Exposed Roof	Flat Roof 2002 Regs.	10mm Stone Chippings, 5mm Felt Bitumen, 150mm Cast Concrete, 135mm GF Insulation 100mm Air Gap 10mm Ceiling Tiles
Ground Floor	Standard Floor Construction 2002 Regs	750mmClay Brickwork 250mm Cast Concrete 100mm EPS Insulation 25mm Chipboard 10mm Carpet
Internal Partitions	Type 2 Plaster, Air Gap, Plaster	13mm Plasterboard 100mm Air gap 13mm Plasterboard
Ceilings	Type 1 False Ceiling with floor above	20mm Carpet 20mm Fibreboard 200mm Air gap 150mm Cast Concrete 300mm Air gap 15mm Ceiling Tiles
Internal Floors	Type 1 False Ceiling with floor above	20mm Carpet 20mm Fibreboard 200mm Air gap 150mm Cast Concrete 300mm Air gap 15mm Ceiling Tiles
Glazing	Type 2 Double Clear Float Glazing	4mm Clear Float Air gap 6mm Clear Float

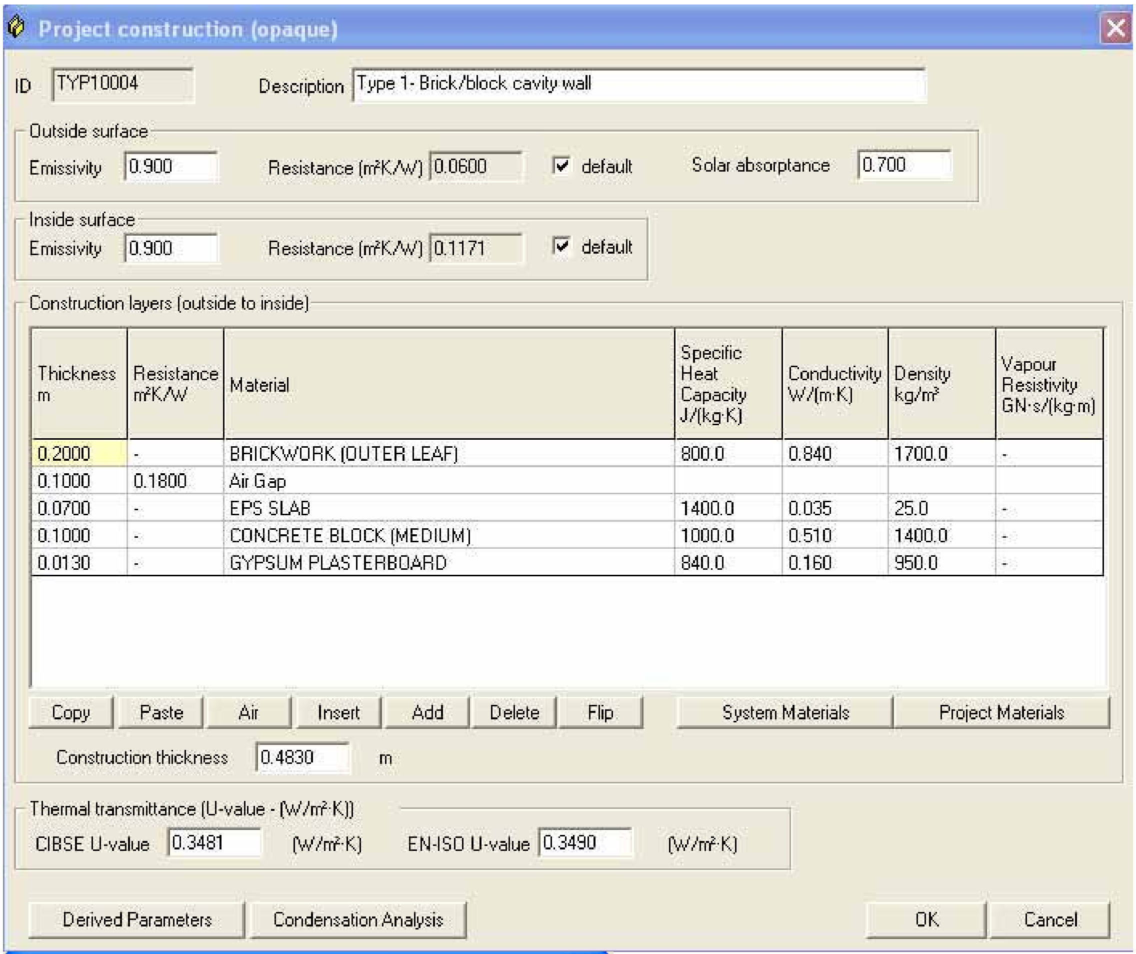
Table B.1: Base Case Element Description and Makeup

Element	U-Value	Admittance	Admittance time lead	Decrement factor	Decrement factor time lag
	W/m²·K	**W/m²·K**	**Hrs**	**m²K/W**	**11.000**
External Wall	0.3481	3.6805	1.56	0.121	1.000
Exposed Roof	0.2479	0.3885	3.03	0.382	7.000
Ground Floor	0.2470	2.1622	2.74	0.000	11.000
Internal Partitions	1.7341	1.8347	0.95	0.993	1.000
Ceilings / Internal Floors	0.6113	1.6969	0.69	0.133	8.000

Table B.2: Base Case Opaque Elements Thermal Properties

Element	CIBSE net U-value	Short-wave shading coefficient	Long-wave shading coefficient	Total shading coefficient
	W/m²·K	**W/m²·K**	**W/m²·K**	**W/m²·K**
Double clear float glazing	2.80050	0.73879	0.11795	0.85675

Table B.3: Base Case Glazed Elements Thermal Properties



ID TYP10004 Description Type 1- Brick/block cavity wall

Outside surface
Emissivity 0.900 Resistance (m^{2}K/W) 0.0600 ☑ default Solar absorptance 0.700

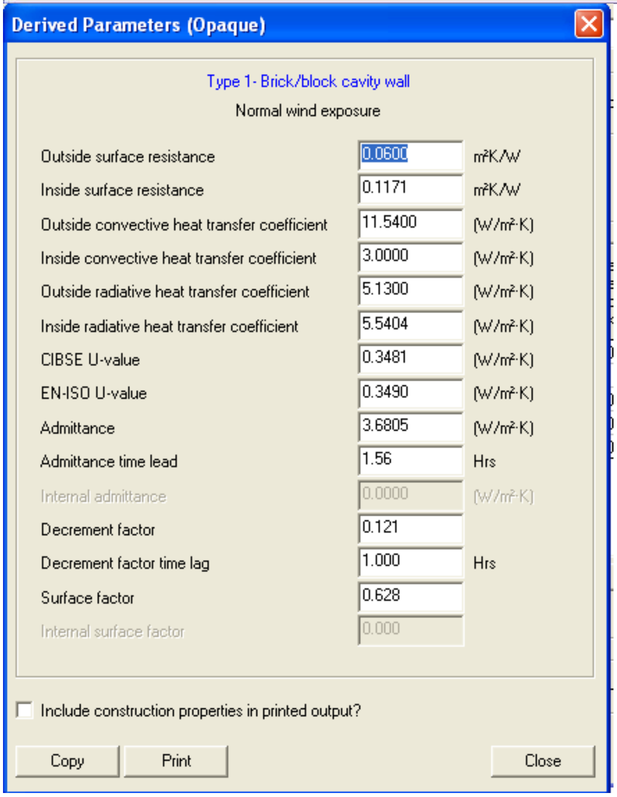
Inside surface
Emissivity 0.900 Resistance (m^{2}K/W) 0.1171 ☑ default

Construction layers (outside to inside)

Thickness m	Resistance m^{2}K/W	Material	Specific Heat Capacity J/(kg·K)	Conductivity W/(m·K)	Density kg/m^3	Vapour Resistivity GN·s/(kg·m)
0.2000	-	BRICKWORK (OUTER LEAF)	800.0	0.840	1700.0	-
0.1000	0.1800	Air Gap				
0.0700	-	EPS SLAB	1400.0	0.035	25.0	-
0.1000	-	CONCRETE BLOCK (MEDIUM)	1000.0	0.510	1400.0	-
0.0130	-	GYPSUM PLASTERBOARD	840.0	0.160	950.0	-

Construction thickness 0.4830 m

Thermal transmittance (U-value - (W/m^2·K))
CIBSE U-value 0.3481 (W/m^2·K) EN-ISO U-value 0.3490 (W/m^2·K)

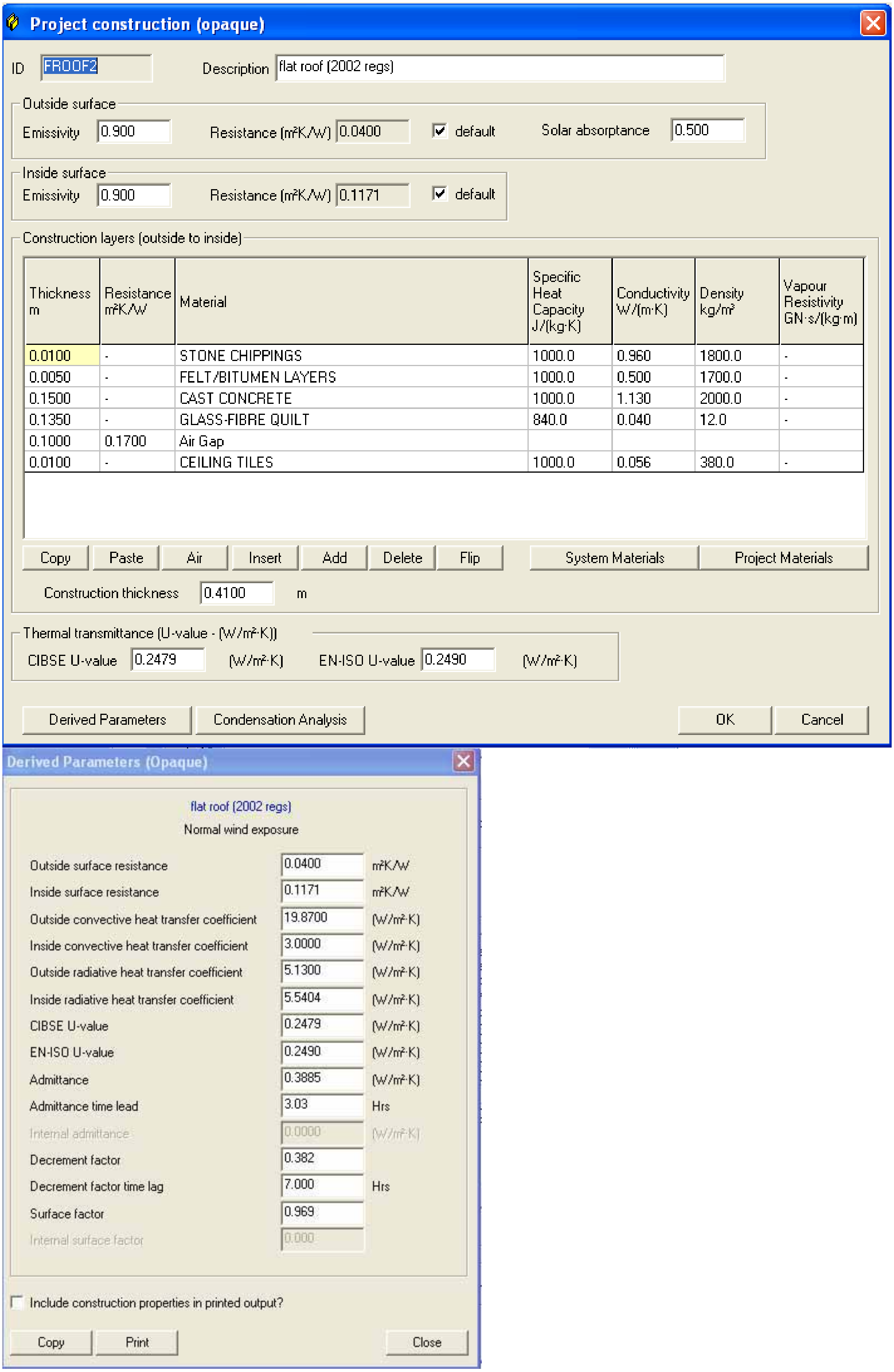


Type 1- Brick/block cavity wall
Normal wind exposure

Outside surface resistance	0.0600	m^{2}K/W
Inside surface resistance	0.1171	m^{2}K/W
Outside convective heat transfer coefficient	11.5400	(W/m^2·K)
Inside convective heat transfer coefficient	3.0000	(W/m^2·K)
Outside radiative heat transfer coefficient	5.1300	(W/m^2·K)
Inside radiative heat transfer coefficient	5.5404	(W/m^2·K)
CIBSE U-value	0.3481	(W/m^2·K)
EN-ISO U-value	0.3490	(W/m^2·K)
Admittance	3.6805	(W/m^2·K)
Admittance time lead	1.56	Hrs
Internal admittance	0.0000	(W/m^2·K)
Decrement factor	0.121	
Decrement factor time lag	1.000	Hrs
Surface factor	0.628	
Internal surface factor	0.000	

☐ Include construction properties in printed output?

Figure B.1: Base Case external wall properties



Project construction (opaque)

ID FROOF2

Description flat roof (2002 regs)

Outside surface

Emissivity 0.900 Resistance (m²K/W) 0.0400 ☑ default Solar absorptance 0.500

Inside surface

Emissivity 0.900 Resistance (m²K/W) 0.1171 ☑ default

Construction layers (outside to inside)

Thickness m	Resistance m²K/W	Material	Specific Heat Capacity J/(kg·K)	Conductivity W/(m·K)	Density kg/m³	Vapour Resistivity GN·s/(kg·m)
0.0100	-	STONE CHIPPINGS	1000.0	0.960	1800.0	-
0.0050	-	FELT/BITUMEN LAYERS	1000.0	0.500	1700.0	-
0.1500	-	CAST CONCRETE	1000.0	1.130	2000.0	-
0.1350	-	GLASS-FIBRE QUILT	840.0	0.040	12.0	-
0.1000	0.1700	Air Gap				
0.0100	-	CEILING TILES	1000.0	0.056	380.0	-

Construction thickness 0.4100 m

Thermal transmittance (U-value - (W/m²·K))

CIBSE U-value 0.2479 (W/m²·K) EN-ISO U-value 0.2490 (W/m²·K)

Derived Parameters (Opaque)

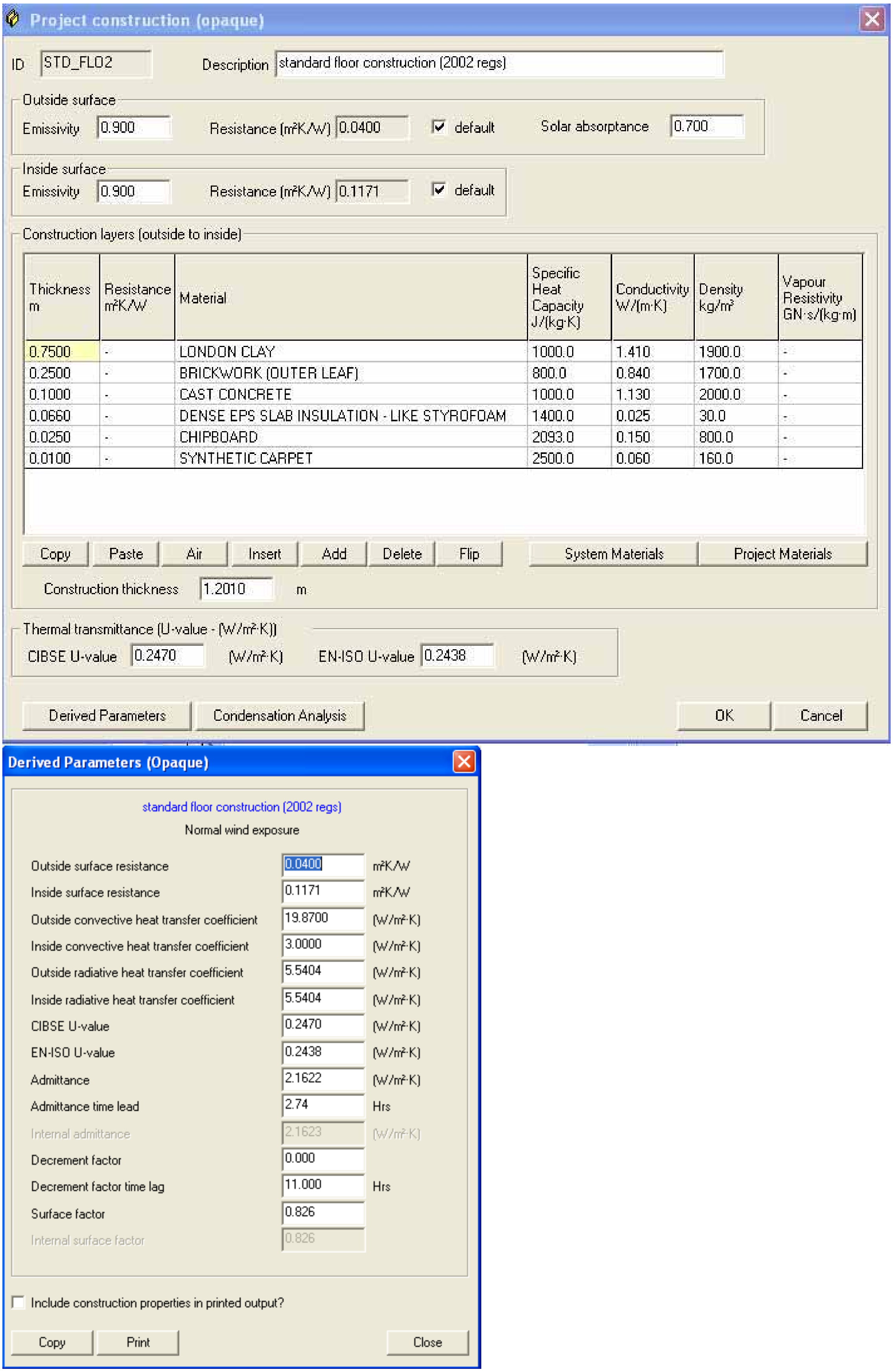
flat roof (2002 regs)

Normal wind exposure

Outside surface resistance	0.0400	m²K/W
Inside surface resistance	0.1171	m²K/W
Outside convective heat transfer coefficient	19.8700	(W/m²·K)
Inside convective heat transfer coefficient	3.0000	(W/m²·K)
Outside radiative heat transfer coefficient	5.1300	(W/m²·K)
Inside radiative heat transfer coefficient	5.5404	(W/m²·K)
CIBSE U-value	0.2479	(W/m²·K)
EN-ISO U-value	0.2490	(W/m²·K)
Admittance	0.3885	(W/m²·K)
Admittance time lead	3.03	Hrs
Internal admittance	0.0000	(W/m²·K)
Decrement factor	0.382	
Decrement factor time lag	7.000	Hrs
Surface factor	0.969	
Internal surface factor	0.000	

☐ Include construction properties in printed output?

Figure B.2 Base Case roof properties



ID STD_FLO2

Description standard floor construction (2002 regs)

Outside surface

Emissivity 0.900

Resistance (m²K/W) 0.0400 ☑ default

Solar absorptance 0.700

Inside surface

Emissivity 0.900

Resistance (m²K/W) 0.1171 ☑ default

Construction layers (outside to inside)

Thickness m	Resistance m²K/W	Material	Specific Heat Capacity J/(kg·K)	Conductivity W/(m·K)	Density kg/m³	Vapour Resistivity GN·s/(kg·m)
0.7500	-	LONDON CLAY	1000.0	1.410	1900.0	-
0.2500	-	BRICKWORK (OUTER LEAF)	800.0	0.840	1700.0	-
0.1000	-	CAST CONCRETE	1000.0	1.130	2000.0	-
0.0660	-	DENSE EPS SLAB INSULATION - LIKE STYROFOAM	1400.0	0.025	30.0	-
0.0250	-	CHIPBOARD	2093.0	0.150	800.0	-
0.0100	-	SYNTHETIC CARPET	2500.0	0.060	160.0	-

Construction thickness 1.2010 m

Thermal transmittance (U-value - (W/m²·K))

CIBSE U-value 0.2470 (W/m²·K)

EN-ISO U-value 0.2438 (W/m²·K)

standard floor construction (2002 regs)

Normal wind exposure

Outside surface resistance 0.0400 m²K/W

Inside surface resistance 0.1171 m²K/W

Outside convective heat transfer coefficient 19.8700 (W/m²·K)

Inside convective heat transfer coefficient 3.0000 (W/m²·K)

Outside radiative heat transfer coefficient 5.5404 (W/m²·K)

Inside radiative heat transfer coefficient 5.5404 (W/m²·K)

CIBSE U-value 0.2470 (W/m²·K)

EN-ISO U-value 0.2438 (W/m²·K)

Admittance 2.1622 (W/m²·K)

Admittance time lead 2.74 Hrs

Internal admittance 2.1623 (W/m²·K)

Decrement factor 0.000

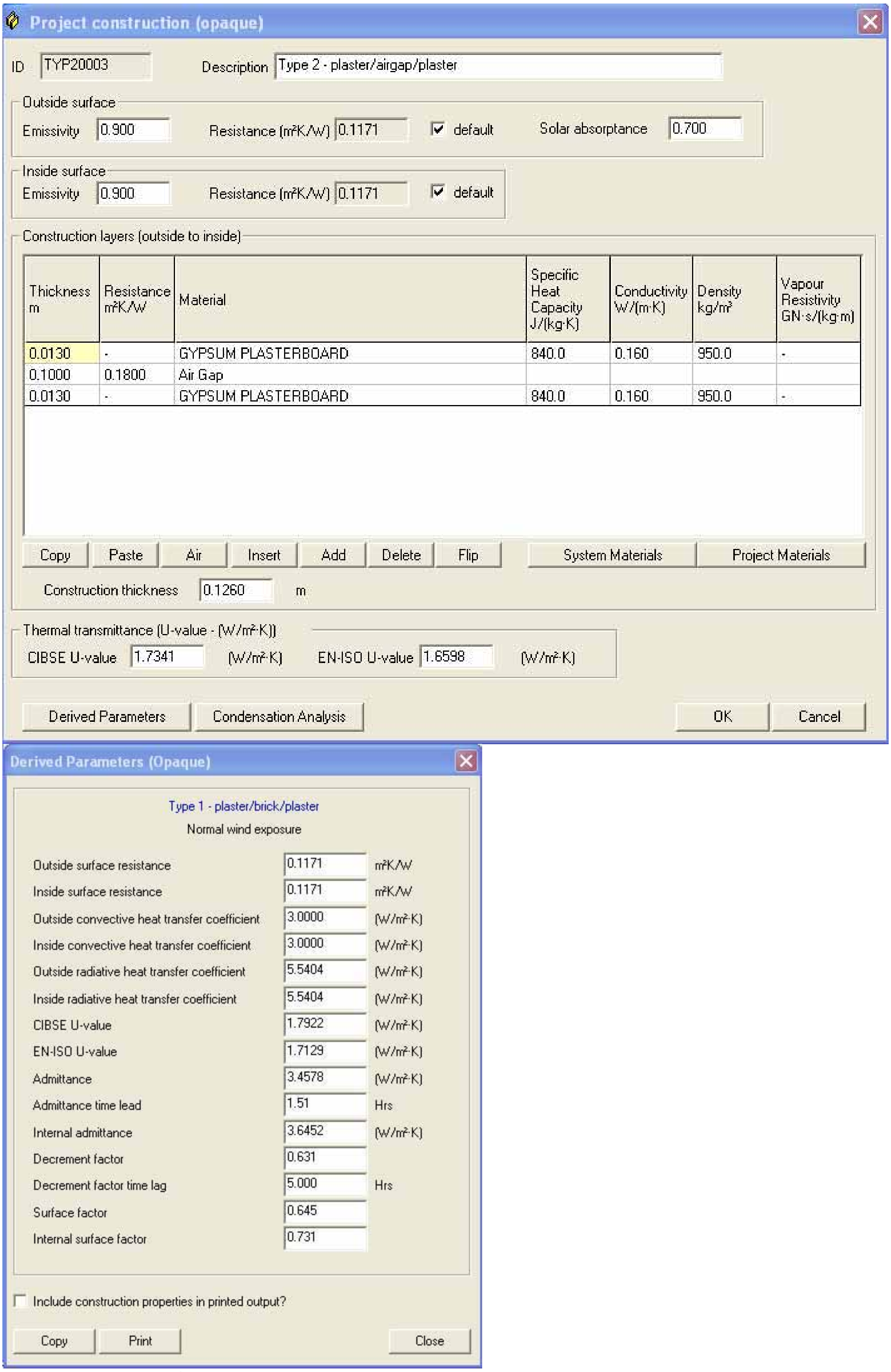
Decrement factor time lag 11.000 Hrs

Surface factor 0.826

Internal surface factor 0.826

☐ Include construction properties in printed output?

Figure B.3: Base Case ground floor properties



ID TYP20003 Description Type 2 - plaster/airgap/plaster

Outside surface
Emissivity 0.900 Resistance (m²K/W) 0.1171 ☑ default Solar absorptance 0.700

Inside surface
Emissivity 0.900 Resistance (m²K/W) 0.1171 ☑ default

Construction layers (outside to inside)

Thickness m	Resistance m²K/W	Material	Specific Heat Capacity J/(kg·K)	Conductivity W/(m·K)	Density kg/m³	Vapour Resistivity GN·s/(kg·m)
0.0130	-	GYPSUM PLASTERBOARD	840.0	0.160	950.0	-
0.1000	0.1800	Air Gap				
0.0130	-	GYPSUM PLASTERBOARD	840.0	0.160	950.0	-

Construction thickness 0.1260 m

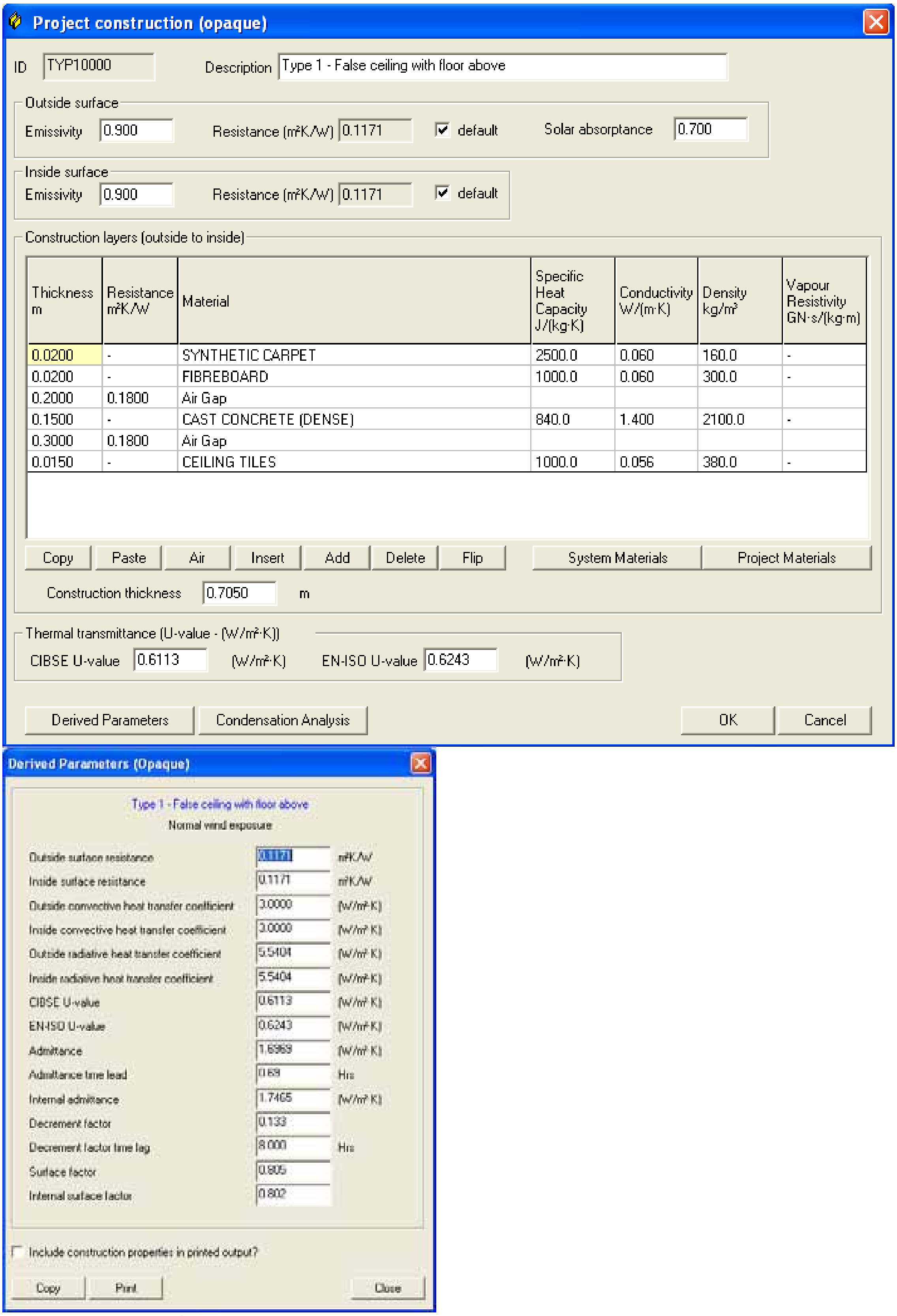
Thermal transmittance (U-value - (W/m²·K))
CIBSE U-value 1.7341 (W/m²·K) EN-ISO U-value 1.6598 (W/m²·K)

Type 1 - plaster/brick/plaster
Normal wind exposure

Outside surface resistance	0.1171	m²K/W
Inside surface resistance	0.1171	m²K/W
Outside convective heat transfer coefficient	3.0000	(W/m²·K)
Inside convective heat transfer coefficient	3.0000	(W/m²·K)
Outside radiative heat transfer coefficient	5.5404	(W/m²·K)
Inside radiative heat transfer coefficient	5.5404	(W/m²·K)
CIBSE U-value	1.7922	(W/m²·K)
EN-ISO U-value	1.7129	(W/m²·K)
Admittance	3.4578	(W/m²·K)
Admittance time lead	1.51	Hrs
Internal admittance	3.6452	(W/m²·K)
Decrement factor	0.631	
Decrement factor time lag	5.000	Hrs
Surface factor	0.645	
Internal surface factor	0.731	

☐ Include construction properties in printed output?

Figure B.4: Base Case internal partition properties



ID: TYP10000

Description: Type 1 - False ceiling with floor above

Outside surface

Emissivity: 0.900

Resistance (m^{2}K/W): 0.1171 ☑ default

Solar absorptance: 0.700

Inside surface

Emissivity: 0.900

Resistance (m^{2}K/W): 0.1171 ☑ default

Construction layers (outside to inside)

Thickness m	Resistance m^{2}K/W	Material	Specific Heat Capacity J/(kg·K)	Conductivity W/(m·K)	Density kg/m^3	Vapour Resistivity GN·s/(kg·m)
0.0200	-	SYNTHETIC CARPET	2500.0	0.060	160.0	-
0.0200	-	FIBREBOARD	1000.0	0.060	300.0	-
0.2000	0.1800	Air Gap				
0.1500	-	CAST CONCRETE (DENSE)	840.0	1.400	2100.0	-
0.3000	0.1800	Air Gap				
0.0150	-	CEILING TILES	1000.0	0.056	380.0	-

Construction thickness: 0.7050 m

Thermal transmittance (U-value - (W/m^2·K))

CIBSE U-value: 0.6113 (W/m^2·K)

EN-ISO U-value: 0.6243 (W/m^2·K)

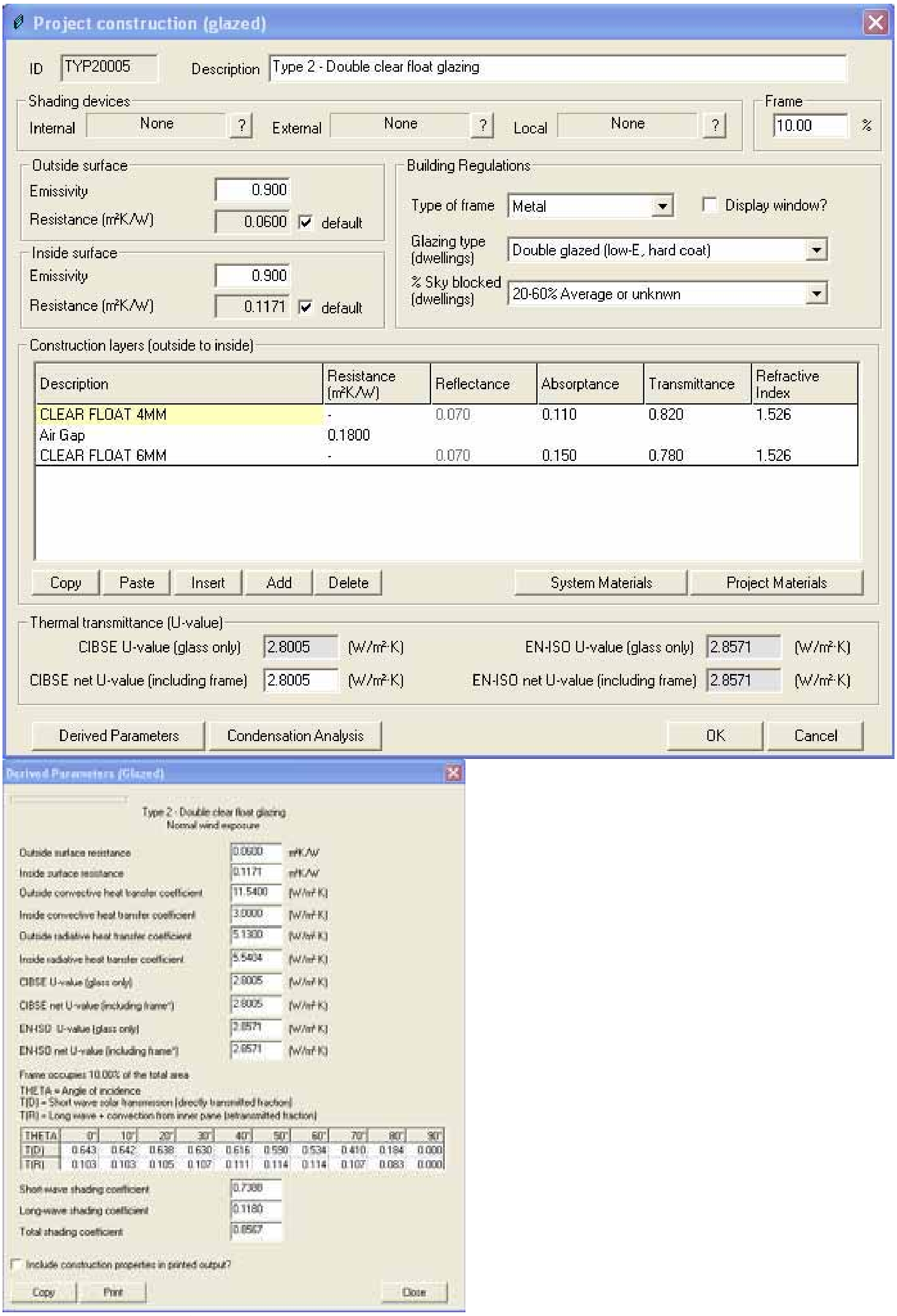
Type 1 - False ceiling with floor above

Normal wind exposure

Outside surface resistance	0.1171	m^{2}K/W
Inside surface resistance	0.1171	m^{2}K/W
Outside convective heat transfer coefficient	3.0000	(W/m^2·K)
Inside convective heat transfer coefficient	3.0000	(W/m^2·K)
Outside radiative heat transfer coefficient	5.5404	(W/m^2·K)
Inside radiative heat transfer coefficient	5.5404	(W/m^2·K)
CIBSE U-value	0.6113	(W/m^2·K)
EN-ISO U-value	0.6243	(W/m^2·K)
Admittance	1.6969	(W/m^2·K)
Admittance time lead	0.69	Hrs
Internal admittance	1.7465	(W/m^2·K)
Decrement factor	0.133	
Decrement factor time lag	8.000	Hrs
Surface factor	0.805	
Internal surface factor	0.802	

☐ Include construction properties in printed output?

Figure B.5: Base Case Internal ceiling / floor Properties



ID TYP20005 Description Type 2 - Double clear float glazing

Shading devices
Internal None ?
External None ?
Local None ?

Frame 10.00 %

Outside surface
Emissivity 0.900
Resistance (m²K/W) 0.0600 ☑ default

Inside surface
Emissivity 0.900
Resistance (m²K/W) 0.1171 ☑ default

Building Regulations
Type of frame Metal
☐ Display window?
Glazing type (dwellings) Double glazed (low-E, hard coat)
% Sky blocked (dwellings) 20-60% Average or unknwn

Construction layers (outside to inside)

Description	Resistance (m²K/W)	Reflectance	Absorptance	Transmittance	Refractive Index
CLEAR FLOAT 4MM	-	0.070	0.110	0.820	1.526
Air Gap	0.1800				
CLEAR FLOAT 6MM	-	0.070	0.150	0.780	1.526

Thermal transmittance (U-value)
CIBSE U-value (glass only) 2.8005 (W/m²·K)
CIBSE net U-value (including frame) 2.8005 (W/m²·K)
EN-ISO U-value (glass only) 2.8571 (W/m²·K)
EN-ISO net U-value (including frame) 2.8571 (W/m²·K)

Type 2 - Double clear float glazing
Normal wind exposure

Outside surface resistance 0.0600 m²K/W
Inside surface resistance 0.1171 m²K/W
Outside convective heat transfer coefficient 11.5400 (W/m²·K)
Inside convective heat transfer coefficient 3.0000 (W/m²·K)
Outside radiative heat transfer coefficient 5.1300 (W/m²·K)
Inside radiative heat transfer coefficient 5.5404 (W/m²·K)
CIBSE U-value (glass only) 2.8005 (W/m²·K)
CIBSE net U-value (including frame*) 2.8005 (W/m²·K)
EN-ISO U-value (glass only) 2.8571 (W/m²·K)
EN-ISO net U-value (including frame*) 2.8571 (W/m²·K)

Frame occupies 10.00% of the total area
THETA = Angle of incidence
T(D) = Short wave solar transmission (directly transmitted fraction)
T(R) = Long wave + convection from inner pane (retransmitted fraction)

THETA	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
T(D)	0.643	0.642	0.638	0.630	0.616	0.590	0.534	0.410	0.184	0.000
T(R)	0.103	0.103	0.105	0.107	0.111	0.114	0.114	0.107	0.083	0.000

Short-wave shading coefficient 0.7388
Long-wave shading coefficient 0.1180
Total shading coefficient 0.8567

☐ Include construction properties in printed output?

Figure B.6: Base Case external glazing properties

Appendix C Dynamic Climatic Data for Dublin

This appendix contains the climatic information for the weather file and solar data used for Dublin of the base case standard office building modelled in IES <VE>.

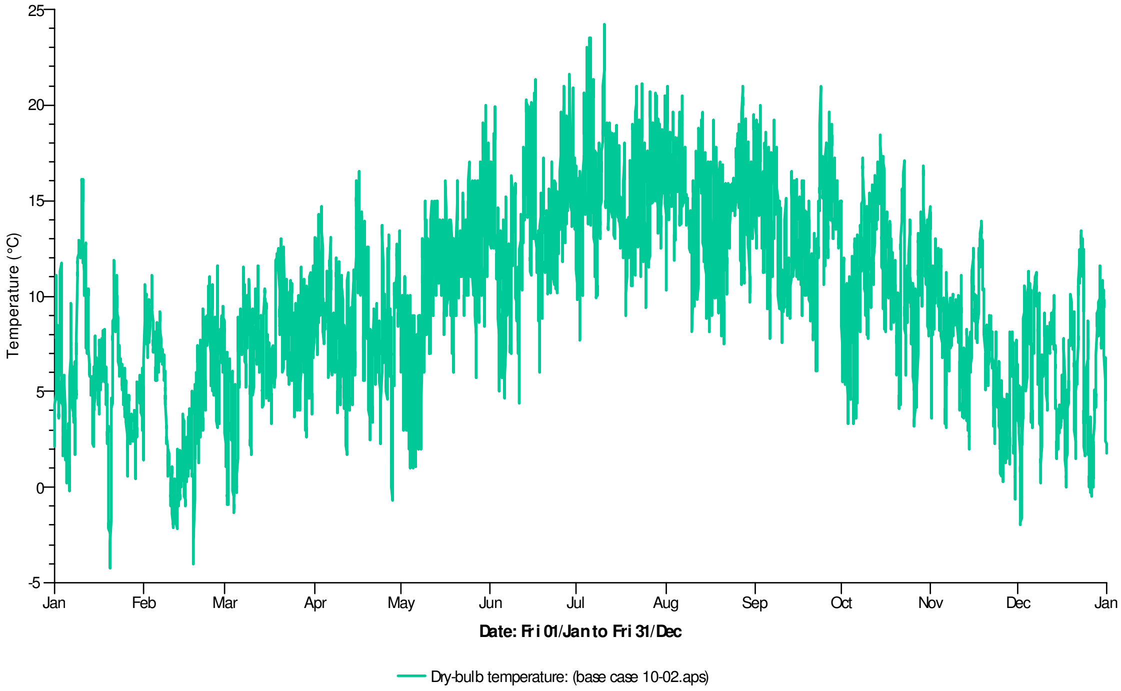


Figure C.1: Annual Dry Bulb Temperature

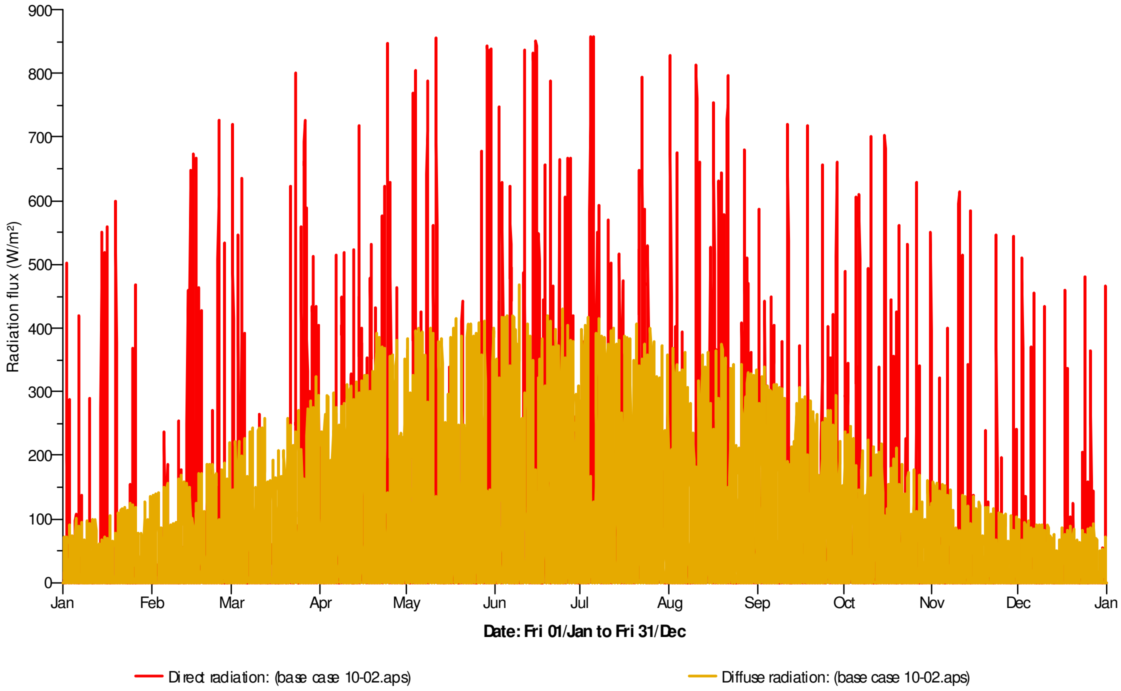


Figure C.2 : Annual direct and diffuse solar radiation

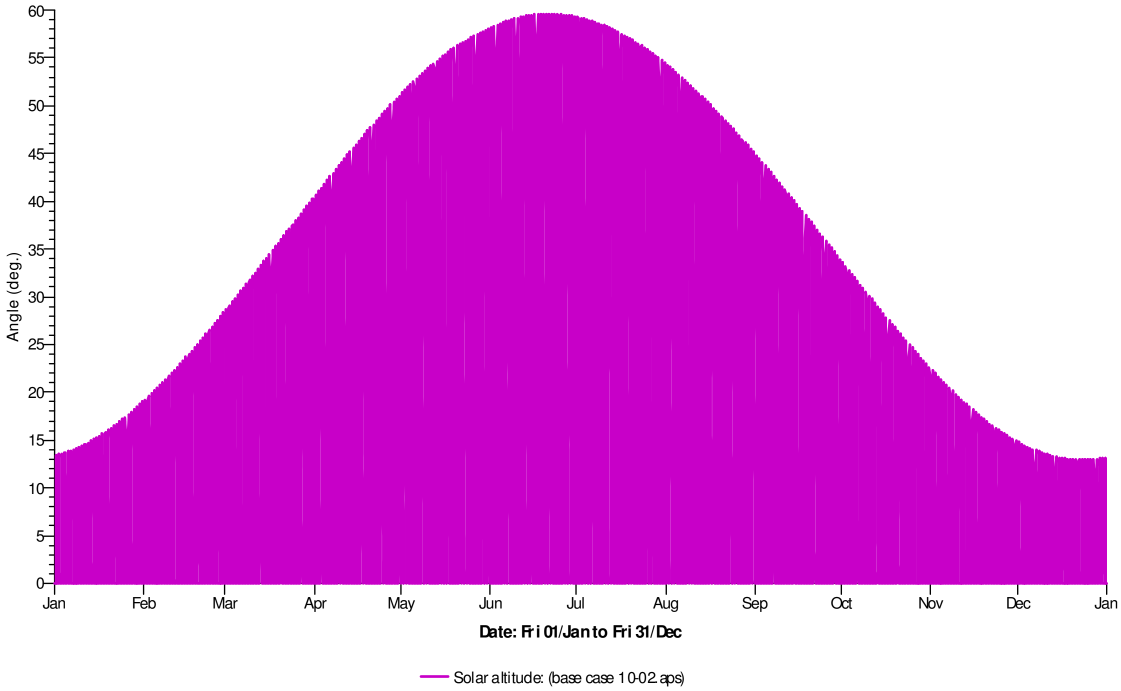


Figure C.3 : Annual solar altitude

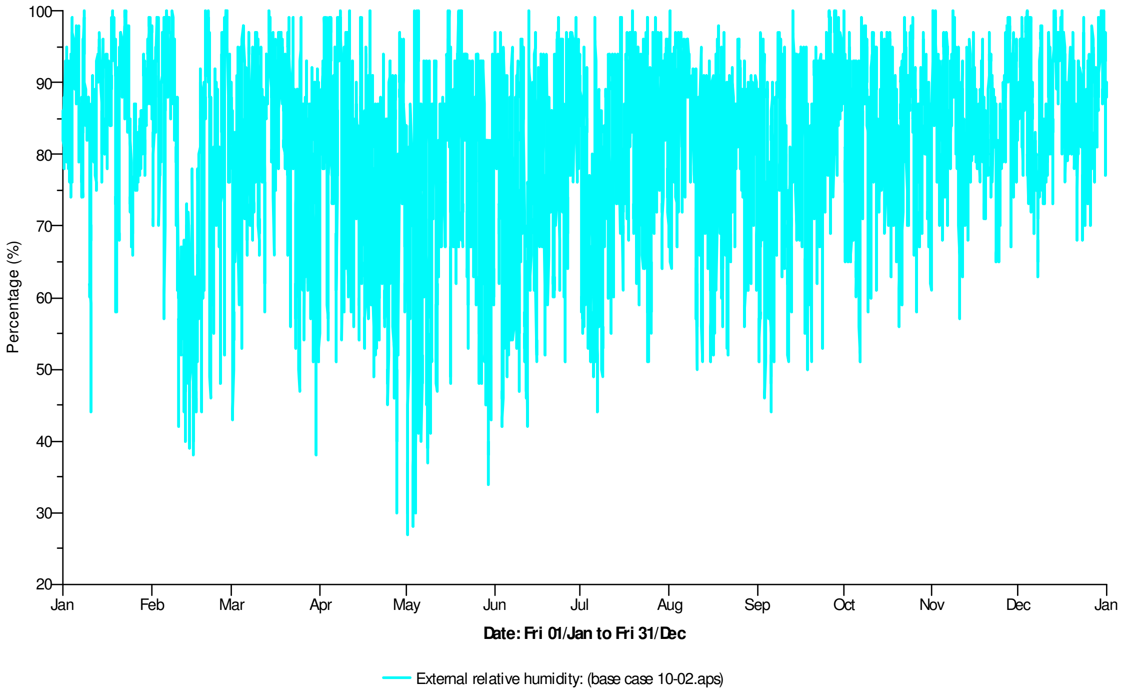


Figure C.4 : Annual relative humidity

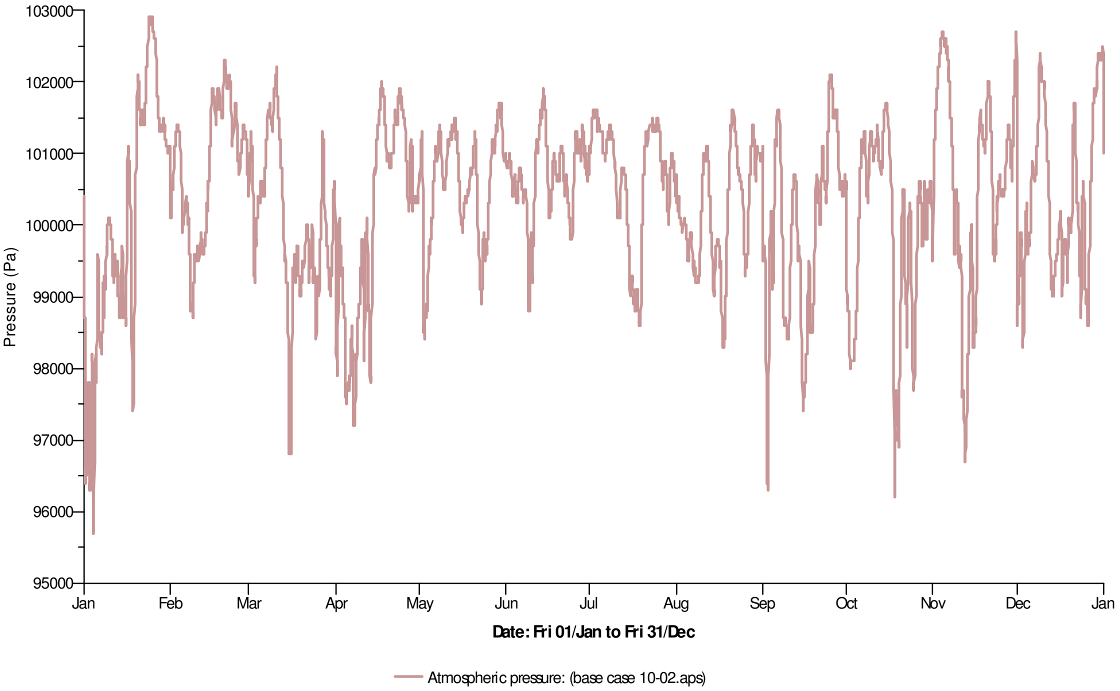
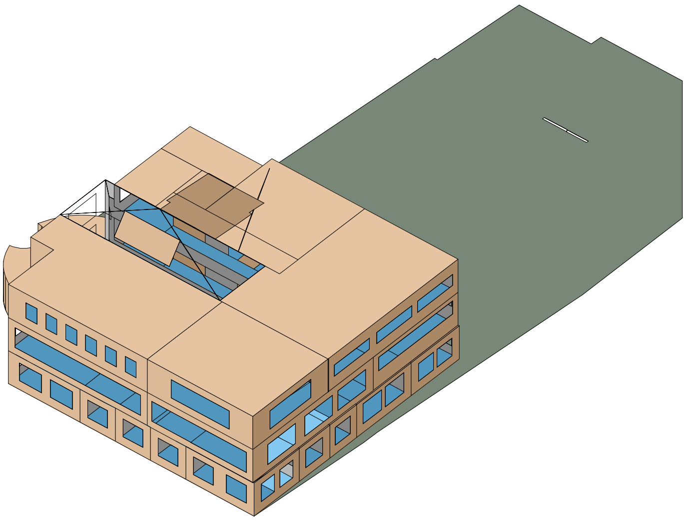


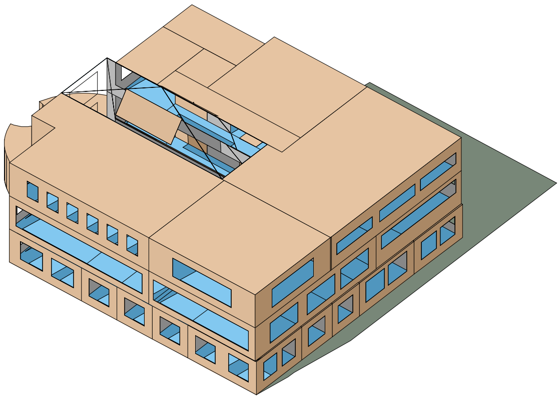
Figure C.5 : Annual atmospheric pressure

Var. Name	Type	Min.	Min. Time	Max.	Max. Time	Mean
Dry-bulb temperature:	Temperature (°C)	-4.2	05:00,20/Jan	24.2	17:00,10/Jul	9.8
Wet-bulb temperature:	Temperature (°C)	-4.6	05:00,20/Jan	18.9	18:00,10/Jul	8.2
External dew-point temp.:	Temperature (°C)	-10.3	20:00,12/Feb	17.2	13:00,28/Jun	6.7
Wind speed:	Speed (m/s)	0.0	09:00,04/Jan	19.5	06:00,18/Oct	4.7
Wind direction(E of N):	Azimuth (deg.)	0.0	09:00,04/Jan	350.0	12:00,04/Jan	197.4
Direct radiation:	Radiation flux (W/m^2)	0.0	01:00,01/Jan	858.0	13:00,05/Jul	65.8
Diffuse radiation:	Radiation flux (W/m^2)	0.0	01:00,01/Jan	468.0	14:00,09/Jun	73.1
Global radiation:	Radiation flux (W/m^2)	0.0	01:00,01/Jan	867.0	13:00,15/Jun	107.7
Solar altitude:	Angle (deg.)	0.0	01:00,01/Jan	59.6	13:00,21/Jun	12.3
Solar azimuth:	Angle (deg.)	7.0	02:00,20/Jul	356.8	01:00,29/Oct	181.2
Cloud cover:	Cloud cover (oktas)	0.0	01:00,01/Jan	8.0	07:00,01/Jan	5.8
Atmospheric pressure:	Pressure (kPa)	95.7	11:00,04/Jan	102.9	09:00,24/Jan	100.3
External RH:	Percentage (%)	27.0	11:00,01/May	100.0	09:00,08/Jan	81.4
External MC:	Moisture content (g/kg)	1.59	20:00,12/Feb	12.42	21:00,10/Jul	6.43

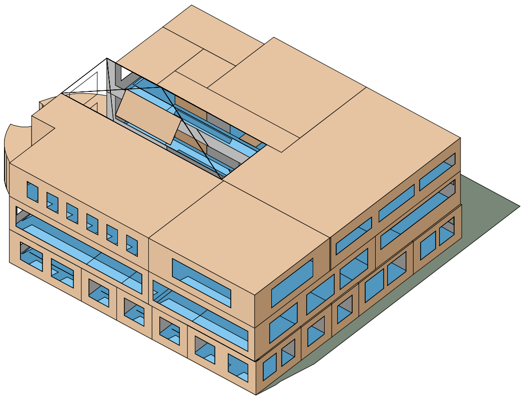
Table C.1: Minimum, Maximum and Mean Climatic Data



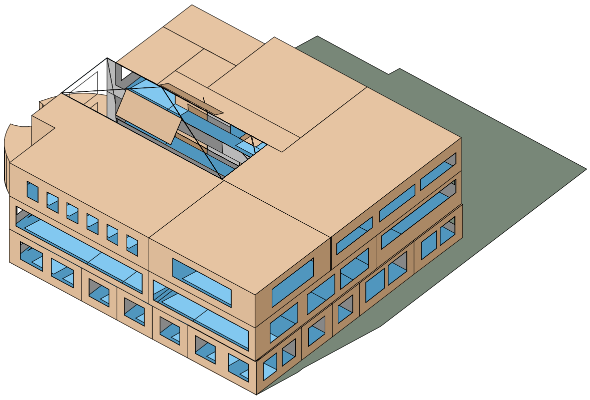
January Shading Analysis



April Shading Analysis



June Shading Analysis



November Shading Analysis

Appendix D Presentation of Results

This appendix contains the presentation of results from the investigation of peak heating and cooling loads and the investigation of the suitability of a building for natural ventilation i.e. the use of a dynamic methodology as an early design step.

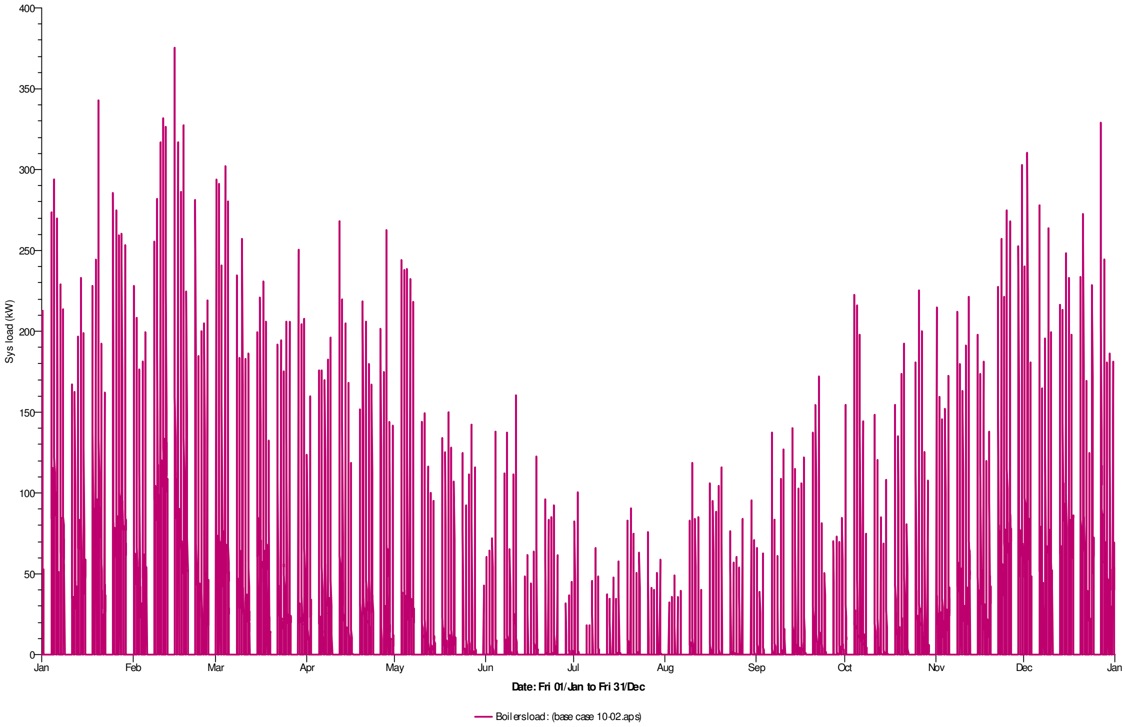


Figure D.1: Dynamic Peak Heating Load

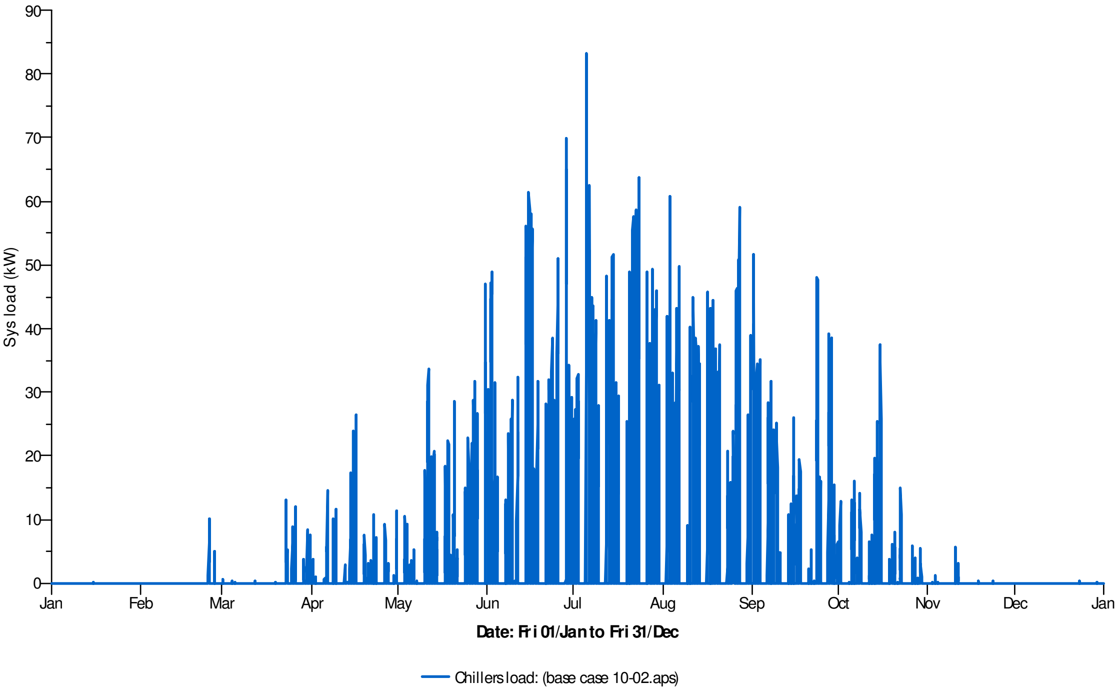


Figure D.2: Dynamic Peak Cooling Load

Table D.1: CIBSE Steady State Heating and Cooling Loads

Summary of building heating and cooling performance.

1. General Summary

Model Data	**Heating Calculation Data**	**Cooling Calculation Data**
Project file: "Base Case.mit"	Heating results file: "Base Case CIBSE.htg"	Cooling results file: "Base Case CIBSE.clg"
Model total floor area = 1663.0 m²	Calculated at 11:42 on 10/Feb/06	Calculated at 11:42 on 10/Feb/06
Model total volume = 4846.9 m³	Calc. Period: January	Calc. Period: Apr - Sep
Number of rooms = 43		

2. System: Main system

2.1 Heating Loads

System Heating Loads

Room heating load (kW)		**Outdoor air primary load (kW)**		**Plant load***	
Sensible	**Humidification**	**Mech vent**	**Aux mech vent**	**(kW)**	**(W/m²)**
241.37	25.91	0.00	0.00	294.01	176.80

*includes pipe & duct heat losses

Room Heating Plant Loads

Room Name	Temperature (°C)		Conduction gain (kW)		Ventilation sensible gain (kW)				Sens. load (kW)	Steady state heating plant load (kW)
	Air	Environmental	External	Internal	Mech vent (outdoor air)	Aux mech vent	Infiltration	Natural vent		
Level 0 0ffice No 1	21.00	21.69	-0.35	-0.00	-0.60	0.00	-0.38	0.00	2.34	1.34
Level 0 Atrium	19.00	20.91	-0.42	-1.30	-1.89	0.00	-1.57	0.00	6.44	5.17
Level 0 cleaner	19.00	22.44	-0.05	-0.12	-1.73	0.00	-0.17	0.00	3.63	2.08
Level 0 Corridor East	19.00	20.16	-0.17	0.24	-0.80	0.00	-0.33	0.00	2.14	1.06
Level 0 Corridor North	19.00	20.08	-0.15	0.21	-0.71	0.00	-0.29	0.00	1.91	0.95
Level 0 Corridor South	19.00	20.22	-0.32	0.24	-1.23	0.00	-0.51	0.00	3.54	1.82
Level 0 Disabled WC	19.00	22.06	-0.03	0.03	-0.90	0.00	-0.09	0.00	1.94	0.98
Level 0 Entrance Foyer	19.00	19.63	-1.09	0.09	-1.17	0.00	-0.98	0.00	5.34	3.15
Level 0 Female WC	19.00	23.50	-0.46	-0.16	-5.80	0.00	-0.58	0.00	12.31	7.00
Level 0 Lift Lobby	19.00	19.79	-0.16	-0.07	-0.50	0.00	-0.21	0.00	1.71	0.94
Level 0 Lift Shaft	12.56	14.06	-0.04	0.40	-0.22	0.00	-0.14	0.00	0.00	0.00
Level 0 Male WC	19.00	23.58	-0.32	-0.04	-4.93	0.00	-0.49	0.00	10.39	5.79
Level 0 Meeting Room 1	21.00	22.44	-1.24	-0.10	-2.78	0.00	-0.77	0.00	8.02	4.89
Level 0 Meeting Room No 2	21.00	22.60	-1.13	-0.07	-2.78	0.00	-0.73	0.00	7.84	4.71
Level 0 Office No 2	21.00	21.66	-0.35	-0.02	-0.60	0.00	-0.38	0.00	2.36	1.35
Level 0 Office No 3	21.00	21.69	-0.35	0.00	-0.60	0.00	-0.38	0.00	2.34	1.33
Level 0 Office No 4	21.00	21.71	-0.37	-0.01	-0.71	0.00	-0.44	0.00	2.70	1.53
Level 0 Office No 5	21.00	21.92	-0.35	0.09	-0.74	0.00	-0.46	0.00	2.64	1.46
Level 0 Stairwell	19.00	19.40	-0.34	0.00	-0.54	0.00	-0.23	0.00	2.12	1.11
Level 0 Training Room No 2	21.00	25.36	-0.95	-0.35	-7.29	0.00	-0.94	0.00	15.62	9.53
Level 0 Training Room No 1	21.00	24.27	-1.71	-0.08	-7.29	0.00	-1.18	0.00	17.00	10.26
Level 1 Atrium	11.71	16.35	-0.40	1.45	0.00	0.00	-1.05	0.00	0.00	0.00
Level 1 Cleaners	19.00	22.56	0.00	-0.12	-1.73	0.00	-0.17	0.00	3.56	2.03
Level 1 Corridor North	19.00	19.76	0.00	-0.14	-0.60	0.00	-0.25	0.00	1.84	0.99
Level 1 Disabled WC	19.00	22.15	0.00	0.03	-0.90	0.00	-0.09	0.00	1.93	0.96
Level 1 Female WC	19.00	23.75	-0.16	-0.20	-5.80	0.00	-0.58	0.00	12.12	6.75
Level 1 File Storage	21.00	22.33	-1.62	0.13	-3.01	0.00	-1.89	0.00	10.56	6.38
Level 1 Lift Lobby	19.00	19.23	-0.31	-0.14	-0.50	0.00	-0.21	0.00	2.00	1.17
Level 1 Lift Shaft	12.80	14.32	0.00	0.37	-0.23	0.00	-0.14	0.00	0.00	0.00
Level 1 Male WC	19.00	23.72	-0.10	-0.14	-4.93	0.00	-0.49	0.00	10.22	5.67
Level 1 Open Plan Office Area SW	21.00	22.01	-2.40	-0.68	-4.19	0.00	-2.62	0.00	15.31	9.89
Level 1 Open Plan	21.00	22.34	-2.57	-0.32	-4.84	0.00	-3.03	0.00	16.87	10.76

Office E										
Level 1 Stairwell	19.00	19.52	-0.23	-0.02	-0.54	0.00	-0.23	0.00	1.97	1.02
Level 2 Atrium	9.02	12.81	-0.33	1.19	0.00	0.00	-0.86	0.00	0.00	0.00
Level 2 Atrium Roof	4.53	4.95	-1.53	1.71	0.00	0.00	-0.18	0.00	0.00	0.00
Level 2 Canteen E	22.00	22.87	-2.60	-0.59	-3.81	0.00	-3.17	0.00	14.80	10.17
Level 2 Canteen N	22.00	22.60	-1.52	-0.36	-1.82	0.00	-1.52	0.00	7.19	5.22
Level 2 Corridor North	19.00	19.47	-0.13	-0.30	-0.60	0.00	-0.25	0.00	1.84	1.28
Level 2 Lift Lobby	19.00	18.75	-0.50	-0.21	-0.50	0.00	-0.21	0.00	2.09	1.43
Level 2 Lift Shaft	12.29	13.76	-0.04	0.40	-0.22	0.00	-0.14	0.00	0.00	0.00
Level 2 Misc 1	21.00	22.08	-1.93	0.04	-2.99	0.00	-1.88	0.00	10.22	6.76
Level 2 Misc 2	21.00	21.91	-2.32	-1.02	-4.19	0.00	-2.62	0.00	14.38	10.15
Level 2 Stairwell	19.00	19.33	-0.34	-0.05	-0.54	0.00	-0.23	0.00	2.11	1.16

2.2 Cooling Loads and Airflow Rates

System Cooling Loads

Peak		Room cooling load (kW)		Outdoor air pre-cooling load (kW)				Peak plant load*(kW)	Engineering Checks		
Month	Time	Sensible	Dehum.	Mech vent sens.	Mech vent lat.	Aux mech vent sens.	Aux mech vent lat.		(W/m²)	(l/(s·m²))	No. People
Jul	15:00	87.06	11.16	0.00	0.00	0.00	0.00	103.13	62.01	6.43	215.71

*includes duct heat gains

Room Cooling Plant Loads

Room Name	Peak		Air temp. (°C)	Plant load (kW)		
	Month	Time		Sensible	Dehumidification	Peak total
Level 0 0ffice No 1	Jul	15:00	23.00	1.48	0.11	1.59
Level 0 Atrium	Apr	01:00	16.22	0.00	0.00	0.00
Level 0 cleaner	Apr	01:00	16.49	0.00	0.00	0.00
Level 0 Corridor East	Jul	16:00	23.00	0.91	0.16	1.07
Level 0 Corridor North	Jul	16:00	23.00	0.92	0.14	1.06
Level 0 Corridor South	Jul	16:00	23.00	1.58	0.25	1.83
Level 0 Disabled WC	Apr	01:00	16.67	0.00	0.00	0.00
Level 0 Entrance Foyer	Apr	01:00	16.31	0.00	0.00	0.00
Level 0 Female WC	Apr	01:00	16.29	0.00	0.00	0.00
Level 0 Lift Lobby	Jul	16:00	23.00	0.51	0.10	0.61
Level 0 Lift Shaft	Apr	01:00	16.43	0.00	0.00	0.00
Level 0 Male WC	Apr	01:00	16.56	0.00	0.00	0.00
Level 0 Meeting Room 1	Jul	16:00	23.00	4.21	0.52	4.73

Level 0 Meeting Room No 2	Jul	14:00	23.00	3.20	0.52	3.72
Level 0 Office No 2	Jul	14:00	23.00	1.43	0.11	1.55
Level 0 Office No 3	Jul	14:00	23.00	1.45	0.11	1.57
Level 0 Office No 4	Jul	11:00	23.00	1.33	0.13	1.46
Level 0 Office No 5	Jul	11:00	23.00	1.33	0.14	1.46
Level 0 Stairwell	Apr	01:00	17.03	0.00	0.00	0.00
Level 0 Training Room No 2	Jul	16:00	23.00	4.57	1.35	5.92
Level 0 Training Room No 1	Jul	16:00	23.00	5.00	1.23	6.23
Level 1 Atrium	Apr	01:00	15.63	0.00	0.00	0.00
Level 1 Cleaners	Apr	01:00	17.31	0.00	0.00	0.00
Level 1 Corridor North	Jul	16:00	23.00	1.43	0.12	1.55
Level 1 Disabled WC	Apr	01:00	17.44	0.00	0.00	0.00
Level 1 Female WC	Apr	01:00	17.13	0.00	0.00	0.00
Level 1 File Storage	Jul	16:00	23.00	5.04	0.57	5.61
Level 1 Lift Lobby	Jul	16:00	23.00	1.47	0.10	1.57
Level 1 Lift Shaft	Apr	01:00	17.51	0.00	0.00	0.00
Level 1 Male WC	Apr	01:00	17.36	0.00	0.00	0.00
Level 1 Open Plan Office Area SW	Jul	15:00	23.00	11.20	0.80	11.99
Level 1 Open Plan Office E	Jul	14:00	23.00	10.07	0.92	10.99
Level 1 Stairwell	Apr	01:00	18.04	0.00	0.00	0.00
Level 2 Atrium	Apr	01:00	14.53	0.00	0.00	0.00
Level 2 Atrium Roof	Apr	01:00	12.86	0.00	0.00	0.00
Level 2 Canteen E	Jul	16:00	24.00	6.26	0.96	7.22
Level 2 Canteen N	Jul	16:00	24.00	4.17	1.21	5.38
Level 2 Corridor North	Jul	15:00	23.00	1.99	0.12	2.12
Level 2 Lift Lobby	Jul	16:00	23.00	2.33	0.10	2.43
Level 2 Lift Shaft	Apr	01:00	16.73	0.00	0.00	0.00
Level 2 Misc 1	Jul	14:00	23.00	6.14	0.57	6.70
Level 2 Misc 2	Jul	16:00	23.00	11.03	0.80	11.83
Level 2 Stairwell	Apr	01:00	17.80	0.00	0.00	0.00

Room Sensible Cooling and Airflow Rates

Room Name	Peak		Air Temp. (℃)		Peak Space sensible (kW)	Airflow (l/s)	Engineering Checks		
	Month	Time	SADB	Return			(W/m^2)	($l/(s\cdot m^2)$)	No. People
Level 0 0ffice No 1	Sep	14:00	15.00	23.00	1.5	156	0.10	9.97	1.74
Level 0 Atrium	Apr	12:00	11.40	19.40	0.6	60	0.01	0.84	0.00
Level 0 cleaner	Jul	09:00	11.00	19.00	0.3	28	0.04	3.63	0.78
Level 0 Corridor East	Jul	16:00	15.00	23.00	0.8	80	0.03	2.66	2.51
Level 0 Corridor North	Jul	16:00	15.00	23.00	0.8	83	0.03	3.12	2.22
Level 0 Corridor South	Jul	16:00	15.00	23.00	1.4	143	0.03	3.07	3.87
Level 0 Disabled WC	Jul	08:00	11.00	19.00	0.2	20	0.05	4.87	1.00
Level 0 Entrance Foyer	Jul	08:00	12.96	20.96	0.4	37	0.01	0.84	0.00
Level 0 Female WC	Jul	08:00	11.00	19.00	1.1	110	0.04	4.17	5.00
Level 0 Lift Lobby	Jul	16:00	15.00	23.00	0.4	44	0.02	2.35	1.57
Level 0 Lift Shaft	Apr	07:00	7.72	15.72	0.1	10	0.01	1.16	0.00
Level 0 Male WC	Jul	08:00	11.00	19.00	1.1	111	0.05	4.95	5.00
Level 0 Meeting Room 1	Jul	15:00	15.00	23.00	3.8	396	0.12	12.44	8.00
Level 0 Meeting Room No 2	Aug	11:00	15.00	23.00	3.1	317	0.10	10.45	7.99
Level 0 Office No 2	Sep	14:00	15.00	23.00	1.5	153	0.09	9.73	1.74
Level 0 Office No 3	Sep	14:00	15.00	23.00	1.5	154	0.09	9.81	1.74
Level 0 Office No 4	Jul	10:00	15.00	23.00	1.5	158	0.08	8.63	2.04
Level 0 Office No 5	Jul	10:00	15.00	23.00	1.5	158	0.08	8.26	2.13
Level 0 Stairwell	Jul	08:00	14.33	22.33	0.2	21	0.01	1.01	1.71
Level 0 Training Room No 2	Jul	10:00	15.00	23.00	4.6	476	0.12	12.22	21.05
Level 0 Training Room No 1	Jul	09:00	15.00	23.00	4.0	418	0.08	8.58	19.03
Level 1 Atrium	Apr	01:00	7.63	15.63	0.0	0	0.00	0.00	0.00
Level 1 Cleaners	Jul	09:00	11.27	19.27	0.3	31	0.04	3.99	0.78
Level 1 Corridor North	Jul	16:00	15.00	23.00	1.3	138	0.06	6.10	1.88
Level 1 Disabled WC	Jul	08:00	11.05	19.05	0.2	20	0.05	5.01	1.00
Level 1 Female WC	Jul	08:00	11.00	19.00	1.1	112	0.04	4.28	5.00
Level 1 File Storage	Jul	09:00	15.00	23.00	5.3	545	0.07	6.97	8.69
Level 1 Lift Lobby	Jul	16:00	15.00	23.00	1.4	143	0.07	7.59	1.57
Level 1 Lift Shaft	Apr	08:00	10.56	18.56	0.1	14	0.02	1.58	1.00
Level 1 Male WC	Jul	08:00	11.22	19.22	1.1	116	0.05	5.19	5.00
Level 1 Open Plan Office Area SW	Jul	15:00	15.00	23.00	10.6	1101	0.10	10.12	12.09
Level 1 Open Plan Office E	Aug	10:00	15.00	23.00	9.7	1008	0.08	8.02	13.98
Level 1 Stairwell	Jul	08:00	15.32	23.32	0.2	23	0.01	1.14	1.71
Level 2 Atrium	Apr	01:00	6.53	14.53	0.0	0	0.00	0.00	0.00
Level 2 Atrium Roof	Apr	01:00	4.86	12.86	0.0	0	0.00	0.00	0.00
Level 2 Canteen E	Jul	09:00	16.00	24.00	6.2	640	0.05	5.07	24.00
Level 2 Canteen N	Jul	16:00	16.00	24.00	4.0	412	0.07	6.81	24.00
Level 2 Corridor North	Jul	15:00	15.00	23.00	1.9	197	0.08	8.73	1.88

Level 2 Lift Lobby	Jul	16:00	15.00	23.00	2.2	232	0.12	12.31	1.57
Level 2 Lift Shaft	Apr	09:00	9.79	17.79	0.1	12	0.01	1.35	0.00
Level 2 Misc 1	Jul	14:00	15.00	23.00	5.9	607	0.08	7.81	8.64
Level 2 Misc 2	Jul	15:00	15.00	23.00	10.4	1081	0.10	9.93	12.09
Level 2 Stairwell	Jul	08:00	15.89	23.89	0.2	25	0.01	1.21	1.71

Location	Fixed Air Changes		Natural Ventilation	
	% Time > 25℃	Cooling Reqd	% Time > 25℃	Cooling Reqd
Level 0 0ffice No 1	44%	Yes	7%	Yes
Level 0 Atrium	3%	No	0%	No
Level 0 Corridor East	24%	Yes	0%	No
Level 0 Corridor North	20%	Yes	1%	No
Level 0 Corridor South	18%	Yes	0%	No
Level 0 Entrance Foyer	2%	No	0%	No
Level 0 Lift Lobby	10%	Yes	0%	No
Level 0 Meeting Room 1	48%	Yes	13%	Yes
Level 0 Meeting Room No 2	51%	Yes	27%	Yes
Level 0 Office No 2	43%	Yes	7%	Yes
Level 0 Office No 3	45%	Yes	9%	Yes
Level 0 Office No 4	42%	Yes	8%	Yes
Level 0 Office No 5	48%	Yes	8%	Yes
Level 0 Stairwell	3%	No	0%	No
Level 0 Training Room No 2	80%	Yes	21%	Yes
Level 0 Training Room No 1	58%	Yes	25%	Yes
Level 1 Atrium	7%	Yes	2%	No
Level 1 Cleaners	19%	Yes	6%	Yes
Level 1 Corridor North	31%	Yes	3%	No
Level 1 File Storage	50%	Yes	7%	Yes
Level 1 Lift Lobby	24%	Yes	1%	No
Level 1 Open Plan Office Area SW	50%	Yes	7%	Yes
Level 1 Open Plan Office E	53%	Yes	4%	No
Level 1 Stairwell	13%	Yes	0%	No
Level 2 Atrium	23%	Yes	4%	No
Level 2 Atrium Roof	29%	Yes	12%	Yes
Level 2 Canteen E	44%	Yes	21%	Yes
Level 2 Canteen N	59%	Yes	18%	Yes
Level 2 Corridor North	41%	Yes	11%	Yes
Level 2 Lift Lobby	31%	Yes	5%	Yes
Level 2 Lift Shaft	20%	Yes	7%	Yes
Level 2 Misc 1	56%	Yes	12%	Yes
Level 2 Misc 2	51%	Yes	16%	Yes
Level 2 Stairwell	17%	Yes	1%	No

Table D.2: Cooling Requirement of rooms with and without natural ventilation

Appendix E Improvement of Energy Performance IES<VE> Results

This appendix contains the presentation of results from the Improvement of Energy Performance calculations in IES <VE>.

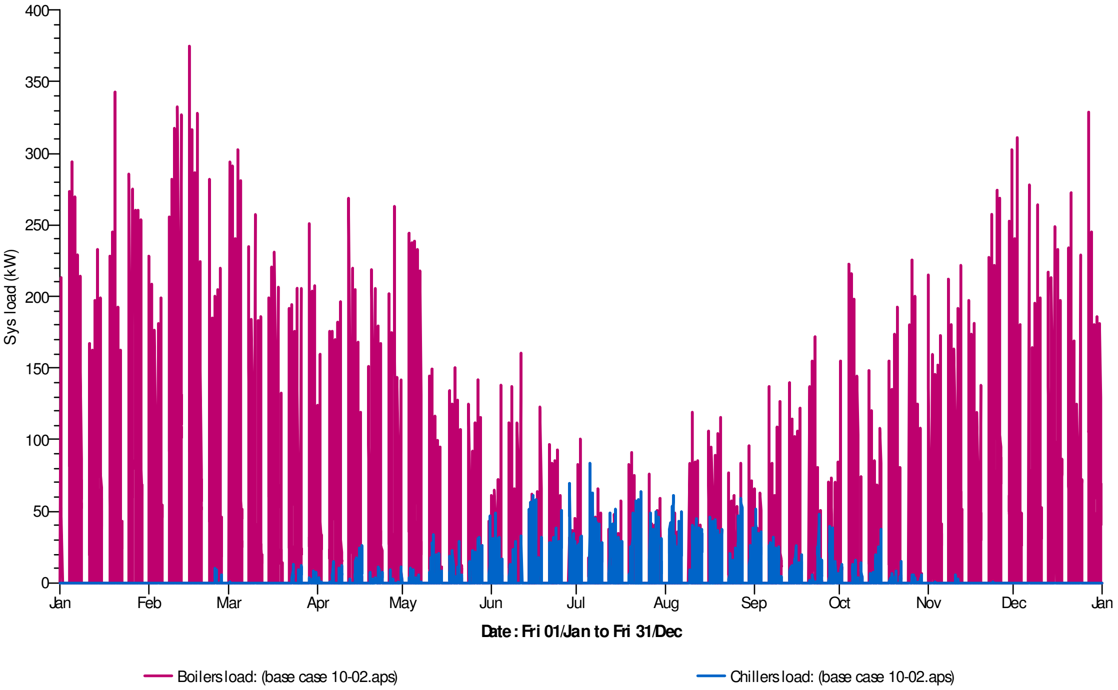


Figure E.1: Base case building boiler and chiller loads

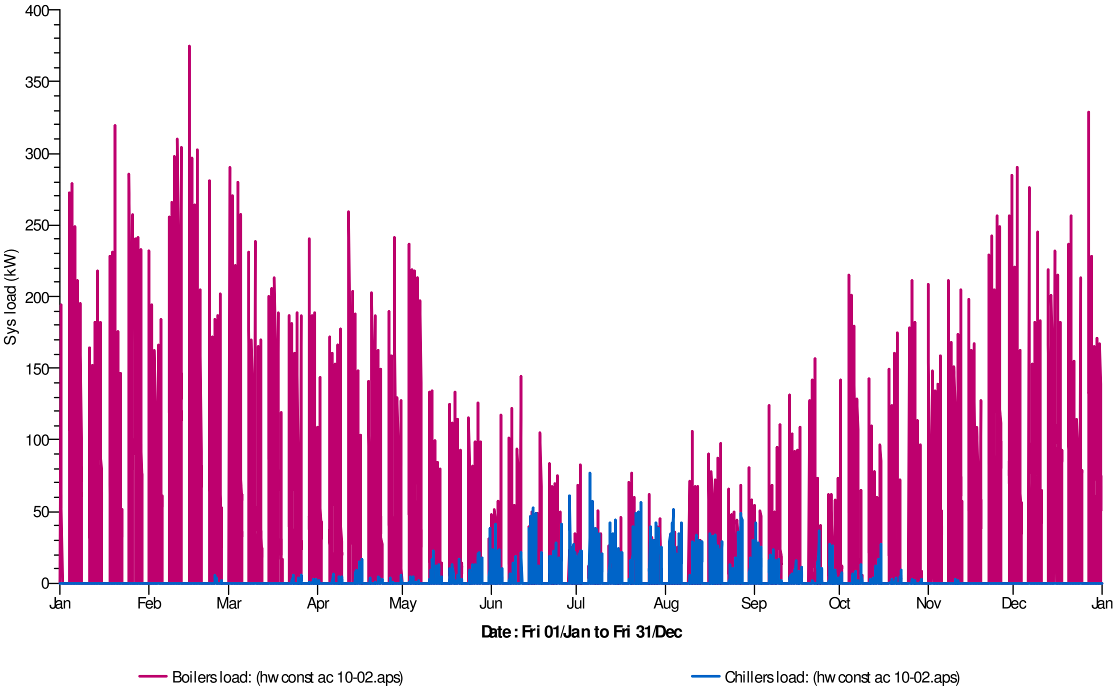


Figure E.2: Heavyweight construction building boiler and chiller loads

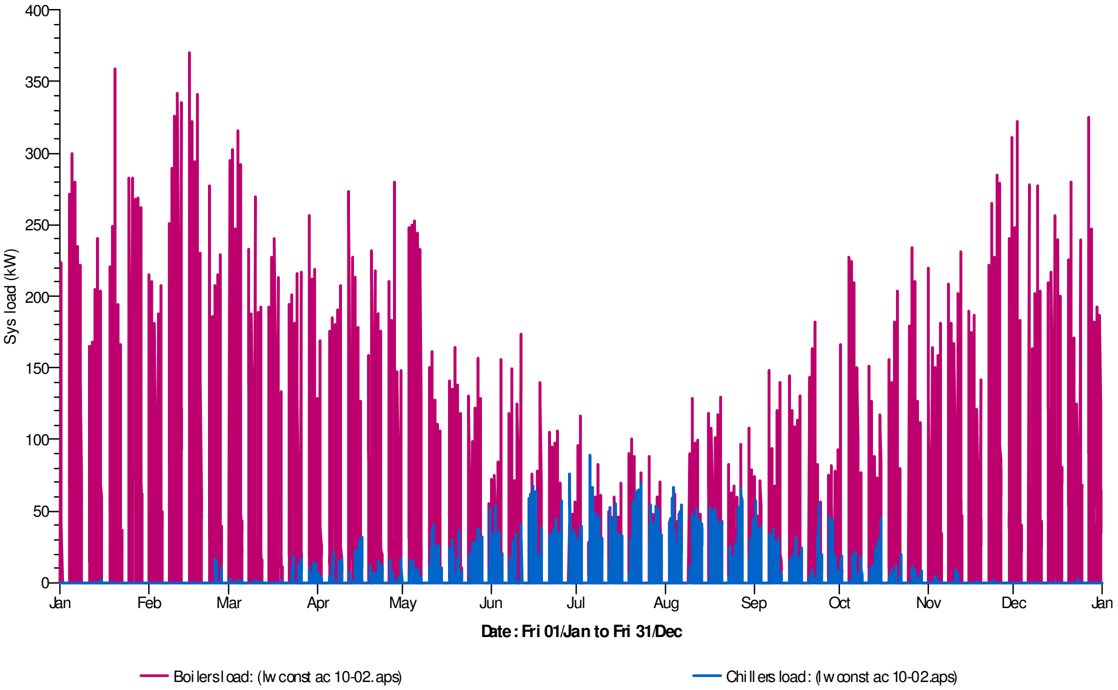


Figure E.3: Lightweight construction building boiler and chiller loads

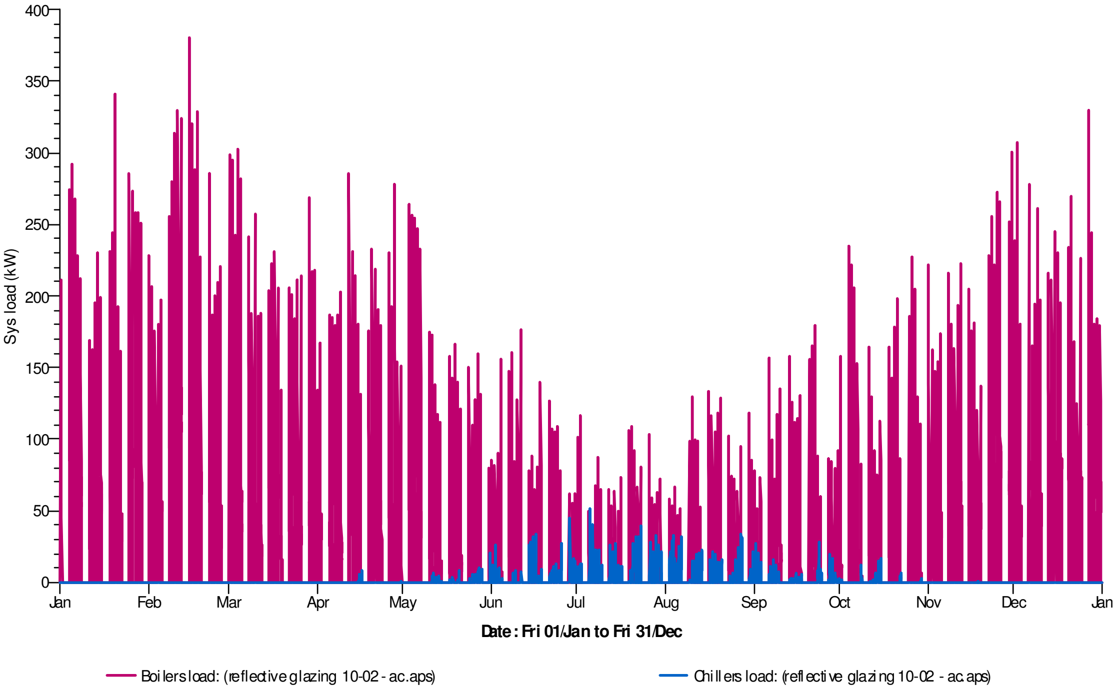


Figure E.4: Reflective blazed building boiler and chiller loads

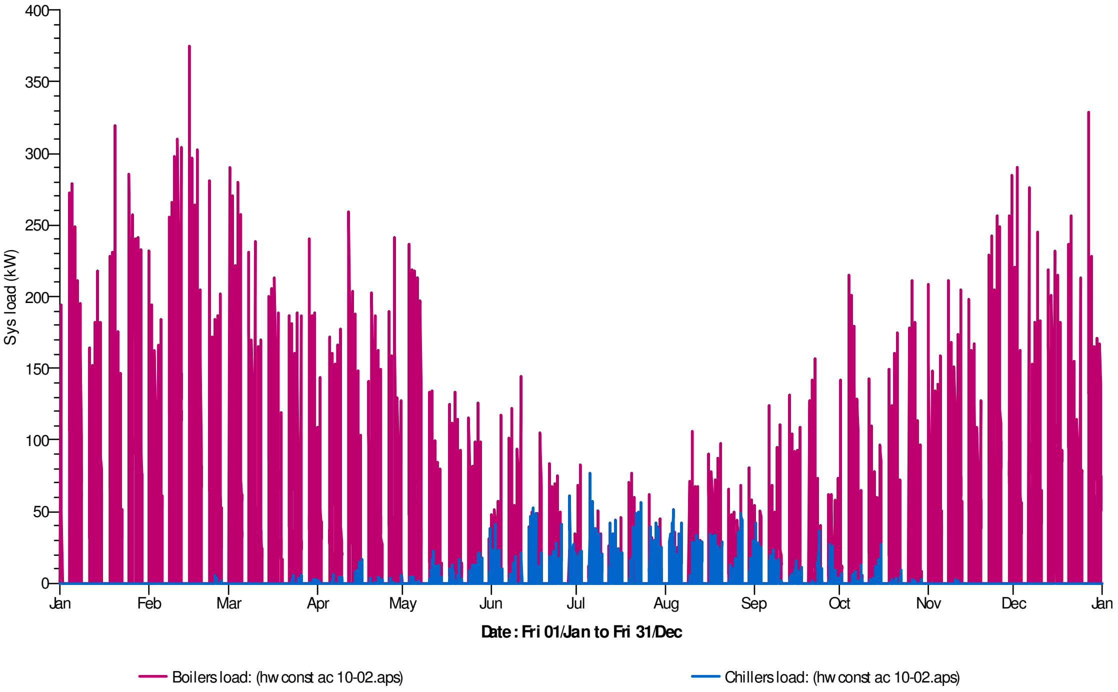


Figure E.5:Absorptive glazed building boiler and chiller loads

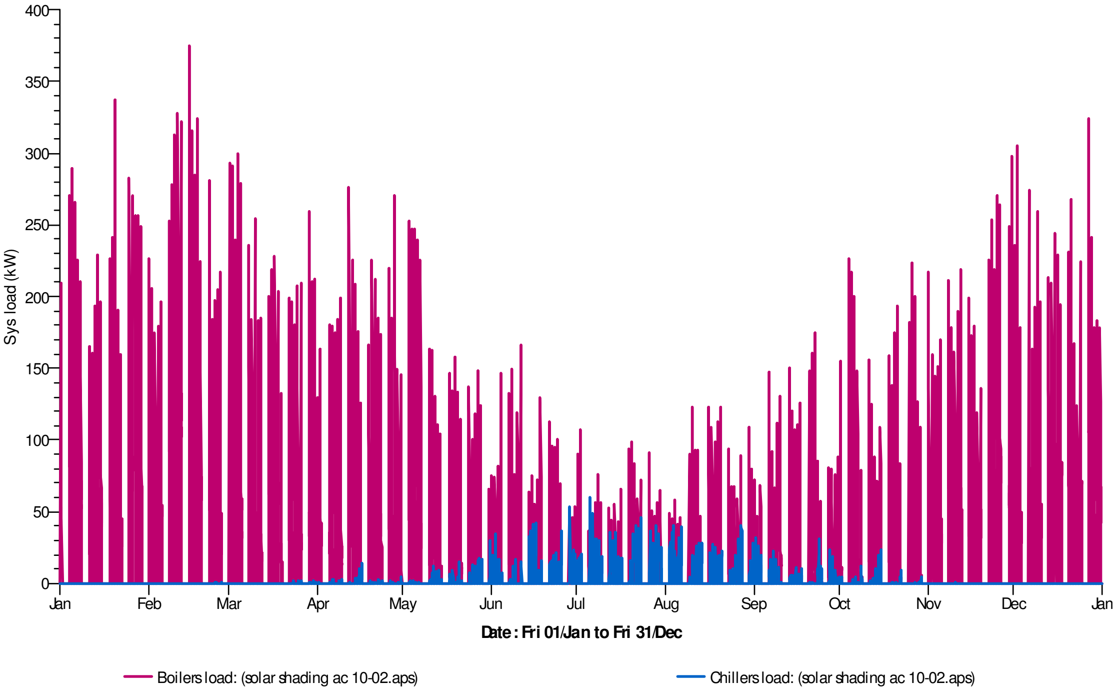


Figure E.6: Solar shaded building boiler and chiller loads

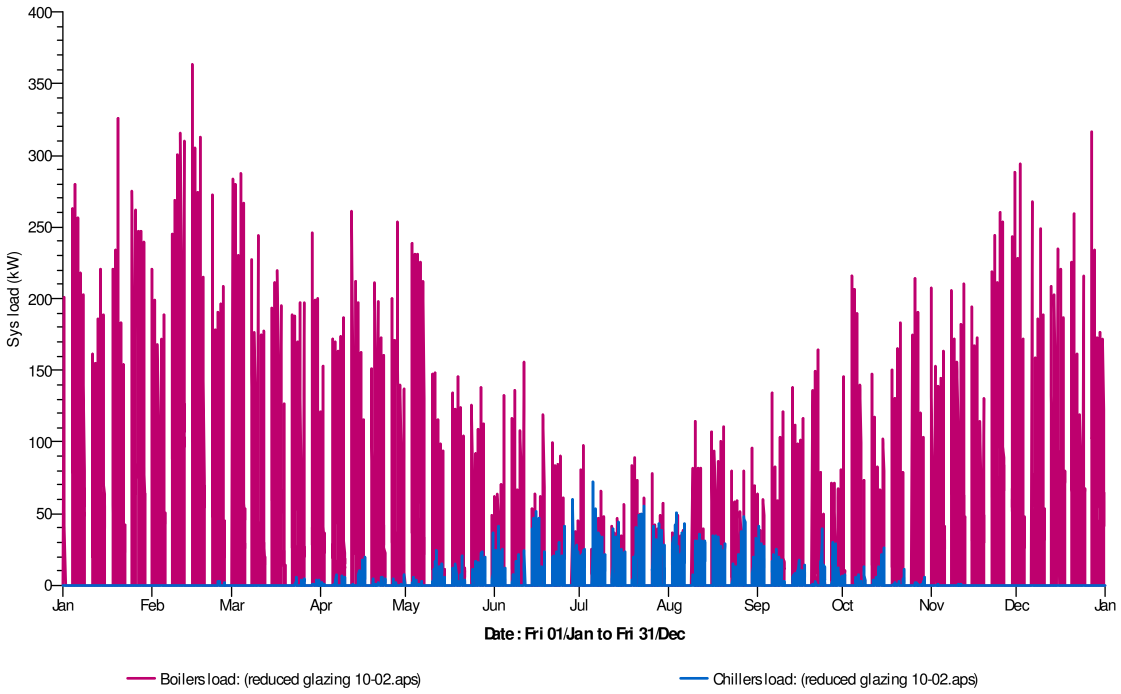


Figure E.7: Reduced glazing boiler and chiller load

Level 0 0ffice No 1 12:30 24 Feb Max Solar Gain - SOUTH

	T_{RES}	Heating Load	Cooling Load	Solar gain (kW)
Base Case	24.06	0	0.316	1.372
Absorb. Glazing	20.97	0.072	0	0.254
Refl. Glazing	21.79	0	0	0.569
Shading	22.30	0	0	0.671
Red. Glazing	22.45	0	0	0.678
Low Mass	24.41	0	0.474	1.372
High Mass	21.96	0	2.56	1.372

Result: Absorptive glazing reduced dry res temp and solar gain and cooling load the most but also increased heating load

Level 0 Office No 2 12:30 24 Feb Max Solar gain - SOUTH

	T_{RES}	Heating Load	Cooling Load	Solar gain (kW)
Base Case	23.92	0	312	1.37
Absorb. Glazing	20.98	74	0	0.253
Refl. Glazing	21.75	0	0	0.566
Shading	22.31	0	0	0.67
Red. Glazing	22.47	0	0	0.677
Low Mass	24.24	0	459	1.37
High Mass	21.83	0	0	1.37

Result: Absorptive glazing reduced dry res temp and solar gain and cooling load the most but also increased heating load

Level 0 Meeting Room No 2 10:30 23 Mar Max Solar Gain - SOUTH EAST

	T_{RES}	Heating Load	Cooling Load	Solar gain (kW)
Base Case	23.97	0	16	3.067
Absorb. Glazing	20.96	1043	0	0.408
Shading	21.25	694	0	0.884
Refl. Glazing	21.36	559	0	1.152
Red. Glazing	21.70	98	0	1.541
Low Mass	24.55	0	380	3.068
High Mass	22.18	0	0	3.068

Result: Absorptive glazing reduced dry res temp and solar gain and cooling load the most but also increased heating load

Level 0 Office No 4 9:30, 5 July Max Solar Gain - EAST				
	T_{RES}	Heating Load	Cooling Load	Solar gain (kW)
Base Case	24.58		1.273	1.282
Shading	23.33		0.481	0.211
Absorb. Glazing	23.10		0.387	0.31
Refl. Glazing	23.45		0.556	0.569
Red. Glazing	23.73		0.705	0.632
High Mass	24.19		1.016	1.282
Low Mass	24.70		1.346	1.283
Result: Shading reduced solar gain the most but absorptive glazing reduced cooling loads and dry res temp the most				
Level 2 Canteen E 9:30, 5 July Max Solar Gain - EAST				
	T_{RES}	Heating Load	Cooling Load	Solar gain (kW)
Base Case	25.67		5.429	5.482
Shading	24.58		2.434	1.224
Absorb. Glazing	24.37		2.06	1.498
Refl. Glazing	24.58		2.629	2.439
Red. Glazing	25.59		5.215	5.432
High Mass	25.48		4.262	5.481
Base Case	25.67		5.429	5.482
Low Mass	26.04		6.282	5.483
Result: Shading reduced solar gain the most but absorptive glazing reduced cooling loads and dry res temp the most				
Level 1 File Storage 9:30, 5 July Max Solar Gain - North East				
	T_{RES}	Heating Load	Cooling Load	Solar gain (kW)
Base Case	25.27		5.005	4.701
Shading	23.74		2.357	1.057
Absorb. Glazing	23.48		2.112	1.17
Refl. Glazing	23.86		2.728	2.093
Red. Glazing	24.26		3.265	2.343
High Mass	25.01		4.585	4.7
Low Mass	25.46		5.344	4.702
Result: Shading reduced solar gain the most but absorptive glazing reduced dry res temp and cooling load the most also increased heating load				

Level 2 Canteen N 13:30, 6 Oct Max Solar Gain - NORTH				
	T_{RES}	Heating Load	Cooling Load	Solar gain (kW)
Base Case	24.67	0	1.261	2.341
Refl. Glazing	23.54	0	0.039	0.921
Absorb. Glazing	24.25	0	0.756	1.771
Red. Glazing	24.58	0	1.149	2.085
Shading	24.60	0	1.183	2.319
Low Mass	25.10	0	1.698	2.341
High Mass	23.53	0	0	2.341
Result: Reflective glazing reduced solar gain the most but High Mass reduced dry res temp and cooling load the most				
Level 0 Training Room No 1 9:30, 5 July Max Solar Gain - NORTH EAST				
	T_{RES}	Heating Load	Cooling Load	Solar gain (kW)
Base Case	24.55		2.867	2.739
Absorb. Glazing	23.15		1.198	0.671
Shading	23.63		1.655	0.87
Refl. Glazing	23.51		1.56	1.222
Red. Glazing	23.77		1.834	1.366
High Mass	24.14		2.293	2.738
Low Mass	24.70		3.075	2.739
Result: Absorptive glazing reduced dry res temp and solar gain and cooling load the most				
Level 1 Open Plan Office Area SW 12:30 24 Feb Max Solar Gain - SOUTH WEST				
	T_{RES}	Heating Load	Cooling Load	Solar gain (kW)
Base Case	24.80	0	3.342	9.842
Shading	23.57	0	0.629	5.45
Absorb. Glazing	21.08	0.216	0	1.98
Red. Glazing	22.80	0	0	3.672
Refl. Glazing	22.61	0	0	4.112
High Mass	24.42	0	0	9.839
Low Mass	25.20	0	4.151	9.844
Result: Shading reduced solar gain but absorptive glazing reduced dry rest the most				

Table E.1: Reduction in Dry Resultant Temperature and Solar Gain

	Abs. Glas Fixed Air Changes		**Absorptive Glazing NV**	
	% Time > 25°C	**Cooling Reqd**	**% Time > 25°C**	**Cooling Reqd**
Location				
Level 0 0ffice No 1	2%	No	0%	No
Level 0 Atrium	1%	No	0%	No
Level 0 cleaner	0%	No	0%	No
Level 0 Corridor East	1%	No	0%	No
Level 0 Corridor North	3%	No	0%	No
Level 0 Corridor South	0%	No	0%	No
Level 0 Disabled WC	0%	No	0%	No
Level 0 Entrance Foyer	0%	No	0%	No
Level 0 Female WC	0%	No	0%	No
Level 0 Lift Lobby	1%	No	0%	No
Level 0 Lift Shaft	0%	No	0%	No
Level 0 Male WC	0%	No	0%	No
Level 0 Meeting Room 1	1%	No	2%	No
Level 0 Meeting Room No 2	1%	No	6%	Yes
Level 0 Office No 2	2%	No	0%	No
Level 0 Office No 3	2%	No	0%	No
Level 0 Office No 4	2%	No	0%	No
Level 0 Office No 5	2%	No	1%	No
Level 0 Stairwell	0%	No	0%	No
Level 0 Training Room No 2	2%	No	15%	Yes
Level 0 Training Room No 1	1%	No	13%	Yes
Level 1 Corridor North	9%	Yes	1%	No
Level 1 File Storage	6%	Yes	2%	No
Level 1 Lift Lobby	4%	No	0%	No
Level 1 Open Plan Office Area SW	9%	Yes	0%	No
Level 1 Open Plan Office E	9%	Yes	0%	No
Level 1 Stairwell	0%	No	0%	No
Level 2 Canteen E	10%	Yes	4%	No
Level 2 Canteen N	26%	Yes	11%	Yes
Level 2 Corridor North	19%	Yes	6%	Yes
Level 2 Lift Lobby	8%	Yes	1%	No
Level 2 Misc 1	11%	Yes	1%	No
Level 2 Misc 2	15%	Yes	8%	Yes
Level 2 Stairwell	0%	No	0%	No
	10	Cooling Reqd	6	Cooling Reqd
	19	No Cooling Reqd	23	No Cooling Reqd
	29		29	

Table E.2: Results from the establishment of a mixed mode building.

Appendix F SBEM Input Variables and Results

This appendix contains the presentation of the inputs required for SBEM and the outputs generated.

iSBEM Data Reflection Report - Actual building

Mon March 10 22:55:41 2008

Project Details	Parameter Value	Comments / Warnings
Name of the project:	"Standard Office - Base Case"	
Building address:	"Standard Office Building"	
City:	"Information not provided by the user"	
Postcode:	"Information not provided by the user"	
Building type:	"OFFICE"	
Weather (location):	LON	
Building height [m]:	9	
Building area [m2]:	1663	
Electric power factor:	<0.9	
Controls correction for lighting systems due to metering and out-of-range alarms:	0	
Building (clockwise) rotation [degrees]:	0	
Notional Building fuel:	GAS	

Owner Details	Parameter Value	Comments / Warnings
Name:	"A Client"	
Telephone number:	"Information not provided by the user"	
Address:	"Cork Road, Waterford"	
City:	"Information not provided by the user"	
Postcode:	"Information not provided by the user"	

Certifier Details	Parameter Value	Comments / Warnings
Name:	"Please, write certifier's name"	
Telephone number:	"99999999999"	
Address:	"Please, write certifier's address & FDAS"	
City:	"Please, write certifier's city"	
Postcode:	"XX XXX"	

SBEM Information	Parameter Value	Comments / Warnings
Calculation engine (version):	v1.2.a (OCT06)	
Interface to SBEM:	"iSBEM"	
Interface to SBEM (version):	"v1.2.a"	

Object Summary	Total Number in Project	Total Related Area [m2]	Comments / Warnings
Envelope/Door Constructions:	10	N/A	
Window/Rooflight Constructions:	3	N/A	
DHW Generators:	2	N/A	
SE Systems:	0	0	
PV Systems:	0	0	
Wind Generators:	0	N/A	
CHP Generators:	0	N/A	
HVAC Systems:	2	N/A	
Zones:	14	1663.9	
Envelopes:	77	4049.5	
Doors:	0	0	
Windows/Rooflights:	17	211	
Additional Thermal Bridges:	0	N/A	

	1/10 Envelope/Door Construction	Parameter Value	Comments / Warnings
>			
.	Name:	Default construction for walls	
.	U-value [W/m2K]:	0.32	
.	Cm [kJ/m2K]:	51	
.	Contains metal cladding:	NO	

	2/10 Envelope/Door Construction	Parameter Value	Comments / Warnings
>			
.	Name:	Default construction for roofs	
.	U-value [W/m2K]:	0.24	
.	Cm [kJ/m2K]:	18.04	
.	Contains metal cladding:	NO	

>	3/10 Envelope/Door Construction	Parameter Value	Comments / Warnings
.	Name:	Default construction for floors	
.	U-value [W/m2K]:	0.33	
.	Cm [kJ/m2K]:	24.2	
.	Contains metal cladding:	NO	

>	4/10 Envelope/Door Construction	Parameter Value	Comments / Warnings
.	Name:	Default construction for doors	
.	U-value [W/m2K]:	0.4	
.	Cm [kJ/m2K]:	15	
.	Contains metal cladding:	NO	

>	5/10 Envelope/Door Construction	Parameter Value	Comments / Warnings
.	Name:	MD External Wall 1	
.	U-value [W/m2K]:	0.32	
.	Cm [kJ/m2K]:	132.17	
.	Contains metal cladding:	NO	

>	6/10 Envelope/Door Construction	Parameter Value	Comments / Warnings
.	Name:	MD Roof 1	
.	U-value [W/m2K]:	0.24	
.	Cm [kJ/m2K]:	4.7	
.	Contains metal cladding:	NO	

>	7/10 Envelope/Door Construction	Parameter Value	Comments / Warnings
.	Name:	MD Ground Floor	
.	U-value [W/m2K]:	0.25	
.	Cm [kJ/m2K]:	45.8	
.	Contains metal cladding:	NO	

>	8/10 Envelope/Door Construction	Parameter Value	Comments / Warnings
.	Name:	MD Internal Wall 1	

.	U-value [W/m2K]:	1.734	
.	Cm [kJ/m2K]:	79.8	
.	Contains metal cladding:	NO	

>	9/10 Envelope/Door Construction	Parameter Value	Comments / Warnings
.	Name:	MD Internal Floor 1	
.	U-value [W/m2K]:	0.61	
.	Cm [kJ/m2K]:	45.8	
.	Contains metal cladding:	NO	

>	10/10 Envelope/Door Construction	Parameter Value	Comments / Warnings
.	Name:	MD Internal Ceiling 1	
.	U-value [W/m2K]:	0.61	
.	Cm [kJ/m2K]:	4.7	
.	Contains metal cladding:	NO	

>	1/3 Window/Rooflight Construction	Parameter Value	Comments / Warnings
.	Name:	Default glazing	
.	U-value for vertical inclination [W/m2K]:	5.279	
.	Total solar energy transmittance for normal incidence:	0.858	
.	Light transmissivity for normal incidence:	0.898	
.	Total solar energy transmittance for all angles of incidence:	0.772	
.	Light transmissivity for all angles of incidence:	0.808	

>	2/3 Window/Rooflight Construction	Parameter Value	Comments / Warnings
.	Name:	MD Base Glazing	
.	U-value for vertical inclination [W/m2K]:	2.985	
.	Total solar energy transmittance for normal incidence:	0.75	
.	Light transmissivity for normal incidence:	0.81	
.	Total solar energy transmittance for all angles of incidence:	0.675	
.	Light transmissivity for all angles of incidence:	0.729	

>	3/3 Window/Rooflight Construction	Parameter Value	Comments /

			Warnings
.	Name:	MD Solar ABS Glazing	
.	U-value for vertical inclination [W/m2K]:	2.33	
.	Total solar energy transmittance for normal incidence:	0.67	
.	Light transmissivity for normal incidence:	0.73	
.	Total solar energy transmittance for all angles of incidence:	0.603	
.	Light transmissivity for all angles of incidence:	0.657	

>	1/2 DHW Generator	Parameter Value	Comments / Warnings
.	Name:	MD DHW 1	
.	Generator Type:	Dedicated DHW boiler	
.	Fuel type:	Natural gas	
.	Generator seasonal efficiency:	0.65	
.	Later than 1998:	NO	
.	Storage system:	NO	
.	Secondary circulation:	NO	

>	2/2 DHW Generator	Parameter Value	Comments / Warnings
.	Name:	Default DHW generator	
.	Generator Type:	Dedicated DHW boiler	
.	Fuel type:	Natural gas	
.	Generator seasonal efficiency:	0.65	
.	Later than 1998:	NO	
.	Storage system:	NO	
.	Secondary circulation:	NO	

>	1/2 HVAC System	Parameter Value	Comments / Warnings
.	**General**		
.	Name:	MD HVAC 1	
.	Type:	Constant volume system (fixed fresh air rate)	
.	**Heating**		

. Heat source: LTHW boiler

. Fuel type: Natural gas

. Generator seasonal efficiency: 0.89

. System also uses CHP: NO

. **Cooling**

. Generator seasonal EER: 3.125

. **Ventilation**

. Heat recovery: No heat recovery

. **Controls Correction**

. Due to metering and out-of-range alarms: 0.05

≥	>	**1/11 Zone**	**Parameter Value**	**Comments / Warnings**
.	.	**General**		
.	.	Name:	z0/01	
.	.	Multiplier:	1	
.	.	Activity:	Cellular office	
.	.	Area [m2]:	109.27	
.	.	Height [m]:	3	
.	.	Air permeability at 50pa [m3/hm2]:	10	
.	.	Number of corners:	1	
.	.	**HVAC and DHW**		
.	.	DHW Generator:	"MD DHW 1"	
.	.	Deadleg length [m]:	2	
.	.	**Ventilation and Exhaust**		
.	.	Zonal ventilation type:	Mechanical	
.	.	Specific fan power for mechanical supply [W/ls]:	1.5	
.	.	Mechanical exhaust:	YES	
.	.	Rate of mechanical exhaust [l/sm2]:	2.08	

Specific fan power for mechanical exhaust [W/ls]:	1.5
Destratification fans:	NO
Heat recovery:	No heat recovery
Demand-Controlled Ventilation:	no demand controlled ventilation

Lighting (General)

Lighting information:	UNKNOWN
Lamp type:	C-T08-F-H-L
Efficient lamps for display lighting:	NO

Lighting (Controls)

Light controls:	MANUAL
Occupancy sensing:	NONE
Time switching for display lighting:	NONE

Global Psi Values [W/mK] for Junctions Involving Metal Cladding

Roof-Wall:	0.6
Wall-Ground floor:	1.15
Wall-Wall (corner):	0.25
Wall-Floor (not ground floor):	0.07
Lintel above window or door:	1.27
Sill below window:	1.27
Jamb at window or door:	1.27

Global Psi Values [W/mK] for Junctions Not Involving Metal Cladding

Roof-Wall:	0.12
Wall-Ground floor:	0.28
Wall-Wall (corner):	0.09
Wall-Floor (not ground floor):	0.18
Lintel above window or door:	0.53
Sill below window:	0.21
Jamb at window or door:	0.2

SBEM is an energy calculation tool for the purpose of assessing and demonstrating compliance with Building Regulations (Part L for England and Wales, Section 6 for Scotland, and Part F for Northern Ireland). Although the data produced by the tool may be of use in the design process, SBEM is not intended as a building design tool.

SBEM Main Output Document for

"Standard Office - Base Case"

Date: Mon March 10 22:55:41 2008

PROJECT DETAILS
Project Name: "Standard Office - Base Case"
Building Type: "OFFICE"
Building address: "Standard Office Building"
City: "Information not provided by the user"
Postcode: "Information not provided by the user"

OWNER DETAILS
Name: "A Client"
Telephone number: "Information not provided by the user"
Address: "Cork Road, Waterford"
City: "Information not provided by the user"
Postcode: "Information not provided by the user"

CERTIFIER DETAILS
Name: "Please, write certifier's name"
Telephone number: "99999999999"
Address: "Please, write certifier's address & FDAS"
City: "Please, write certifier's city"

Postcode: "XX XXX"

SBEM INFORMATION
Calculation Engine (version): v1.2.a (OCT06)
Interface to SBEM: "iSBEM"
Interface to SBEM (version): "v1.2.a"

WHOLE BUILDING ENERGY AND CARBON DIOXIDE PERFORMANCE

Carbon Dioxide Emissions (KgCO_2/m^2•annum)

Calculated CO_2 emission rate for the notional building	59.1 KgCO_2/m^2•annum
Improvement factor	0.2
LZC benchmark	0.1
Target CO_2 Emissions Rating (TER)	42.6 KgCO_2/m^2•annum
Building CO_2 Emissions Rating (BER) for building as designed	87.8 KgCO_2/m^2•annum

PROJECT DETAILS

Project Name: "Standard Office - Base Case"

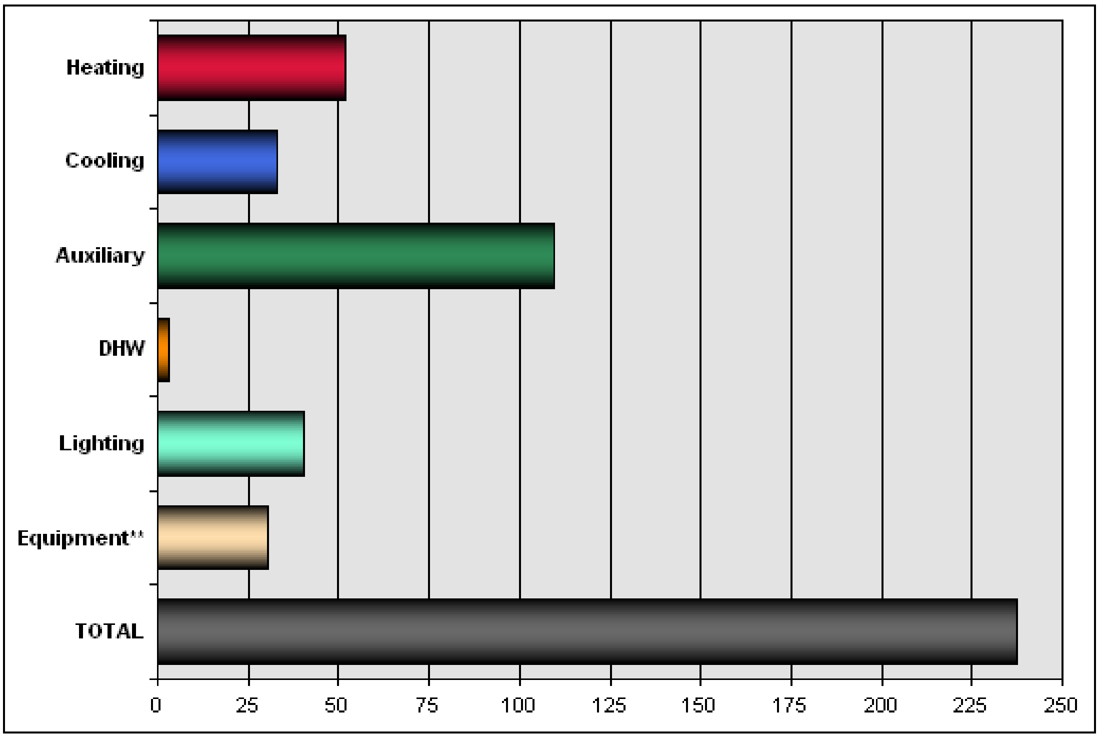
Building Type: "OFFICE"

Weather (location): LON

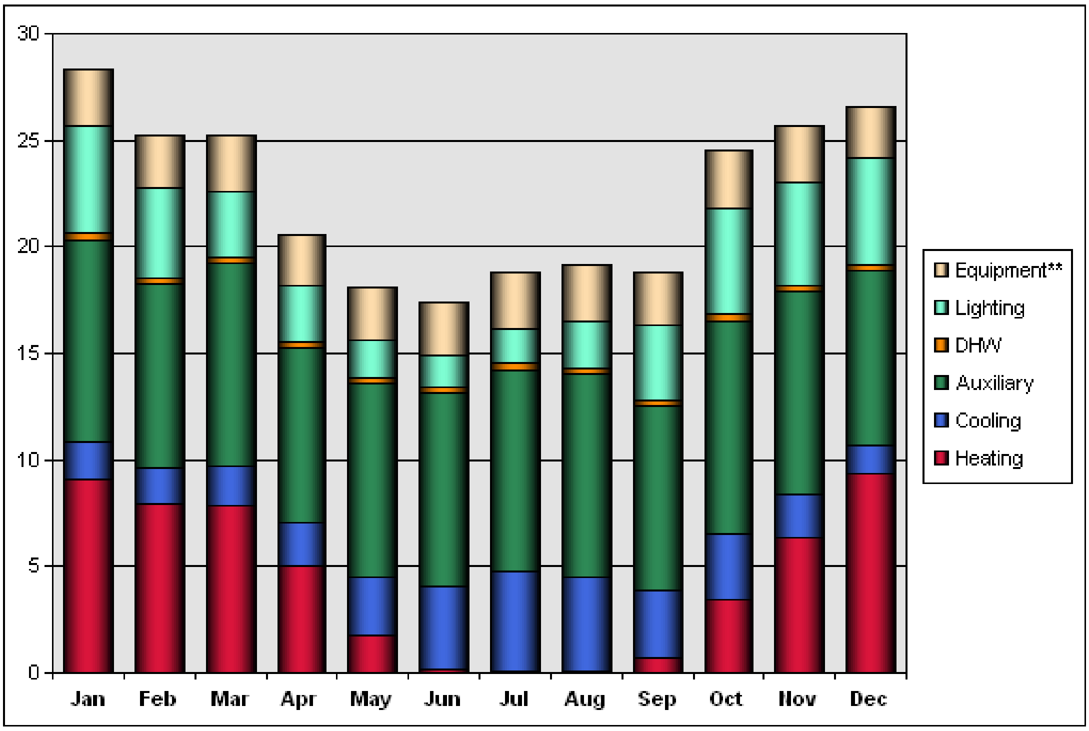
Building height: 9 m

Building floor area: 1502.92 m^2

Building Energy by End Use (kWh/m$_2$)*



Building Monthly Energy by End Use (kWh/m$_2$)*



Building Systems Energy (kWh/m^2•annum)

Month	Heating (kWh/ m^2•annum)	Cooling (kWh/ m^2•annum)	Auxiliary (kWh/ m^2•annum)	DHW (kWh/ m^2•annum)	Lighting (kWh/ m^2•annum)	Equipment (kWh/ m^2•annum)	TOTAL (kWh/ m^2•annum)
Jan	9.1	1.7	9.5	0.3	5	2.6	28.3
Feb	7.9	1.7	8.6	0.3	4.3	2.4	25.2
Mar	7.9	1.8	9.5	0.3	3.1	2.6	25.2
Apr	5.1	2	8.2	0.2	2.7	2.3	20.6
May	1.7	2.8	9.1	0.3	1.7	2.5	18.1
Jun	0.1	3.9	9.1	0.3	1.5	2.5	17.4
Jul	0.1	4.7	9.5	0.3	1.6	2.6	18.8
Aug	0.1	4.4	9.5	0.3	2.2	2.6	19.1
Sep	0.7	3.2	8.6	0.3	3.5	2.4	18.8
Oct	3.4	3.1	9.9	0.3	5	2.7	24.6
Nov	6.3	2.1	9.5	0.3	4.9	2.6	25.7
Dec	9.3	1.3	8.2	0.2	5	2.4	26.5
TOTAL	51.8	32.8	109.4	3.2	40.4	30.6	268.2