ENVIRONMENTAL IMPACT AND PERFORMANCE OF TRANSPARENT BUILDING ENVELOPE MATERIALS AND SYSTEMS

A portfolio submitted for the degree of Doctor of Engineering

by

Syreeta Robinson-Gayle

Department of Mechanical Engineering,
Brunel University

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ABSTRACT

Building envelopes are elements with a long lifetime, which provide a barrier between internal and external space and contribute to the internal environmental conditions provision. Their complex role ensures a large impact on the environmental and energy performance of a building and the occupant perception of a space. This study looks at the use of novel materials and processes to help reduce the environmental impact of buildings by improving façade and transparent roof design.

There are three main strands to the work. First, novel building components, ETFE foil cushions were examined. Physical testing has shown that ETFE foil cushions compare favourably to double glazing in terms of thermal and daylighting performance which was also noted as one of the most likeable feature by occupants. Environmental impact analysis has indicated that ETFE foils can reduce the environmental impact of a building through reduced environmental burden of both the construction and operation of the building.

Secondly, a cradle-to-gate Life Cycle Analysis (LCA) was carried out for float glass, which considered the environmental impacts of glass manufacture. The embodied energy was calculated to be 13.4 ± 0.5 GJ per tonne while the total number of eco-points 243 ± 11 per tonne. It is shown that float glass is comparable to the use of steel, and highly preferable to the use of aluminium as a cladding panel.

Finally, a concept design tool (FAÇADE) was developed by defining a large number of office facade models and employing dynamic thermal, daylighting and environmental impact modelling to create a database which can be accessed through a user friendly interface application. A parametric analysis has indicated that using natural ventilation where possible can reduce the environmental impact of offices by up to 16%. Improving the standard of the façade and reducing the internal heat loads from lighting and equipment can reduce environmental impact up to 22%.

This study makes a significant contribution to understanding the environmental impact of building envelope individual and integrated components.

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

1. BACKGROUND INFORMATION

The Engineering Doctorate Programme (EngD) is a four-year research degree, awarded for industrially-relevant research, based in industry and supported by a programme of professional development courses. The EngD Programme is sponsored by the Engineering and Physical Science Research Council (EPSRC) and was set up in response to industrial needs for more industrially-orientated research students. The industrial perspective in the work included in this portfolio was provided by Buro Happold Consulting Engineers who provided additional to EPSRC sponsorship as required by the EngD Programme.

At present, there are ten EngD centres based in British universities. The work included in this portfolio was carried out within a centre managed jointly by Brunel University and the University of Surrey. The programme administered by the Brunel/Surrey EngD centre is based on the theme of "Environmental Technology". All research work carried out aims to 'provide graduates with the necessary skills to balance environmental risks with all of the traditional variables of cost, quality, shareholder value and legislative compliance'. The Brunel/Surrey programme aims to balance a number of competing interests. The research engineer must balance both academic and industrial requirements of the research while considering the environmental issues inherent in the project undertaken. Figure E1 sums up the three elements of an EngD research project.

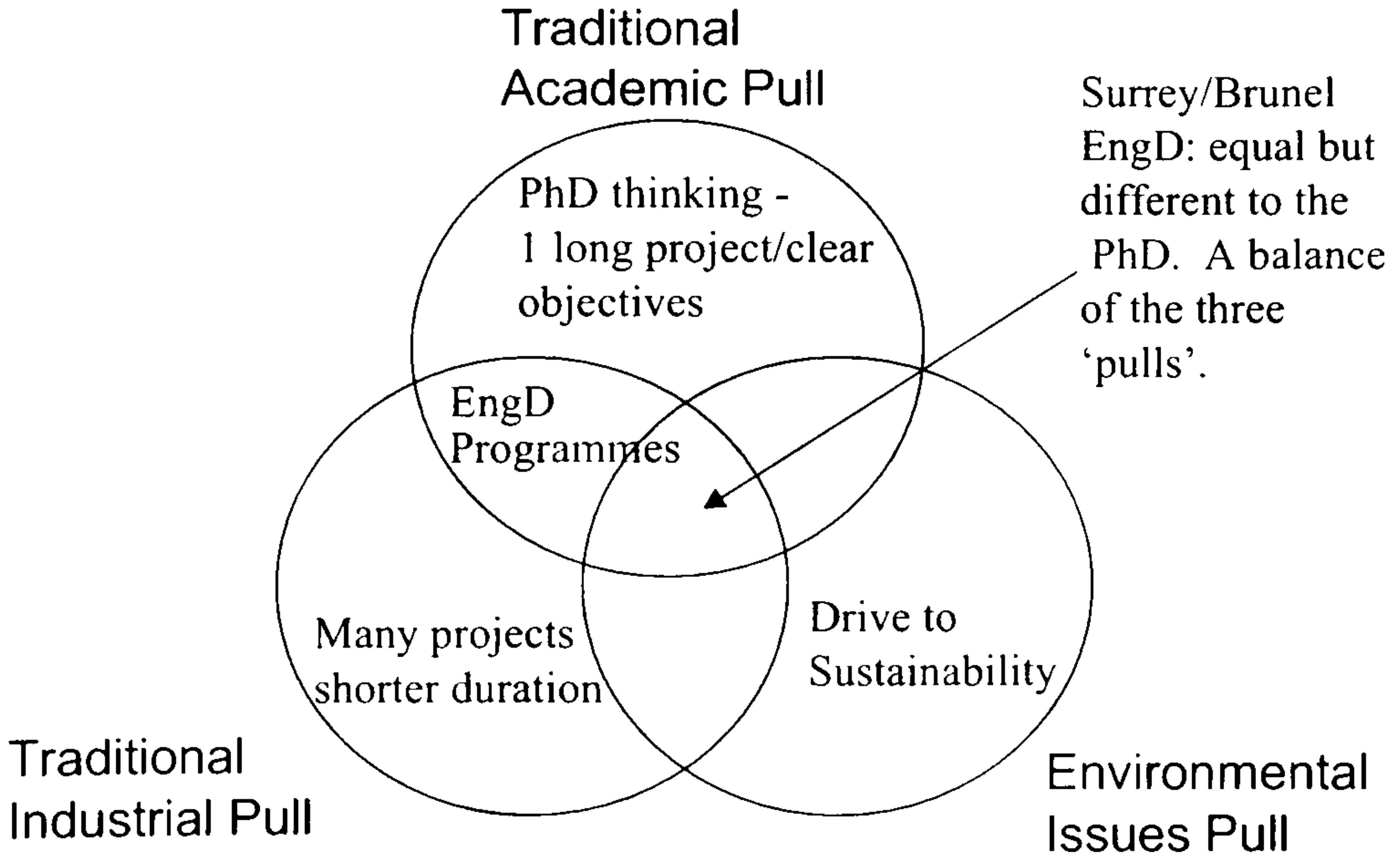

Figure E1: The three elements of an EngD research project (EngD Course Handbook, 2002).

The EngD programme includes complementary courses that must be completed by the EngD candidates, named by the Programme Research Engineers. These courses have the following aims:

- To present a view of the relationship between engineering and the environment including sociological aspects.
- To provide professional development in key business skills and competencies.
- To close any gaps in the knowledge required to undertake the research project.

The programme of courses is comprised of compulsory and elective modules and the completion of a relevant assignment is usually required after the course. The modules taken and successfully completed during this research are outlined in Table E1.

Table E1: Modules completed by the Research Engineer.

Year 1	1. Induction course: Communication & Leadership I 2. Clean Technology and Sustainability 3. Project Management 4. Life Cycle Approaches 5. Hands on Audit 6. Risk Perception and Management 7. +elective – Conference Project Management 8. +elective – Advanced Life Cycle Analysis
Year 2	9. Sociology I: Research Methods 10. Research Methodology 11. Leadership II 12. Environmental Law
Year 3	13. Sociology II: Environmentalism 14. Risk Management 15. Marketing 16. Scientific Paper Writing 17. +elective – EPSRC Graduate School
Year 4	18. Talking to the Media 19. Financial Management

Research Engineers participate in the EngD annual conference attended by all Research Engineers, supervisors and invited delegates. Research Engineers write a paper on their research which is included in published proceedings and present this to the conference either orally or with a poster. The following papers were written for the EngD conferences (in addition to publications listed in Section 4):

1. Robinson-Gayle S, Kolokotroni M, Cripps A, Tanno S, (1999). *ETFE Foils: Application as a Building Material,* Proc. Engineering Doctorate in Environmental Technology Annual Conference 1999, Brunel University and the University of Surrey, 14-15 September 1999.
2. Robinson-Gayle S, Kolokotroni M, and Tanno S, (2000). *ETFE Foil Cushions: Effect on Internal Environment Performance,* Proc. Engineering Doctorate in Environmental Technology Annual Conference 2000, Brunel University and the University of Surrey, 12-13 September 2000.
3. Robinson-Gayle S, Kolokotroni M, and Tanno S, (2002). *A simple tool to integrate the environmental performance and impact of facades in buildings,* Proc. Engineering Doctorate in Environmental Technology Annual Conference 2002, Brunel University and the University of Surrey, 12-14 January 2002.

In addition to attending courses, submitting assignments and presenting the results of their project to the EngD Conferences, Research Engineers complete a progress report every six months. The aim of these progress reports is to inform the EngD Programme Management Committee and supervisors of the progress made towards the completion of research projects at given stages during the programme.

This section (Section 1) gave a brief introduction to the EngD Programme in order to describe the broad framework of the research work included in this portfolio. The following sections of the executive summary describe the research carried out. This includes an introduction to the research topic and objectives (Section 2). Section 3 describes the research methods and main results of the three research projects presented in this portfolio. A statement of the original facets of this research work follows together with a list of papers published in scientific refereed journals and conferences (Section 4). Section 5 lists the participation of the Research Engineer in commercial projects to give an understanding of the experience gained by the Research Engineer during the 4 years of the EngD Programme. Finally, Section 6 describes the contents and layout of this portfolio.

2. INTRODUCTION TO THE RESEARCH TOPIC AND OBJECTIVES

The construction sector accounts for 46% of the greenhouse gas emissions in the UK (CIBSE, 1999a). This sector also has a large impact on resource depletion and is cited as one of the most environmentally polluting industries (Chatfield, 1998). This data relates to both domestic and commercial buildings and is exacerbated by the variety of the building stock. The commercial building sector represents an opportunity to make significant improvements in the environmental impact of the construction industry, because commercial buildings have a shorter demolition and refurbishment cycle (Aldaberth, 1997). This has led government and other agencies to focus on the reduction of greenhouse gases emitted from the construction industry as a method of reducing the overall greenhouse emissions of the UK.

The processing, manufacture, transport and erection of buildings is an energy-intensive process, but the length of building occupation ensures that the use phase of construction attracts the greatest environmental impacts. The environmental impacts associated with use phase of construction are primarily influenced by two parameters; building design and user behaviour. Energy-conscious design and occupant education can influence the energy consumption of the building during the use phase.

The building envelope is an element with a long lifetime which performs several tasks; a barrier between the internal and external space, admittance of daylight, control of solar gain, provision of thermal insulation and in some cases provision of natural ventilation. The complex role of the building façade means that it can have a large impact on the energy performance of a building and the occupant perception of a space.

The application of new technologies to the building façade can reduce the energy consumption and environmental impact of a building in one of the following ways:

- The façade can be instrumental in the application of low-energy environmental technologies, e.g. passive solar design, design for daylighting.

- Novel methods and materials can be applied to the façade design to reduce embodied energy and energy consumption of the building.
- Current building technology can be used optimised to provide lower energy use.

Research Objectives

In line with the above, the main aim of this research programme has been to use novel materials and processes to help reduce the environmental impact of buildings by improving façade and transparent roof design. The specific objectives were the following:

- Investigate, understand and provide information on the best use and environmental impact of novel materials for building facades.
- Investigate and understand in depth the environmental impact of façade materials and systems through their life cycle.
- Develop an assessment method to investigate the impacts of façade choices on internal and environmental performance of buildings.

These have been achieved by carrying out three complementary research projects:

1. A novel building material was examined and an assessment of the impacts this material has on the environmental impact of buildings was carried out.
2. An environmental assessment method was applied to a construction material in a novel way.
3. A concept design tool was developed, which can be used to assess quickly the environmental impacts and internal conditions created when implementing a particular façade technology in office buildings.

3. RESEARCH METHODS AND MAIN RESULTS

This section summarises the research methods and main research results from the three research projects carried out as part of this EngD Programme.

3.1 Project A: ETFE Foil Cushions And Their Use In Buildings

ETFE Foil cushions are a multi-layer cladding system that consist of several layers of ETFE foil (100μm -200μm thick) heat sealed and clamped in a frame. They are inflated using a small pump to a pressure of 250 – 400 Pa and "topped up" intermittently. ETFE was first used as a roofing material in a building in Burgers Zoo, Arnheim in the Netherlands in 1981. It has subsequently been used in various buildings predominantly in the United Kingdom and Germany. This project examined both the effects of ETFE manufacture and its use in buildings and considered its performance in terms of fitness for purpose and in comparison with glass; the common alternative. The project was a collaborative project and was completed with the contribution of several staff members of Buro Happold Consulting Engineers and external organisations. The main results are summarised below while the details of the work carried out are discussed in Part A of this portfolio.

Physical Properties

Several tests were carried out, mainly investigations into materials properties. A series of light transmission tests were carried out at the Pilkington Technology Centre and National Physical Laboratory (NPL) and a set of thermal tests were carried out at the British Board of Agrément (BBA). Finite element analysis was additionally carried out to extend the results of the thermal tests. The Research Engineer did not carry out the tests or computational analysis but the interpretation of the results has formed a significant part of the work performed.

Lighting tests has shown that ETFE transmits 94 – 97% of visible light, a higher percentage of visible light than 6mm single glass, which only transmits 89%. The frequencies of light transmitted are of a wide enough spectrum to encourage the growth of plans and promote good colour rendering. Light is transmitted at a 180° angle through the cushions with little scatter.

Thermal tests on a small sample of ETFE foil cushion showed that the average U-value is 2.6 Wm^2K^{-1}. This equates with values measured for double glazing. These tests also showed that the thermal transmission through the frame has a large impact on the overall U-value of the cushions.

The results from the finite element analysis correlated well with the physical measurements carried out by the BBA. This is because radiative heat transfer is the main mechanism of heat transfer which can be accurately modelled using the finite element technique. This is useful because the complex configuration of ETFE Foil Cushions means that standard U-value calculations are very difficult to carry out with any degree of accuracy. The application of this method to a built example showed that larger cushions had a lower U-value closer to 2.1 Wm^2K.

Environmental Performance

The life cycle phases of ETFE Foil cushions were considered in terms of their impact on the environment and some comparisons are made with glass and other materials. It was concluded that there are some adverse environmental impacts that result from ETFE manufacture. However, these must be balanced against the adverse environmental impacts from the use and manufacture of glass. Using ETFE can reduce the overall embodied energy of a structure. The use of ETFE instead of double-glazing can provide energy consumption reductions due to the improved U-value. The low density of the ETFE foil cushions also results in a reduced steel structure.

Overall, it is concluded that ETFE foil is an appropriate technology for certain building applications. This is the case particularly where the volume of space is large and high light levels are required. The physical characteristics of the material enable it to be used in a variety of situations where a large expanse of glass is not suitable. These allow the weight of the structure to be greatly reduced whilst providing the same level of stability. ETFE foils can improve the environmental performance of a building from two points-of-view; there is the opportunity to reduce the overall environmental burden incurred from the construction process itself

3.2 PROJECT B: LIFE CYCLE ANALYSIS (LCA) OF ARCHITECTURAL GLASS

Following the theme of environmental impact of building façade materials, this project carried out a cradle-to-gate LCA of Pilkington float glass which considered the environmental impacts of glass manufacture. The work carried out is presented in detail in Part B of this portfolio. The method of analysis and main results are summarised below.

A full LCA was carried out for a specific Pilkington float glass plant. This included a full inventory analysis of 356 flows. The individual flows associated with the float glass process are useful for calibrating the system and investigating any opportunities for improvements. However, it is difficult to evaluate the overall result in this format, hence, the flows were used to produce two types of results, the embodied energy (ee) of the system and the environmental impact in eco-points. These two analytical methods allow the raw data to be compared with other systems and express the results from the LCA in more familiar units. This part of the work was carried out using the LCA software tool (TEAM^{TM}).

Embodied Energy: This was calculated to be 13.4 ± 0.5 GJ/tonne. The contribution of four subsystems to the total embodied energy of the float glass process was calculated; building, process, raw materials and transport. From these, *process* and *raw materials* make the highest contribution to embodied energy; 74.8% and 23.3% respectively. The *building* subsystem contributes 0.4% whilst *transport* contributes 1.5%.

The eco-point rating method selected for this study is the Eco-Indicator 99, which is based on a scoring approach to integrate all impact parameters in one final value. This method was developed by two Dutch companies in 1995 (DUIJF Consultancy BV and PRé Consultants) and has since been updated to produce the Eco 99 indices (Goedkoop, 1998 and Goedkoop, 2000). The Eco-indicator method reduces the environmental flows in the inventory using 10 indicators which are then weighted using a reduction factor. This reduction factor is associated with the seriousness of the significant harm caused by the environmental impact. The 10 indicators are grouped by the sphere they affect into impact categories. There are three separate impact categories which are weighted:

- Damage to human health; measured in DALYs (Disability Adjusted Life Years). This is an indicator developed by the World Health Organisation.
- Damage to Ecosystem Quality; and in particular effects on diversity measured in PDF (Potentially Disappeared Fraction).
- Damage to Resources; this category looks at the surplus energy required to extract lower quality mineral resources and includes the depletion of agricultural and bulk resources.

Eco-points: The total number of eco-points was calculated to 243 ± 11 per tonne. The contribution of the three impact categories was also calculated. It was found that approximately 85% of the eco-points are associated with the *Damage to Human Health* indicator, 12.5% with *Damage to Resources* and 2% with *Damage to Ecosystems.* From the 85% of the *Damage to Human Health* eco-points approximately 56% are contributed to *respiratory effects* and 28% to *climate change damage.* Arranging the eco-points attributed to the Pilkington Float glass process by sub-system, it was calculated that a building contributes 0.3%, the process 33.2%, raw materials, 65.6% and transport 0.8%. Building and transport contributions are small as in the embodied energy index but the effect of process and raw materials is inversed. This is mainly due to respiratory effects of raw materials (in particular soda ash) which are included in the calculation of eco-points.

Both of the described indicators suggest that the environmental burdens associated with the Pilkington Float Glass Plant examined are in line with those that would be expected by a plant of this type in the UK. A comparison of the eco-points attributed to other primary processed materials (presented in Part B) has shown that Pilkington Float glass is comparable to the use of steel, and highly preferable to the use of aluminium as a cladding panel. The use of float glass in a cladding panel would provide other benefits to the building space, such as natural light and a connection with the external environment.

3.3 PROJECT C: FAÇADE CONCEPT DESIGN TOOL

During the first two years of this EngD Programme and through involvement in a number of commercial projects, it became apparent that key decisions about the building façade are usually taken during the concept design stage of a building while decisions about the method of providing the environmental conditions are often taken later in the design process. It was decided that for the remaining period of the EngD Programme to address this issue by developing a concept design tool, which allows the design team to investigate the effect of façade design on the resulting internal environmental conditions and energy use. The concept design tool has been developed by carrying out detailed thermal, lighting and environmental impact modelling for a number of generic office building façade designs and a range of parameters which directly affect the environmental performance of an office building. This project focussed on the development of a façade concept design tool for a number of generic office building façade designs. The study focuses on offices because they are the service sector building type which consumes a high percentage of delivered energy (17%), (DTI, 1997). This is comparable to the retail (18%) and hotel and catering (17%) building sectors. Office building types and energy consumption by type and service are well documented in the UK. Moreover, occupants of office buildings are more permanent and stable and therefore the opportunity of influencing the operational energy consumption is high.

This section summarises the rationale and methodology for developing the concept design tool. A more detailed discussion is included in Part C of this portfolio.

Concept design models can be divided into two categories:

- Results are extracted from built-in databases derived from advanced modelling for a specified number of cases (in the form of parametric analysis) and weather data (usually country restricted).
- Results are calculated from built-in (usually energy and thermal) simplified or fast-to-run algorithms and appropriate databases for other variables of interest such as lighting and acoustics.

In this project, it was decided to develop a tool using the 'database' approach because:

- the results would be based on detailed and advanced modelling and therefore more accurate;
- user misinterpretation of results would be more difficult as the selection of cases is restricted by the development of the tool.

The tool was developed by using three simulation models:

- A dynamic thermal simulation model provided energy demand and internal thermal conditions data, (TAS).
- A steady state lighting simulation model calculated the lighting environment based on the optical properties associated with the façade, (Ligthscape).
- A Life Cycle Analysis (LCA) accounting tool (SimaPro), calculated the impacts associated with the construction and use of the building based on information about the construction and energy use in the building over a fixed time.

The following parameters were considered for the development of the building model:

- Office type
- Facade type
- Shading type
- Internal environmental conditions and energy practice
- External conditions.

The combination of the above parameters resulted in 150 building models. Simulations were carried out with the three software systems and a database was created with required outputs. Visual Basic programming was used to create the front end of the tool through which the user can interrogate the database. Two levels of information are contained within the output parameters. Annual summary outputs have been chosen for the first level while more detailed information is provided at a second level.

Summary Output: This includes information on the following parameters:

- Heating Demand
- Cooling Demand
- Maximum comfort temperature.
- Number of hours that maximum temperature exceeds 25°C and 28°C.
- Minimum comfort temperature.
- Daylight Levels.
- Embodied Energy.
- Eco-points.

Detailed Output: In addition to the summary output, more detailed information about the examined façade is provided by the tool as follows:

- Thermal comfort. Average hourly comfort internal temperature and relative humidity can be assessed in a tabular or graphical form. These data are provided for one week for each month of the year. In addition, extreme comfort internal temperature and relative humidity for the coldest and hottest month of the year are provided.
- Lighting. Daylight distribution diagrams are provided which represent average conditions using the overcast sky model. In addition, minimum and maximum availability daylight distribution diagrams are provided.
- Heating and cooling energy demand: These are provided for each month of the year and by category (heating, cooling, humidification and dehumidification).
- Environmental Impact. Eco-indicator points are provided for each orientation, which can be presented by sphere of impact, or sub-system responsible for the impact.

Parametric Analysis

A parametric analysis of a subset of case study buildings was carried out. The summary performance indicators were presented for two of the building options; the high standard façade with low internal gains and the standard façade system with high internal gains are presented. These cases were presented for both naturally-ventilated and air-conditioned buildings.

Naturally-ventilated buildings have a lower environmental impact, up to 16%, than air-conditioned buildings. The application of appropriate shading can help to overcome overheating and reduce cooling loads, particularly in facades with large areas of glazing. Improving the standard of the façade and reducing the internal heat loads has beneficial environmental effect, reducing the environmental impact by 17% in naturally-ventilated façades and 22% in air-conditioned façades.

The parametric analysis shows that the double-skinned façade offers a reduction in the heating energy load associated with a curtain wall façade. The double-skinned façade has the highest embodied energy of the façade types, 2120 MJ/m^2, however, the use of this façade can reduce environmental impact of the curtain wall by up to 20%. This can lead to significant energy savings and reduction in environmental impact in office buildings in urban environments, because the curtain wall is one of the most popular façade types in the bespoke prestige office.

In conclusion, the FACADE selection tool which has been developed can directly help designers to realise potentially significant reductions in the energy consumption and environmental impact of office buildings by selecting at the concept design stage optimum façade design for typical urban office buildings. The parametric analysis facility may also help designers to take informed decisions about the concept design of façades for other building types and different climatic conditions.

4. ORIGINAL CONTRIBUTION TO THE BODY OF KNOWLEDGE

The particular facets of the work that are original are listed below:

- A novel material that can be used as an alternative to glass for transparent parts of a building's roof was studied. Its properties have been quantified for the first time and its applicability to buildings has been demonstrated through field measurements.
- The application of the life cycle analysis technique to architectural glazing which included previously ignored contributory data.
- A concept design tool was developed for evaluating the effect of the façade design on the building internal thermal and lighting conditions, energy demand and environmental impact in office type buildings in England.

4.1 List of publications

The research results of this EngD programme have been published, both in peer reviewed journals and presented at both academic and professional conferences. The peer reviewed journal papers can be found in Appendix E1.

PEER REVIEWED JOURNAL PAPERS

1. Robinson-Gayle S, Kolokotroni M, Cripps A, Tanno S, (2001). *ETFE Foils: Application as a Building Material*, Construction and Building Materials, Vol 15, pp323-327.
2. Robinson-Gayle S, Kolokotroni M, Tanno S and Cripps A, (under review). *Environmental Impact Conceptual analysis for Office Building Typical Facades*, submitted to Building Research & Information.

Peer Reviewed Conference Papers

3. Robinson-Gayle S, Kolokotroni M and Tanno S, (2001). *ETFE Foil Cushions: Effect on Internal Environmental Performance*, Proc. CLIMA2000 Conference, Napoli, Italy, 15-18 September 2001.

Professional Conference Papers

4. Kolokotroni M, Robinson-Gayle S, and Tanno S, (2001). *ETFE Foil Cushions in Roofs and Atria*, ICBEST-2001, Proc. International Conference on Building

Envelope Systems and Technology (ICBEST), Vol 2, pp305-309, Ottawa, June 2001.

5. Kolokotroni M, Robinson-Gayle S, and Tanno S, (2001). *Improving the Performance of ETFE Cushions*, ICBEST-2001, Proc. International Conference on Building Envelope Systems and Technology (ICBEST), Vol 2, pp89-100, Ottawa, June 2001.

Articles in Professional Journals and Publications for Research Dissemination

6. Robinson-Gayle S (2002). *Environmental Impacts of Fibre Reinforced Composites.* In Cripps A, Fibre Reinforced composites in construction C564, Construction Industry Research and Information Association (CIRIA) London.
7. Robinson-Gayle S, Kolokotroni M, Cripps A and Tanno S, (1999). *Foil Wrapped - Research Shows That ETFE Can Be A Suitable Alternative To Glass In Roofing Projects*, Building Design, August 27, 1999.
8. Robinson-Gayle S and Tanno S, (1999). ETFE Foil Cushions as an Alternative to Glass in Roofs and Atria: General Introduction. Buro Happold, London.
9. Robinson-Gayle S and Wang H, (1999). ETFE Foil Cushions as an Alternative to Glass in Roofs and Atria: Detailed Materials Investigation. Buro Happold, London.
10. Robinson-Gayle S, (1999). ETFE Foil Cushions as an Alternative to Glass in Roofs and Atria: Buildings in Use. Buro Happold, London.

5. INVOLMENT IN COMMERCIAL PROJECTS

In the spirit of the EngD Programme, the Research Engineer has gained valuable engineering experience by participating in commercial projects carried out by the sponsoring organisation Buro Happold Consulting Engineers. A brief description of these projects follows:

HIGHBURY STADIUM

The proposed new Arsenal Stadium in Highbury is at the stage D of the planning process. The client Arsenal Football Club was interested in maximising the amount of daylight in the wavelength range of 400 – 700 nm, which reaches the pitch as this is thought to have a direct effect on the growth of the grass.

Several translucent polymeric materials were proposed for the lip of the roof. It is relatively easy to analyse the amount of total hemispherical light transmitted through a sample. However, in order to measure the light transmitted at various angles a tool which transmits single wavelengths and collects them at single angle must be employed. The National Physical Laboratory (NPL) has a tool that is capable of measuring angular hemispherical transmittance. The Research Engineer procured a series of physical test to aid the selection of the most appropriate material for this application.

FINSBURY SQUARE

The Bloomberg Building at 50 Finsbury Square was one of the first buildings that the Research Engineer had an involvement with when this EngD Programme started in 1998. This building was completed in 2000 and has been occupied by Bloomberg L. P. for the past three years. The structure is eight storeys high with a double glazed curtain wall set behind a large stone exo-skeleton.

The failure of a stone element resulted in the original contractor (Malling Precast Ltd) carrying out extensive remedial work. The Research Engineer carried out a 100% visual survey of the building in order to determine the condition of the façade before this work commenced. Subsequently, she was involved in weekly inspections to ensure the quality of the remedial work. This gave an opportunity to investigate the as-built drawings and analyse the method of stone failure. It also gave an opportunity to carry out some post remedial inspections of various fixings in the structure. A final post remedial work inspection was carried out in conjunction with another firm of consulting engineers in order to ensure that the contractor had not caused any additional damage to the façade during the remedial works.

POLYMER COMPOSITES IN CONSTRUCTION

Polymer composites are currently in use in the construction industry where complex lightweight structures are required, or as *in situ* reinforcement beams. The project that Buro Happold have become involved in attempts to provide full and clear information about the use of polymer composites in construction to designers and architects. It was commissioned by the Construction Industry Research Information Agency (CIRIA). The resulting document discusses why this class of material is not more widely used in construction, addressing issues such as: strength, safety and environmental impact. The Research Engineer has written a chapter of the document which describes an environmental assessment of composites in construction and the effects of their use on the environmental impact of the resulting structures.

BBC WHITE CITY

Buro Happold Consulting Engineers are providing engineering services to the new development at White City for the BBC. According to their 20/20 vision strategy, the BBC aim to procure sustainable structures that can adapt to the changing nature of their business for the next century. There will be eight new buildings built on the site where the current BBC White City One stands, although only two of them have been entered for planning in this phase.

The central office building is a mixed mode building using natural ventilation and other passive techniques with mechanical heating and ventilation to provide the best internal conditions. This would mean providing the maximum heating and cooling during the peak seasons, using a combination of methods for part of the year, whilst using only passive techniques for the autumn and spring. The main effort of the Research Engineer was a study to maximise the amount of time that passive systems can be used. This has involved an attempt to provide an LCA approach to the servicing and design of the buildings on the site.

Conclusion

The work of a Façade Engineer at Buro Happold is mainly concerned with the building envelope and its interaction with other spheres, such as:

- architectural demands
- internal conditions
- structural integrity
- interaction with weather and external conditions
- compliance with legislation and codes

The involvement of the Research Engineer in the above mentioned projects has transformed the Research Engineer from one who had a scientific research background into a practical engineer. The Research Engineer was trained as a Materials Scientist and as such has an in depth knowledge of materials from a microscopic view point. The construction industry uses a limited palette of materials in a variety of macroscopic ways, relying on the properties of the materials to further the design process. Detailed involvement with the construction industry through inception to construction and eventually remediation has allowed the Research Engineer to develop an expert understanding of the construction process. This knowledge has informed the direction of this EngD: leading to the development of the research described in Part C of this portfolio.

Conversely, Buro Happold's involvement in this project has led to greater integration of the façade design process with other disciplines internally. Buro Happold Façade Engineering is now more aware of the environmental impact associated with the structures design. Questions about the ethics associated with a design are asked as standard rather than as an after-thought. Buro Happold has considered this EngD successful enough to sponsor three more EngD students, two of whom are from the Brunel/Surrey EngD program.

6. CRITICAL REVIEW

This portfolio describes work carried out by the research engineer between 1998 and 2002, during this period the legislative framework to the use of transparent materials in buildings. This critical review intends to review the background to the research and discuss the work carried out with regard to these changes.

6.1 THE RISE OF FENESTRATION

The design of the façade has an influence on the behaviour, character and of a building and the façade may account for between 10 and 30% of the total building cost (Fernandez 2001). Changes in construction technology have allowed a major shift in the design of buildings. The "light box", a lightweight structure with a mainly transparent skin, is the now the normal expression of prestige architecture. Load bearing structure has moved to the building core and the external wall has remained an object of expression (Colomban 1997). This has allowed the growth of façade technologies and the development of façade engineering as a separate discipline with its own vernacular. An unfortunate side effect has been the creation of buildings whose internal conditions are not optimal. Mechanical processes, which have a high energy consumption, have bridged the gap between constructed and required internal environments. Recent research has been devoted towards the effort to integrate the architectural aspirations for the façade with its required performance and contribution towards reducing the energy consumption of the building as a whole.

Transparency in architecture

The use of glass in architecture is a metaphor for transparency based on a paradigm that began after the first world war. The ideal of transparency both physically and metaphorically has had a major influence on the development of construction in the 20th century. The wholly glass construction was envisioned before it could be built. German writer Scheebart (1914) described a world revivified by glass architecture.

> If we want our culture to rise to a high level, we are obliged for better or for worse, to change our architecture, and this only becomes possible if we take away the closed character from the rooms in which we live. We can only do that by introducing glass architecture which lets in the light of the sun the moon and the stars not merely through the windows, but through every possible wall, which be made entirely of glass.

Several technological changes, most notably the development of consistent steel products for the structure, the advent of air conditioning (Banhan 1969) and improvements in glass manufacturing processes, enabled the realisation of the wholly transparent glass building.

Swieten (2003) argues that the supremacy of glass as a material will be ended in the near future by the lack of architectural expression that the material affords due to the lack of contrast. Although the use of completely transparent towers, such as those envisioned by Meis Van der Rohe, see Figure E2, may become outmoded, glass and similar transparent materials will always form a major component of buildings due to the requirement for engagement with the external environment and a preference for daylight in internal spaces.

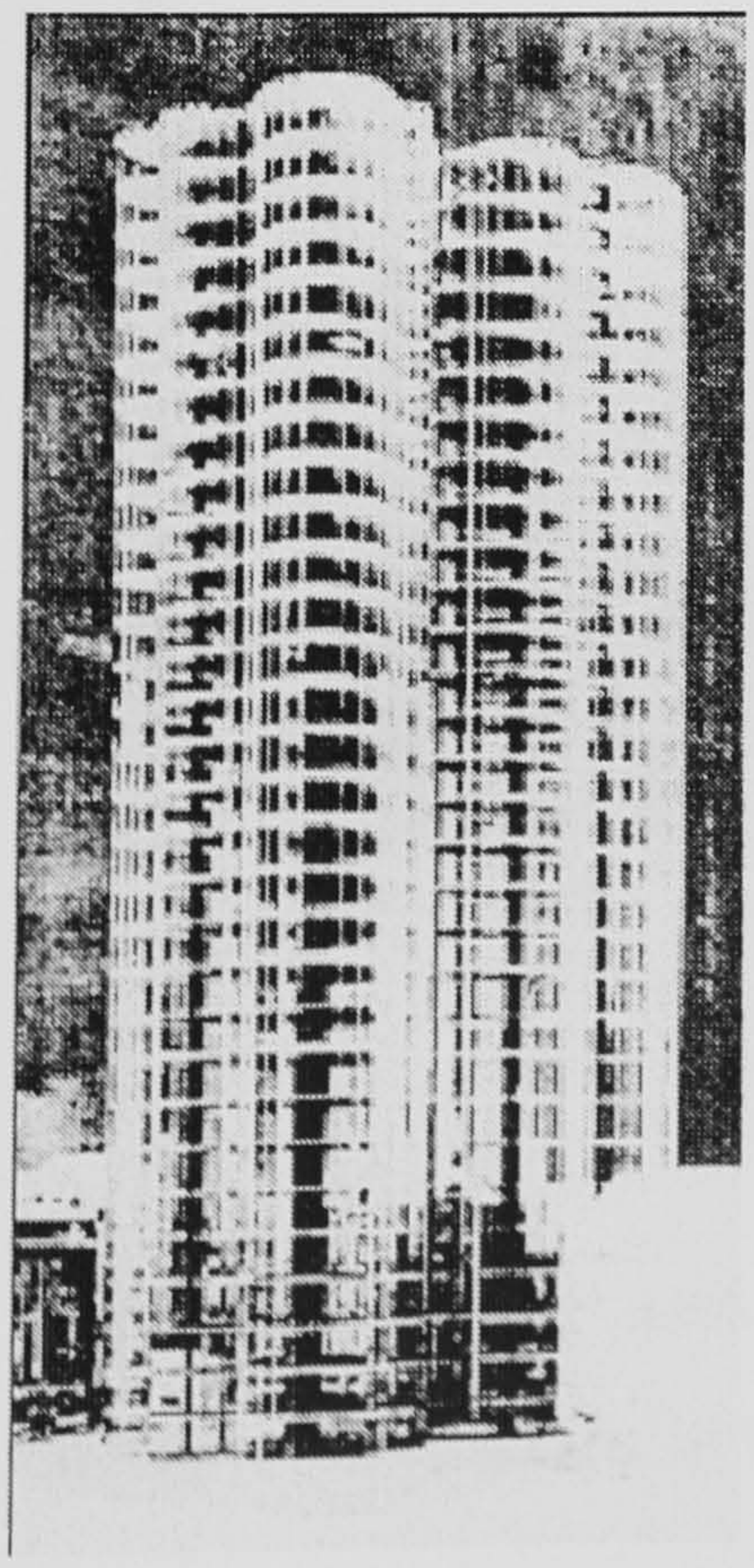

Figure E2 Glass skyscraper designed for the Berlin Art Exhibition 1922.

The problems of using large areas of glazing in external walls include:

- Solar glare.
- Unequal solar radiation on those sitting near the glazing.
- Increased energy consumption.

Energy Consumption

Energy use in buildings has been monitored and analysed with the intention of benchmarking energy use (Moss 1994, Field 1992, DTI 2002 and DETR 1998) for In 1994 buildings accounted for 46.6% of UK final energy consumption and 46.9 % of CO2 emissions. Non-domestic buildings in the public and commercial and industrial sectors accounted for 13.1% of UK final energy in consumption in 1994 (Moss, 1994) this proportion had remained static and was still 13% in 2001. However this is a rise from 19.23 to 20.85 million tonnes of oil equivalent and increase of 12% over five years, Figure E3. Oka (1993) linked the consumption of energy in Japan to the energy consumed by the building lifecycle to give a total energy consumption of 8-12 GJ/m^2 of floor area for typical office buildings.

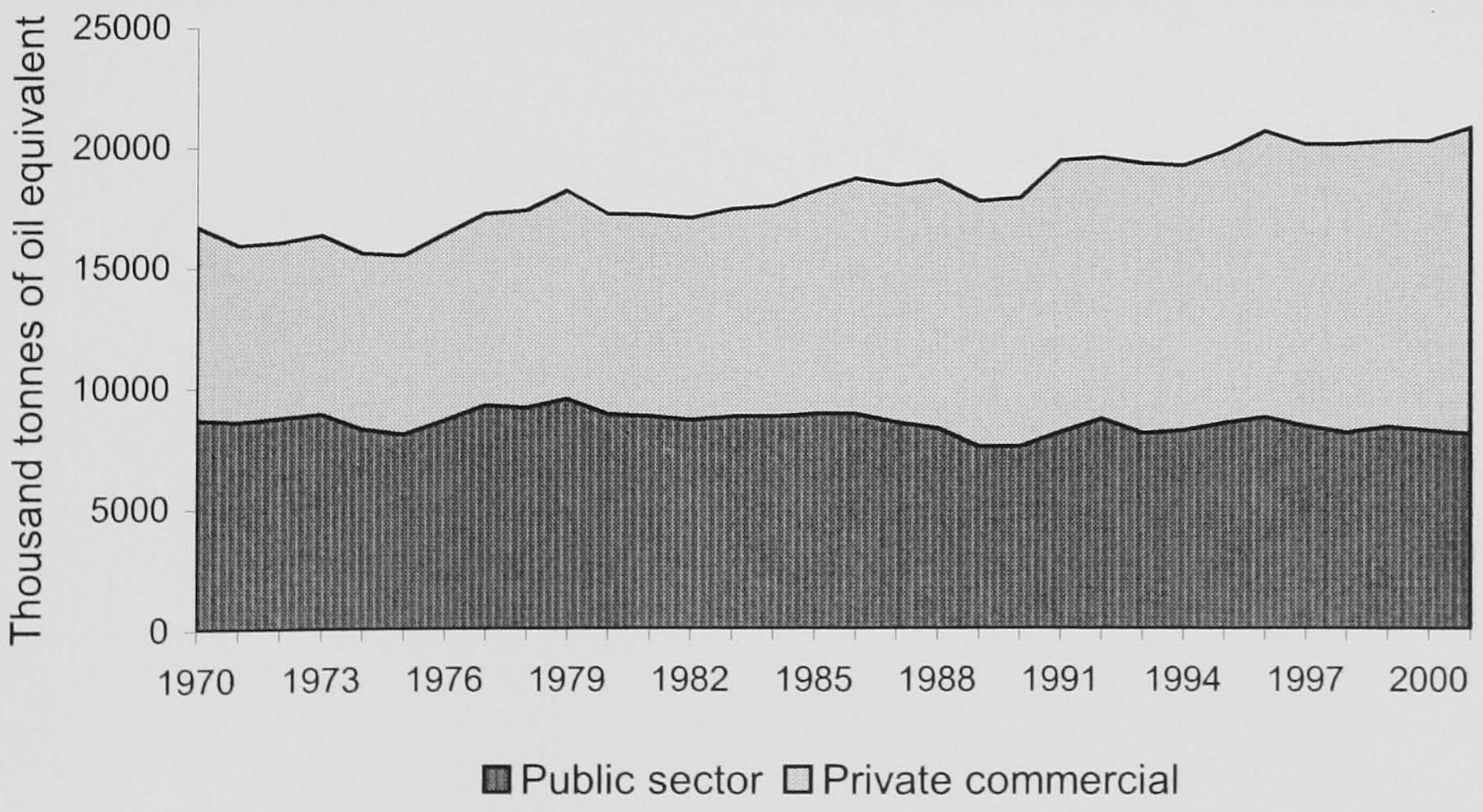

Figure E3 Service sector energy consumption 1970 to 2001. Source: DTI (2002) Energy consumption in the UK.

The way that energy is consumed in buildings in this sector has changed over the past thirty years, the use of coal and oil has fallen in line with other sectors and the use of electricity has changed.

The projections for energy demand are that the energy required by will increase by approximately 1% p.a. until 2010 (DTI 2001), with energy demand from non-domestic public and commercial sectors increasing from 13% to 14% of total final energy demand. This can be directly traced to increase of lighting and air conditioning in commercial buildings. Service sector consumption has been affected by an increase in the output, i.e. an increase in the size of this sector level of employment and changes in technological innovation. This increase would have been larger if there had not been improvements in energy intensity, which are both energy efficiency and structural changes to the public and private sectors. It is a combination of more efficient heating systems and improved energy management leading to appliances being switched off when not in use.

The energy efficiency of new buildings is critical to a sustainable future (Sorrell 2003), because new construction allows the greatest opportunities to incorporate energy efficient technologies into a building. Choices made about the form, fabric and orientation of a building will determine the building's performance throughout its life

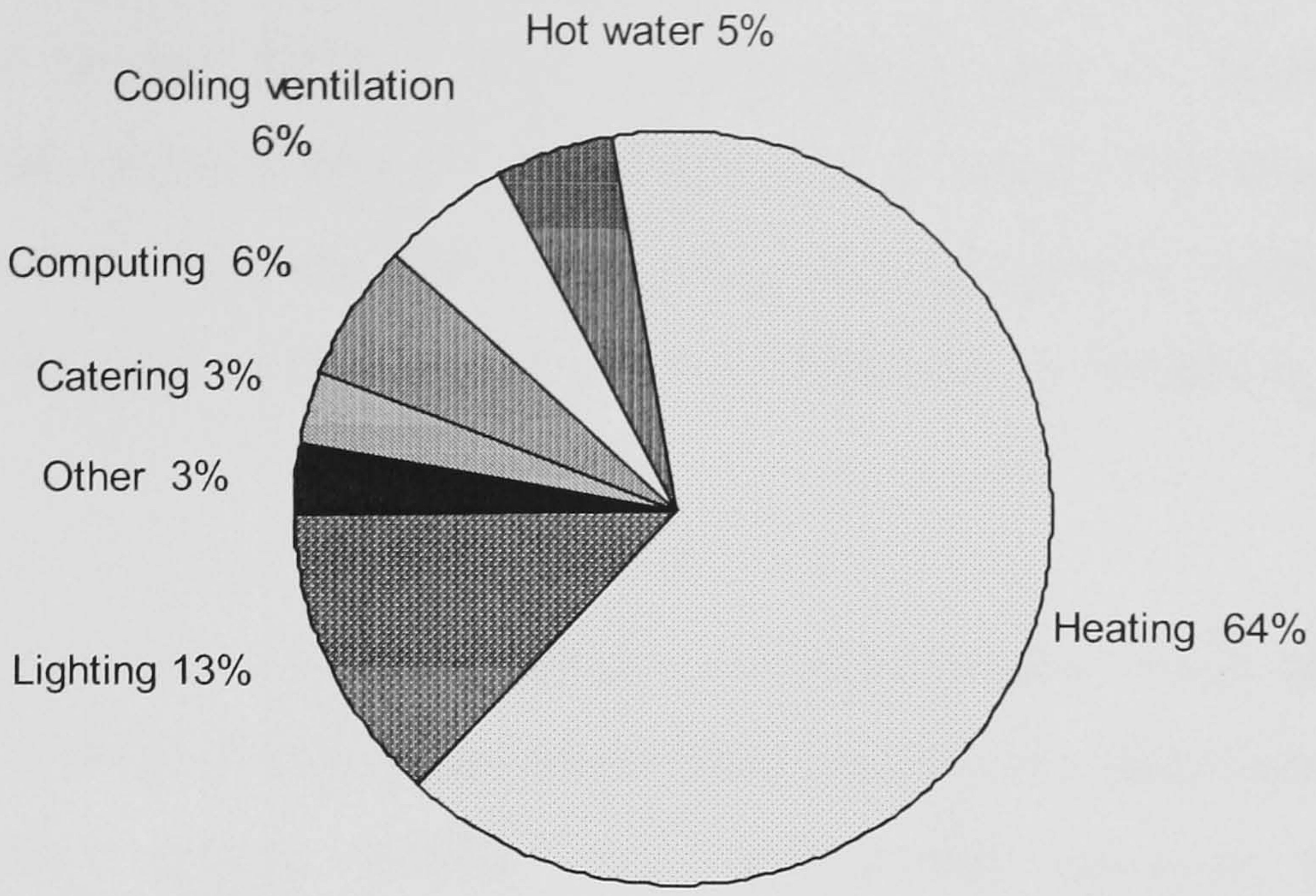

Figure E4 Energy consumption by end-use: UK commercial buildings 2000.
Source: DTI (2002)

Figure E4 shows that while space heating remains the single largest energy consumer for commercial buildings, lighting, computing and cooling and ventilation are also significant contributors. Addressing the following can reduce energy consumption in buildings:

- artificial lighting,
- additional space heating,
- cooling ,
- mechanical ventilation
- and increasing the energy efficiency of computers.

Daylighting reduces energy consumption by decreasing a reliance on artificial light (Leslie 2003). This results in a reduction of internal cooling load from the lights as well as the removal of the energy consumed by the lighting. This reduction can be substantial, studies show energy savings of as much of 50% along the window wall (Bodart 2002). However, the energy efficiency of lighting has improved and new office lighting systems may demand as little power as 10 W/m^2. This means that the potential savings in new office buildings is lower, but when combined with daylighting low energy bulbs can have a large impact on the energy consumption of buildings. Daylighting also has a beneficial impact on the productivity of the building occupants (Lynes 1980). These improvements can be worth more, financially, to a building tenant than the reduction in the electricity bill. Daylighting is at it's most effective when combined with an automatic lighting system which alters the artificial lighting to compensate for increases and decreases in external light levels.

A reduction in the requirement for space heating can best be achieved by increasing the efficiency of the heat production and reducing the uncontrolled heat losses from a building. Losses occur mainly through gaps and around openings and heat transmission directly through the building fabric. As the architecture of commercial buildings changes there are more solar gains which result in the requirement for mechanical cooling. Cooling requirements can be controlled by reducing heat gains, either internal gains from equipment or external solar gains which enter the building through the façade.

Energy efficiency in new buildings is critical to the reduction of energy consumption in the UK (Sorell 2003). Sorrell proposed the following boundaries to the introduction of energy efficient technologies. This study concluded that the inclusion of energy efficient technologies and design were impeded by the fractured nature of the construction industry. Sorrell proposed that an improvement in the energy efficiency of buildings would be aided by the use of non- competitive partnering processes and improvements in the supply of information, education and design tools to the construction industry. Lowe (1996) argues that there are three main methods of reducing energy consumption:

- Legislative Change,
- Change in social attitudes,
- Financial penalties.

Legislative change can force innovation in materials and applications as well as changing the focus for new developments and research and forcing building designers to investigate different options from those currently available. However, the most effective of these is likely to be a change in social attitudes, which can influence the society's willingness to accept and apply the new legislation. Lowe considers financial penalties as a blunt instrument as consumers do not search for best price for fuel frequently enough. If tariffs are used to make the market more price sensitive to fuel prices there is always the possibility that this might result in fuel poverty for vulnerable sections of society. These increases in fuel process rely on a change in social attitudes to engender acceptance.

Financial incentives should be added to the list proposed by Lowe as a method of reducing energy consumption. These incentives are either direct, such as the "green boiler scheme" which subsidises the cost of energy efficient boilers for members of the public, or indirect, like the investment in research. Governments have funded research through grants to Universities, the Partners in innovation program which sponsors the link between the private and public sector, and the funding of the International Energy Agency (IEA) etc. Government fosters research into the areas where they wish to see improvements by determining the qualification criteria for accept grant applications.

The following sections focus on the legislative attempts to improve energy efficiency and the research into energy efficiency and facades.

6.2 BUILDING REGULATIONS

The Building Regulations are legal requirements that must be fulfilled in order for buildings to gain planning consent. Part L of the Building Regulations intends to control the amount of fuel and power consumed by buildings. This part of the regulations were revised in 2000, the new document was under consultation for several years and was finally introduced in 2002 as a replacement to Part L 1995 (DOE 1995). The main change was the division of the document into two parts, Part L1 which covered the requirements for residential buildings and Part L2 for non-residential buildings. Other significant changes include:

- Addressing the summer as well as the winter performance of buildings.
- A requirement for testing of air –tightness.
- A requirement for minimum heating and air conditioning plant efficiency.
- A more stringent requirement of the fabric insulation.

Part L (1995) included U-values, air-tightness guidance and heating system guidance all of which were aimed towards the reduction of heating energy. In the new part L of the Building Regulations the summer performance has also been taken into consideration with a requirement to avoid solar overheating. This requirement can be achieved by limiting the ratios of glazed to solid area. The maximum area allowed is maximum of 50% glazing and a minimum of 32% glazing, this should be compared with the glazing proportion typically employed in curtain walling (between 75% and 100% glazing). Larger glazing areas can comply with the guidance, however, they are only allowable if the total solar gain averaged through the hours of 07:00 and 17:30 are less than or equal to 25 W/m^2. This is when the building is subject to the maximum solar irradiances for the building location in July during the period of 1976 -1995.

Less obvious, but equally important are the strict requirement for the testing of air tightness, this has an influence on the interfaces between façade systems including window and ventilation openings. The previous document stated that losses through infiltration should be limited and showed reliable methods for reducing them. The new regulations state that this should be physically tested unless the building is smaller than $1000m^2$. Physical testing of air leakage involves the sealing of all building openings, such as vents and ducts, and the pressurisation of the building using large fans, this can be a massive undertaking.

One of the changes to the building regulation, which has received the most attention, is the alteration to the requirements for thermal transmittance through the building fabric. Table E2 shows the changes in the permitted U-values limits that have been imposed under the new regulations. The ratio in which the solid and glazed areas must be applied remains the same (40% glazing). The U-values stated in both documents refer to the average U-values including any thermal bridging through the building fabric.

Table E2 Comparison of U-values from Part L 1995 to 2002.

Building Element	**1995 U-values W/m^2K**	**2002 U-values W/m^2K**
Roofs	0.25	0.16 -0.25
Exposed walls	0.45	0.35
Exposed floors and ground floors	0.45	0.25
Semi-exposed walls and floors	0.6	0.35
Windows, personnel doors and rooflights.	3.3	2.0 – 2.2
Vehicle access and similar large doors	0.7	0.7

Source: (a) Table 5, DOE (1995), (b) Table 1, DTLR (2002).

The inclusion of a section which looks at overheating is due to the increased proportion of building energy spent on cooling in non-residential buildings. (DTI 2001)

The Influence On Façade Design

The effect of the inclusion of a solar overheating clause in the Building Regulations, is perhaps intended to result in the ultimate reduction of the glazing areas in buildings. However, the avoidance solar overheating is unlikely to be the limiting factor for the façade glazing ratio. It is more likely that the thermal transmittance through the fabric will limit the glazing ratio. The use of spectrally selective solar coatings and external solar shading will enable a highly glazed façade to continue in use. This means that the façade will become more active and textured with the inclusion of varying types of solar shading rather than the clear transparent envelope desired in the 1980s and 1990s.

The thermal transmission through glazed facades can be controlled by the reduction of thermal transmission through both the glass and the framing. One of the methods of improving the U-value through the glazing is the use of Low-e coatings.

Low-e coatings are thin film coatings of metal oxides deposited on the surface of the glass to reduce the emissivity and thus reduce the thermal flow of heat through the glazing. The coating is deposited using either a vacuum deposition method known as DC Magnetron sputtering or chemical vapour deposition. In 1997 the nominal annual production of capacity for vacuum coating of architectural glass was 100 million square metres, 7% of the total annual float glass production at that time (Schaefer 1997). The introduction of the new Building Regulations is likely to increase this proportion, because the use of Low-e coatings is the simplest and cheapest method of achieving the new U-value requirements.

The use of metal framing systems for glazing in office buildings is popular for two main reasons, aesthetics i.e. the thin profile that is provided by metal framing systems, and the ability of a steel and aluminum framing system to act as a structural member (span from floor to floor). However, the use of metal framing systems increases the U-value of a façade when compared to uPVC and wood. This legislation will force improvements in the metal framing systems currently in vogue and may result in the development of alternative systems.

The double skinned façade presents an opportunity to pass the regulations whilst retaining a highly glazed façade. A double skinned façade consists of two layers of curtain walling with a large air space typically larger than 0.5m in depth. The addition of the extra outer skin provides a buffer space between the internal façade and the external environment. This increased façade space can be controlled in a number of ways, either as a mechanically ventilated space or naturally ventilated space, but there are many variations somewhere in between the two. This configuration has been hailed as a method to bring natural ventilation into high rise office towers (Compagno 1999). This type of façade uses existing façade products and is flexible in configuration which enables the model to be adapted to many situations.

Avasoo (2003) argues that this façade type has existed in Sweden for the past thirty year as a "2 + 1 window" and that the first double skin building was built in Sweden in 1976 by Bengt Warne architects. The building that is usually cited as the first of this type is an office building in Farnborough in 1980, in this instance the "double skin" was employed to enable the use of natural ventilation with a noisy eternal environment.

The main disadvantage of the double skinned facade is the complexity of controlling the temperatures in the interstitial zone. It can be difficult to encourage the correct speed of air through the cavity. If the air-flow is too fast there is not enough air transferred into the space. The space becomes a solar chimney with elevated temperatures in the cavity at the higher levels of the building. The double-skinned façade (Evans, 1997b) is heavily criticised for trying to square the circle whilst remaining in the mode of modern architectural solutions. Evans points out, that towers are not the only way to provide high density office space, but in a sprawling city like London with limited building space it might be the most efficient. This type of façade is particularly useful in applications where the wind driven pressure is

6.3 INTERNATIONAL ENERGY AGENCY RESEARCH.

The International Energy Agency (IEA) research programme analyses methods of reducing the environmental impact of construction. This work is divided into annexes, research project areas, which are investigated by international teams of academics. The remit of the IEA Annex 32, Integrated Building Envelope Performance Assessment was to have an annex whose remit was to investigate the influence of transparent building elements. The objective of the annex was to investigate how energy efficiency, which is important to society as a whole, for the reasons which have already been discussed could be incorporated into general building performance criterion which interest the architects and owners of buildings. Lowe (1996) investigated the introduction of pricing as a mechanism to introduce an energy efficiency bias in construction, however the research discovered that macro-economic measures are blunt instruments in this respect and disproportionately affect those who can least afford to pay thus engendering fuel poverty. The authors of Annex 32 linked energy performance to the overall system performance, based on fitness for purpose in order to improve the quality and durability of façade construction. This has been done by reduction of the annex into two sub tasks:

A. The development of a methodology for the evaluation and optimisation of building envelopes, based on a fitness for purpose rationale.
B. Application of the developed methodology to envelope performance testing, advanced envelopes, and the optimisation of retrofits and traditional envelopes.

The result of this extensive research project are four documents and several research papers (Hendricks 2000, Rudbeck 2000, Baker 2000, Christian 2000 and Hauglustaine 2000)

The first tool that was developed by the Annex 32 team (Hendricks 2000) was a matrix that can be used to assess Façade Systems, it is checklist of items to be covered by the façade. The use of this checklist is supposed to match the fitness for use requirements with the properties of a particular façade system and to establish a minimum performance level for each parameter. Hauglustaine (2000) describes the client as a innocent who is carried along by their base requirements and financial constraints, but buffeted during the process by the desires of the design team. Hauglustaine also describes the design process in the terms of a negotiation between the client and the design team to produce a building that is acceptable to both parties. However, in order to negotiate the client must have some knowledge of the building process and requirements. In practice this is often achieved by the client hiring a team of experts to manage the process (Project managers), but traditionally this role has been performed by the Architect. In this type of construction process the Architect is the client's representative, mediator between the rest of the design team and client whilst being simultaneously the head of the design team. Halgustaine describes how building tools might be used to develop a set of minimum requirements which and can be the start of the negotiation.

Baker (2000) applies the methodology developed to two advanced façade systems, Building Integrated Photovoltaics (BIPV) and Active Envelopes (double skinned facades). The aim of these technologies is to reduce the environmental impact of buildings, most notably the energy consumption of the buildings, whilst maintaining the comfort of the occupants. The application of the assessment methodology to the two types of facades raised areas where a lack of information about the façade typology could lead to inappropriate specification.

6.4 REVIEW OF PORTFOLIO

This is a review of the work carried out in this portfolio with regard to the changes in the Building Regulations.

Review of Part A

ETFE has become more widely used than it was in 1998 when the research began, however, it is still a novel material and rarely used in buildings in the UK. It is hoped that with the published research papers, conference papers and talks to building professionals that presented the research carried out in this portfolio, ETFE will be routinely considered with the other transparent roofing materials as an alternative to glass. The use of ETFE in buildings can help to produce savings in steel structure and aid day-lighting where it was not previously possible to use glass. The increase of the thermal insulation required by the new Part L2 of the Building Regulations is considered in a comparison of the performance of both an ETFE and glass rooflight. This research presented in the portfolio can be furthered by the use of new data available from ETFE buildings, such as the Eden Project, and the comparison with similar glass buildings. If a suitable ETFE manufacturer can be convinced to participate the application of the life cycle analysis methodology which was applied to Pilkington float glass, as described in Part B of the portfolio, could be applied to ETFE. This would enable a more detailed comparison of the environmental effects of glass and ETFE than was possible during the work presented here.

Review of Part B

Part B, the energy consumption due to the use of materials has been under study for some time and has resulted in an awareness of the embodied energy in as a materials as a selection issue. However as has been previously discussed energy consumption alone cannot be used a guide to environmental sustainability or environmental quality. The use of the eco-indicator 99 methodology in the Life Cycle Assessment of architectural float glass has allowed the wider characterisation. This has also allowed a wider identification of the most harmful part of the processes and raised areas for improvement with the manufacturer. The company, which participated in this process, has used the data gathered to alter their procurement process in favour of a less environmental harmful option. The company has also stated a wish to apply the methodology to more products in their large portfolio. The success of this study means that this methodology should be applied to other building elements. It would be useful to use environmental assessment data available other than embodied energy as a comparison when trying to compare architectural glass with alternative transparent insulating materials.

Review of Part C.

Sorell (2003) and others have argued for greater level of information available to the design team at the earliest stages of design to produce the best results. Baker (2000) added that this information should take into account the overall performance of the façade as well as the energy cost. This part of the portfolio details the development of the Façade Selection Tool in which the energy performance, internal conditions, façade requirements and environmental impact have been integrated so that these indicators can be considered at the sketch stage of building design.

The methodology applied to the life cycle analysis of architectural float glass in Part B of the Portfolio has been applied to whole façade systems in Part C. This is to provide an environmental assessment of the overall impact of the various façade choices. The building typology used in this study was developed with regard the new Part L2 of the Building Regulations.

7. STRUCTURE OF THE PORTFOLIO

This portfolio has been structured in three parts as follows:

This chapter is written in the form of an executive summary which introduces the research topics, outlines the research objectives, methods and results, contribution to knowledge and lists all publications derived from this work. It also outlines involvement in commercial projects.

Part A discusses the work carried out into ETFE Foil cushions and their use in buildings. It describes the physical properties of the material, and presents an environmental assessment of the material.

Part B discusses the results of a cradle-to-gate Life Cycle Analysis (LCA) of Pilkington float glass. LCA theory and environmental impact parameters are presented. The results focus on the embodied energy of float glass and the environmental impact is calculated using Eco-Indicator 99 eco-points.

Part C presents the development of a concept design tool for evaluating the thermal and lighting effects of facades on the office building's internal environment and energy use. The rational behind the development of the tool based on the database approach is discussed, the advanced simulation tools used for the analysis are presented and the required inputs and outputs identified. A parametric analysis based on the results is presented.

The portfolio closes with some general conclusions based on the results of the work carried out during this EngD Programme and suggestions for further work.

PART A

ETFE FOIL CUSHIONS AND THEIR USE IN BUILDINGS

PART A: ETFE FOIL CUSHIONS AND THEIR USE IN BUILDINGS

Alternatives to traditional fenestration solutions have been available for a great many years; one of which is Ethylenetetrafluoroethylene (ETFE), a co-polymer of poly-ethylene and tetrafluoroethylene. This material has been used for the past twenty years in atria and other overhead glazing applications (Tanno, 1997).

Part A of the portfolio presents work which was carried out into the use of ETFE Foil cushions in buildings. This part of the portfolio examines both the effects of ETFE manufacture and its use in buildings. This study has considered performance both in terms of fitness for purpose and in comparison to glass; the common alternative. Chapter A1 discusses the application of transparent materials to roofs and atria (which is their main application in buildings) as well as the use of polymers in these applications. Chapter A2 presents the physical properties of ETFE and tests carried out. In chapter A3 the environmental impact of the material is examined. Conclusions about the use of ETFE Foils in buildings are presented in chapter A4.

CHAPTER A1 INTRODUCTION

Building fenestration can be responsible for significant impacts on the environment created within a building, affecting, either adversely or beneficially, both the health and perceptions of the occupants. The impact of buildings on the external environment is widely acknowledged, with consensus at the moment on continuing to build new buildings whist ensuring that all buildings have the minimum environmental impact possible.

Use of atria and skylights in modern climate adapting buildings.

The role of buildings is to moderate the environment, which often means excluding the external environment in order to provide a suitable internal environment. Yet, it is possible to use the positive aspects of the external environment and provide a compromise between the inside and the outside. Atria have often been seen as an intermediary between the internal and external space particularly with regard to climate control. They can be used as a design element in climate-adapting buildings; i.e. those that attempt to moderate the external environment rather than isolate it. Robertson (1992) lists the following as features of climate-adapting buildings:

- Efficient daylighting.
- Good orientation.
- Efficient solar radiation control.
- Natural ventilation.

A wish to provide environmentally sensitive, "healthy" and aesthetically pleasing buildings has increased the use of glass in buildings for atria and skylights in order to ensure efficient daylighting. Yet, this can substantially increase the embodied energy of buildings and have an effect on solar radiation control. There are other problems presented by the use of glass in overhead situations:

- Safety in the event of breakage and fire.
- Maintenance issues, in particular access for cleaning.
- Structural issues with regard to the weight of glass in unsupported areas of structure.
- Cost, the high specification of overhead glazing required by law can be expensive.

These issues have led to a plethora of alternatives to glass being tried, mainly polycarbonates, but they have all had limited success. A successful alternative to glass requires the ability to provide the benefits of using glass without the drawbacks. As well as satisfying the concerns already raised a polymeric alternative should include a flexible sealing system to take into account thermal expansion and improve air-tightness.

Polymeric alternatives to glazing

Synthetic polymers have been used in construction since the 1950s. Polymers like polyethylene and polycarbonate have been used as an alternative to glass; particularly in the agricultural sector in glasshouses and cold frames (Mulder, 1998). The use of these materials has allowed the formation of the novel structures such as the "poly tunnel". However, the substitution of glass with polymers for vision glazing and roofing in high profile office-based construction is limited. This has been mainly due to the perceived faults of the popular polymers used in these applications such as; low resistance to UV causing degradation through oxidisation and poor surface toughness resulting in whitening and loss of transparency over time.

The pressure for high performance glazing

An interest in the performance, both thermal and optical, of glazing materials is not new. In 1945 the American Society for Heating and Ventilating Engineers (ASHVE) later to become ASHRAE commissioned a study into the performance of glass in buildings (Parmelee, 1948a and Parmelee, 1948b). The work was intended to standardise the values given to consumers of glass as well as pushing improvements in the properties of glass. The project was described as:

"...of value and interest not only to those people who make and sell glass, but to every air conditioning engineer who is faced with problems in cooling load and I think, perhaps, to a larger extent than he normally realises, to the heating engineer."

Dr D'Eustachio, Pittsburg, Pa. (1948)

The push for improvement of glazing materials has continued with change being forced in part by a tightening of the regulations, such as the revision of Part L of the building regulations, regarding the insulative value of glazed areas. The focus has been on improving existing transparent insulating materials and developing new materials which can be applied in these situations (Platzer, 1987). The thermal performance of glass in buildings has been improved by the use of multiple panes, the addition of heavy gases such as argon, and the application of metallic surface coatings to reduce the emissivity of the glass (Clarke, 1998). Similarly the structures of the polymeric materials have changed to improve their building performance; open box structures which incorporate air have been used to increase the insulative value of polycarbonate and the surface chemistry of polycarbonate has been altered to reduce scratching.

The search for glazing alternatives with high insulative value and high chemical and UV resistance has led to the use of ETFE, a transparent polymer, in buildings. ETFE has been used both as a single layer membrane and as a multi-layer cushion with some insulative value for the past twenty years. The present study is primarily concerned with the use of ETFE Foil cushions, although materials properties are discussed in terms of the bulk material.

ETFE in buildings

ETFE Foil cushions are a multi-layer cladding system that consists of several layers of ETFE foil (50μm -250μm thick) heat sealed and clamped into a frame. The "cushions" are inflated to a pressure of between 250 – 400 Pa dependent on the size of the cushions and the application. This pressure is maintained by intermittent use of a pump.

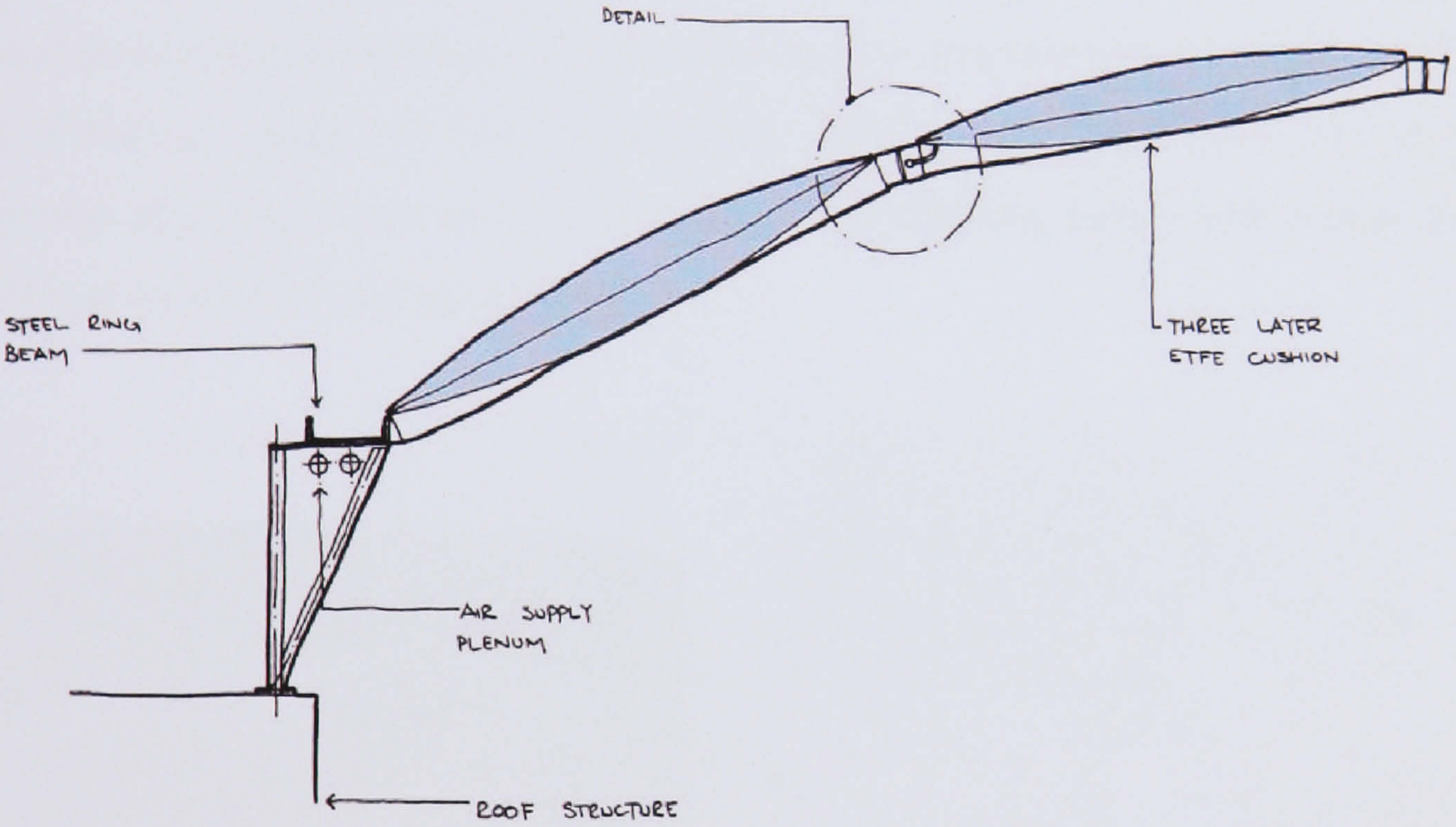

Figure A1: Schematic representation of ETFE Foil Cushion system.

ETFE was first used in this inflatable configuration (Figure A1) in a small building in the Burgers Zoo complex at Arnheim in the Netherlands in 1981. Despite its use in mainland Europe ETFE was not very widely used in the UK until the mid 1990s. When the research project commenced in 1997, ETFE was used in only few public buildings, notably Westminster and Chelsea hospital, but it was rarely applied in offices. ETFE Foil cushions have subsequently been used in various buildings predominantly in the United Kingdom and Germany. The cushions allow a high performance flexible roof with double curvature to be constructed (Cook, 1994). Some see the use of ETFE Foil cushions as a natural progression in the functional changes which the building façade is undergoing:

> "The development of ETFE foils has made it possible to create multi-layered wide-span membranes."
>
> Lang (2001)

ETFE foils have been used in situations where neither glass nor other transparent insulating materials (TIMs) could be used either because of the weight of the system or the geometry required. An example of this is the Eden Project, designed by Nicholas Grimshaw Architects as a series of bio-domes in Cornwall. As the site was a previously disused loam pit, this resulted in a weight restriction because of the poor load-bearing capacity of the soil (Schttich, 2001). The use of ETFE Foil cushions allowed the construction of two structures of interlocking domes with a span of up to 124 meters with no internal columns.

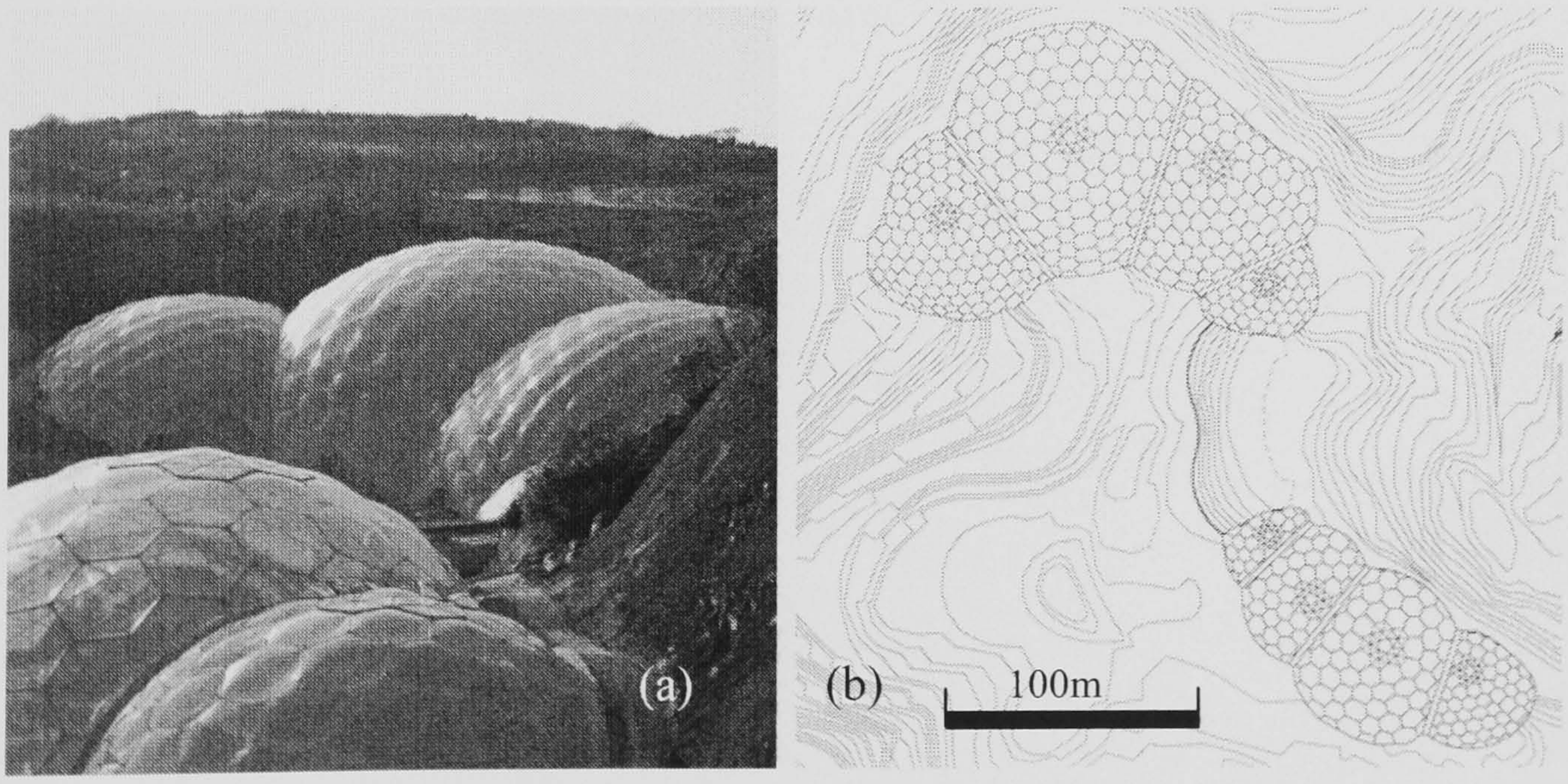

Figure A2: The Eden Project, (a) during construction (b) in plan.

Another advantage of the use of ETFE Foil cushion systems in buildings is the ease of construction and installation (Morris, 1992). A well-detailed system can be installed on site in days rather than weeks. The low density of ETFE and the thickness of sheets means that the panels required for an entire roof can be transported to site using one vehicle with no need for large areas of on-site storage or the multiple transport vehicles often associated with the installation of glazing.

The basic function of ETFE is to modify the environment inside a building to the benefit of its occupants; in order to judge this it is necessary to investigate the properties of ETFE. The following section describes the physical properties of ETFE.

CHAPTER A2 PHYSICAL PROPERTIES

This chapter describes the physical properties of ETFE, including a description of the tests which were carried out to ascertain the thermal and lighting characteristics of the ETFE Foil sheets. To illustrate the influence that the bulk material's properties have when embodied in a built example a case study is presented which looks at a typical possible application for ETFE use in buildings.

ETFE Foil is a co-polymer of polymer of poly-ethylene and tetrafluoroethylene (Teflon®). This co-polymer displays characteristics of both of the parent materials; it is easily moulded, blown and extruded like polyethylene and showing the anti-adhesive properties attributed to Teflon. Unlike other polymer roofing materials, ETFE is very stable and able to resist chemical and UV attack so that its optical properties are not diminished by exposure. Outdoor weathering tests have been carried out by the manufacturers and to date samples have been exposed for 25 years.

Table A1: Comparison of the physical properties of ETFE and glass.

	ETFE FOIL	GLASS
Ultimate Tensile Strength N/mm^2	40 - 46	50 -100 (toughened) 10 – 20 (annealed)
Melting Range °C		
T_g (glass transition temp)		600
T_m (melting temp)	150	1200
Hardness N/mm^2	31 - 33	5500
Yield Stress N/mm^2	30 - 35	
Fracture Mechanism	Plastic Deformation	Brittle Fracture

The comparison of the properties of ETFE and Glass, in Table A1, highlights the differences in the way that loads are carried in structural applications. Glass is a brittle material with a higher Ultimate Tensile Strength (UTS) than ETFE. When it is being used in glazing applications it deals with loads with a plate bending action and when two panes of glass are used to carry the load they have a composite action with the outer pane carrying the majority of the load. The loads are transmitted to the framing mechanism through a flexible material such as silicone or neoprene gaskets.

to ensure that the load transfer does not result in a point failure. Thermal expansion in glass is dealt with by including an expansion gap and some flexibility in the framing mechanism.

The ETFE foil cushion uses trapped air inside the cushions to provide stiffness and help to resist wind uplift. Thermal expansion in the material is dealt with by elastic movement in the material and the rigidity of the framework is kept intact. This increases the air tightness of the ETFE Foil cushion system. This is an important attribute as the ability to provide controlled ventilation is a feature of modern energy conserving construction. The yield stress of ETFE is temperature dependent.

As part of this project, several tests were carried out, mainly investigations into materials properties. A series of light transmission tests were carried out at the Pilkington Technology Centre and National Physical Laboratory (NPL) and a set of thermal tests were carried out at the British Board of Agrément (BBA). The Research Engineer did not carry out the tests which are presented in this chapter, but the interpretation of the results of these tests has formed a significant part of her work. The background and methodology for these two types of test have been included here for completeness.

A2.1 LIGHT TRANSMISSION

One of the physical properties which makes ETFE foil cushions an attractive alternative to glazing is the high light transmittance. A series of emissivity and light transmission tests were carried out by the Pilkington Technology Centre (Pilkington, 1999) to ascertain the full spectrum analysis of ETFE foil samples of varying thicknesses and tints. The samples were chosen to give a representative sample of the different transmittances, and thicknesses typically used in construction, as follows:

- 80μm clear
- 100μm clear
- 100μm white
- 150μm clear
- 200μm clear
- 200μm white.

The optical properties of the above mentioned ETFE Foil samples were measured in the following manner: A calibrated Perkin Elmer PE883 spectrophotometer was used. This equipment is capable of measuring the spectral reflectance of a sample from 5,000 nm to 50,000 nm and calculating the normal emissivity of a sample to the standard set out in BS 6993 Part 1 Appendix A. In order to determine the emissivity of ETFE, a single sample of 100μm material was selected. The thickness of the sample was measured, (at 0.01 mm), using a calibrated micrometer. The thinness of the material allowed the assumption that both the emissivity and the spectral reflectance was the same for both surfaces of the material. The calibrated spectrophotometer was then used to measure the spectral transmission of each sample from 295nm to 2500nm at 1m intervals. An internal calculation program was used to produce transmission and reflection graphs and to calculate the following parameters to BS standards where applicable:

- Light transmission to ISO 9050.
- Light reflectance to ISO 9050.
- Direct solar heat transmission ISO 9050 (Parry Moon).
- Solar heat reflectance to ISO 9050 (Parry Moon).
- UV transmission ISO 9050 to 380nm.
- UV transmission 310 –400nm (Parry Moon).
- Solar absortance.
- Total solar heat transmission ISO 9050 (modified for air mass 2).
- Short wave shading coefficient.
- Long wave shading coefficient.
- Total shading coefficient.
- U value to BS 6993 part 1.
- Descriptive code.
- Solar gain factors.

The effective emissivity for the ETFE samples was measured at 0.89. The effective emissivity is required to adjust both the light transmittance and the thermal transmittance of the material.

The spectrophotometer used for these measurements required samples of single-sheets of ETFE so the values for whole cushions have been calculated rather than measured. These calculated values assume a maximum air gap of 150mm between the layers of ETFE Foil at the centre of the sample cushions.

The results from the solar transmission tests, presented here in Table A2, show that while the clear ETFE Foils have high solar and light transmission, 91-94% and 90% - 93% respectively, it is possible to alter this by adding pigments to the material. This means that ETFE can be altered to provide solar control.

Table A2: Summary results for the visible radiation transmission of various ETFE Foils.

		80µm clear	100µm clear	150µm clear	200µm clear	100µm white	200µm white
Light	Transmittance	0.93	0.93	0.91	0.90	0.45	0.37
	Reflectance	0.07	0.07	0.08	0.09	0.50	0.59
Solar	Direct transmittance	0.94	0.93	0.92	0.91	0.55	0.47
	Reflectance	0.06	0.07	0.07	0.08	0.39	0.47
	Absorbtance	0.00	0.00	0.01	0.01	0.06	0.06
	Total transmittance	0.94	0.93	0.92	0.91	0.57	0.49
Shading coefficient	Short wave	1.08	1.07	1.06	1.05	0.63	0.54
	Long Wave	0.00	0.00	0.00	0.00	0.03	0.02
	Total	1.08	1.07	1.06	1.05	0.66	0.56
UV	Transmittance to 380 nm	0.88	0.86	0.83	0.76	0.06	0.01
	Transmittance to 400nm	0.89	0.87	0.83	0.79	0.13	0.06
Solar gain factors (environmental)	Mean	0.86	0.86	0.85	0.84	0.52	0.45
	Alt. Light	0.70	0.69	0.69	0.68	0.43	0.37
	Alt. Heavy	0.52	0.51	0.51	0.51	0.32	0.28
Sample thickness	mm	0.082	0.105	0.155	0.206	0.097	0.205

A full spectrograph of the light transmission is shown in figure A3 in order to illustrate the amount of light transmitted through an ETFE Foil cushion sample. The X axis shows the wavelengths of light and the Y axis give the percentage of transmission, shown in black, and the reflectance, shown in red. This graph shows that there is very high transmittance through the sample between 500nm and 2000nm. This is confirmed by the values in Table A2. It also shows that there is some absorbance of radiation between 2000nm and 2500nm The low overall absorbency of energy in these wavelengths however, explains the insensitivity of the material to UV light degradation. This energy is either transmitted or reflected.

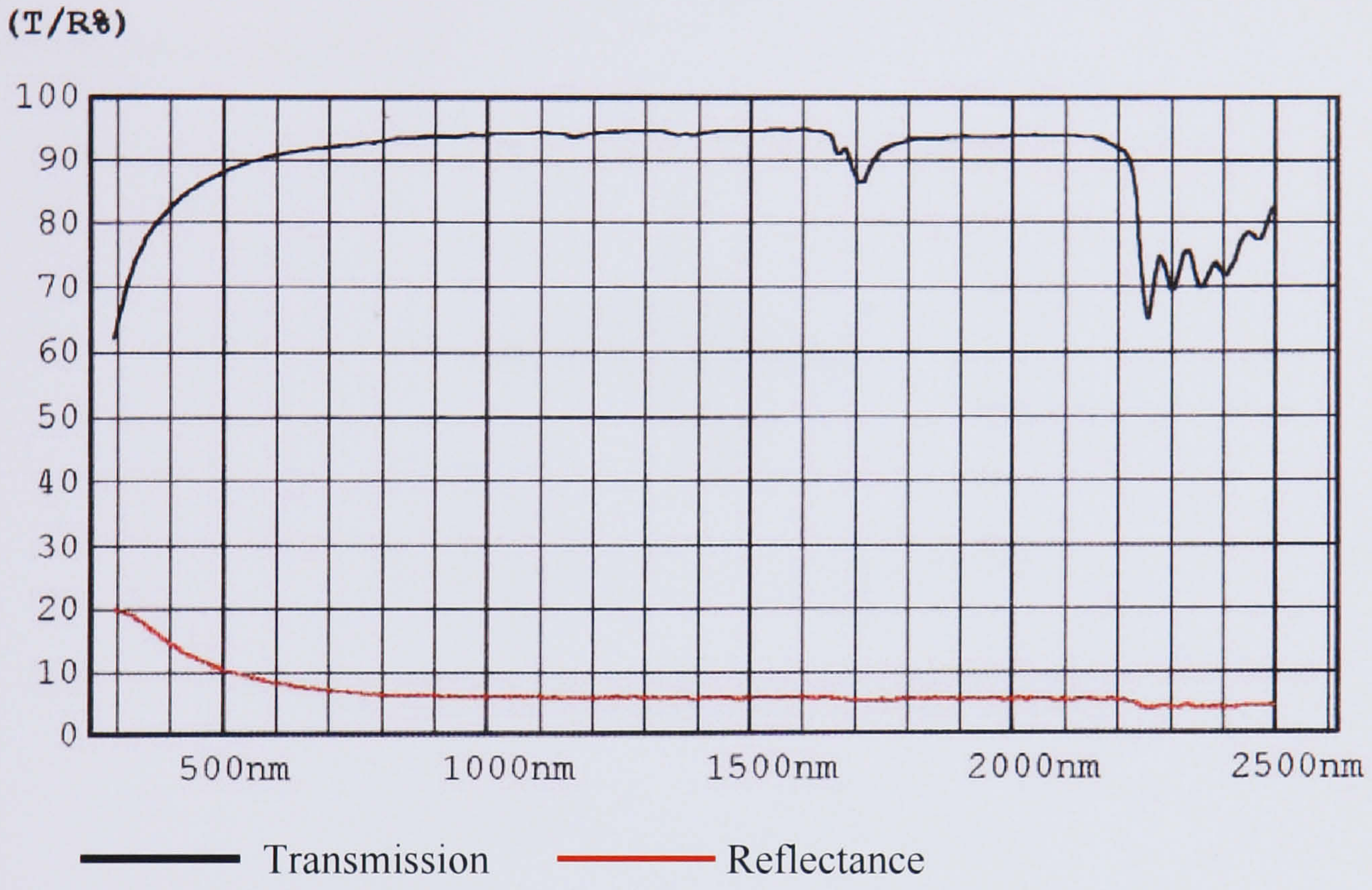

Figure A3: Optical transmittance through a sample of 100µm thick clear sheet of ETFE.

Increasing the quantity of light transmitted into a space does not necessarily provide a higher quality internal environment. Design for natural daylighting takes into account not only the total percentage of light transmitted but also the range of frequencies transmitted, which is important for colour rendering (CIBSE, 1999d).

The direct transmittance through a sample is a useful value for the comparison of materials, but it does not take into account that there is diurnal and annual movement in the angle of the likely light source (i.e. sun). In order for the effects of an ETFE Foil cushion roof to be calculated throughout the year more detailed investigations were carried out. These sets of tests were carried out by the National Physical Laboratory (NPL) who calculated the angular hemispherical transmittance.

The samples were measured at 0/t geometry, which is normal to the sample. A known quantity of light is passed through the sample. All of the light transmitted through the sample was collected and measured, Figure A4. This method was used to give the total hemispherical transmittance of a particular wavelength, accurate to within ±0.3%. This procedure was repeated at an interval of 10nm for the wavelengths between 400nm and 700 nm.

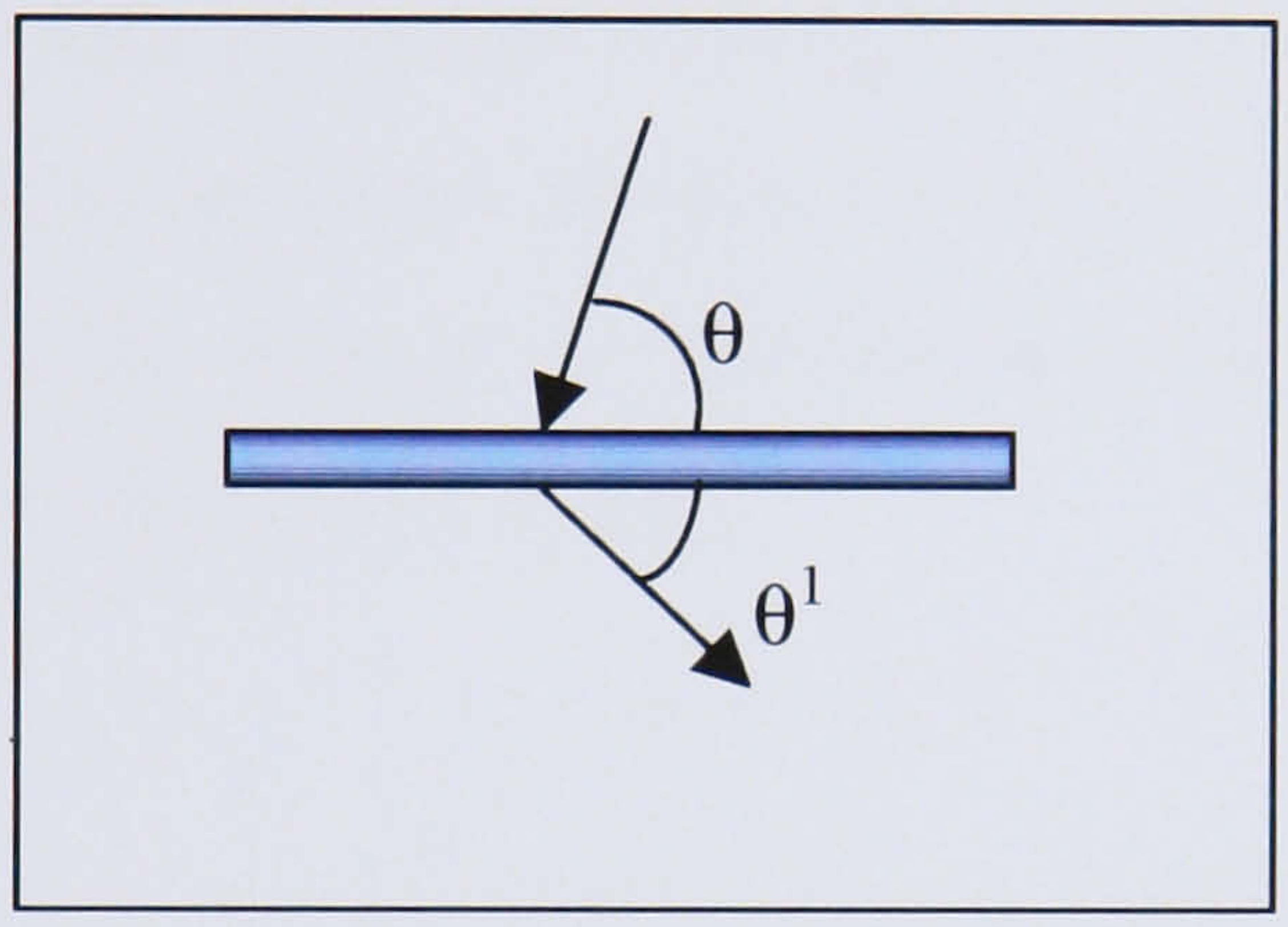

Figure A4: Angular hemispherical transmittance.

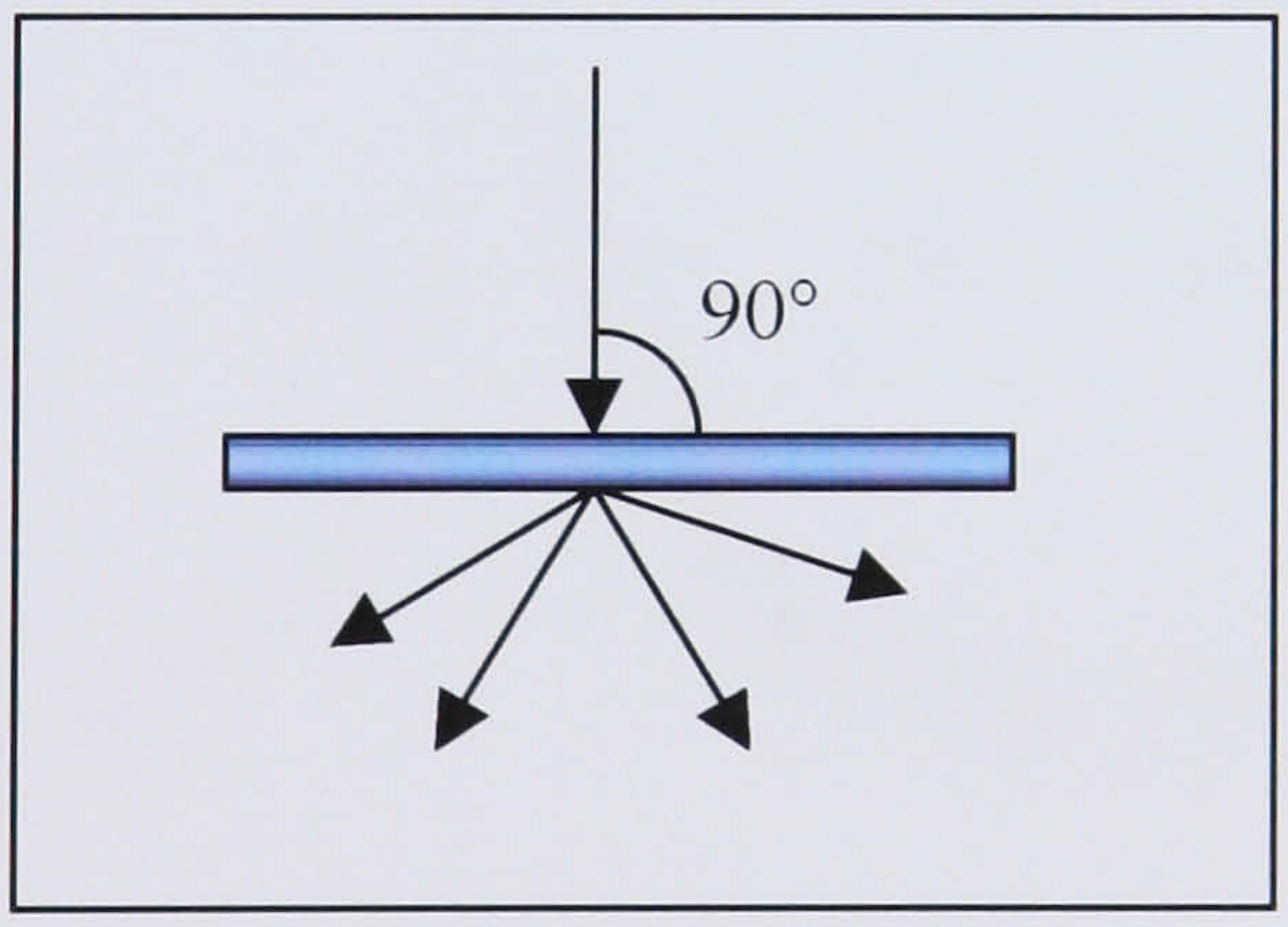

Figure A5: Total hemispherical transmittance.

Using the data from the total hemispherical transmittance tests a suitable wavelength for the angular hemispherical transmittance test was selected. Then a known quantity of light at a particular wavelength was passed through the sample at an angle θ, the quantity of light which passes through the sample is measured at angle θ^1, as shown in Figure A4. This technique enables the measurement of the angular variation of scatter due to the light being incident on the sample at different angles and then passing through the material, there is an uncertainty of ± 0.2% associated with this method.

Figure A6 shows the transmittance of light through ETFE Foil at varying angles. The lines represent the transmittance through the material at different angles of incidence, while the X axis gives the angle of the detector relative to the source of the light and the Y axis gives the percentage of light transmitted. Analysis of the graph shows that the transmission through the sample is insensitive to the angle of incidence. There is little scatter or distortion of the beam of light transmitted. In all cases over 80% of the light transmitted through the sample is at 180° to the angle of incidence. This is very similar to the total transmittance through the sample. The impact of this is that even at low sun angles the majority of sunlight and daylight will be transmitted through the material into the interior of atria.

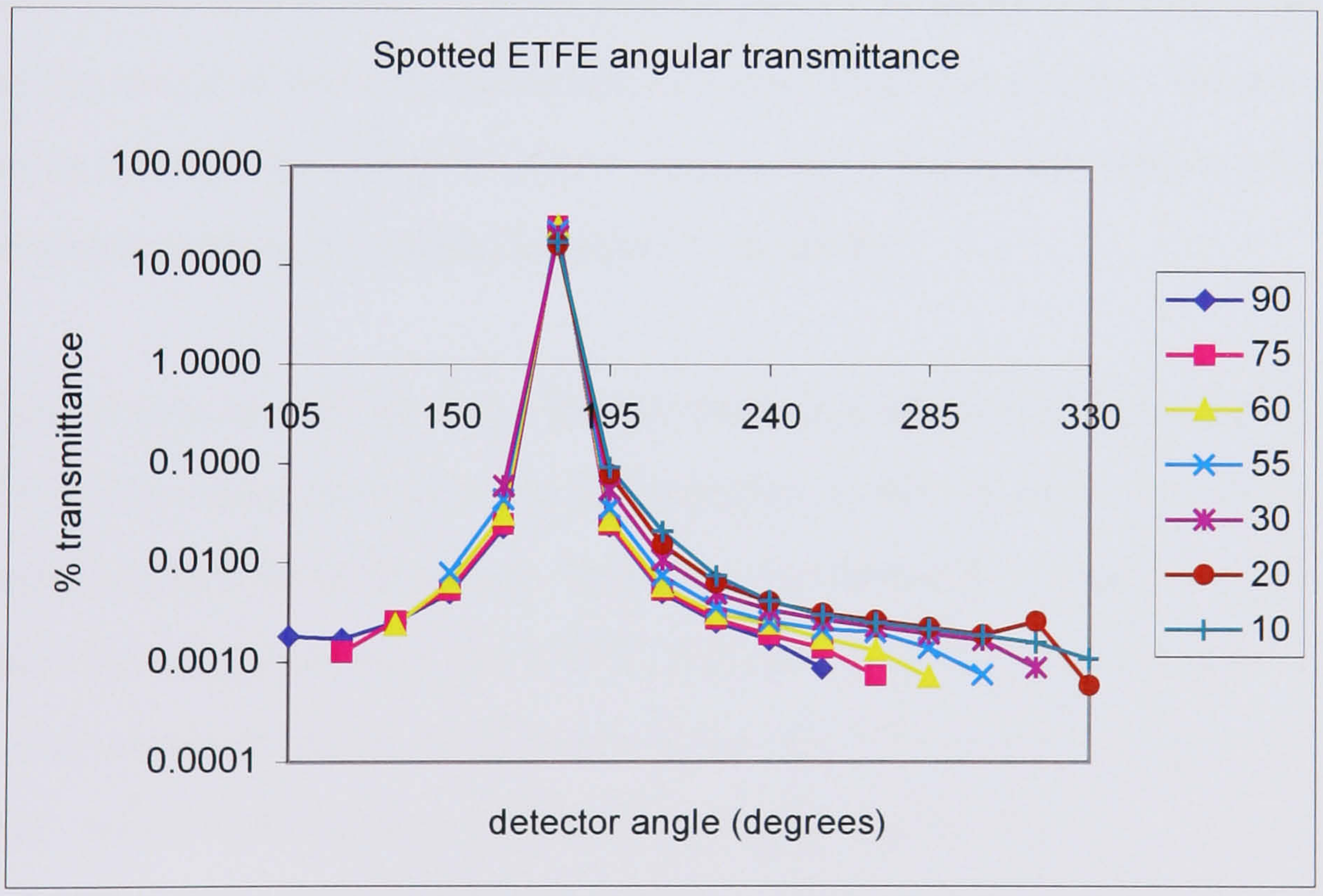

Figure A6: Angular transmittance of 100µm ETFE sheet at various sample and detector angles.

A2.2 THERMAL MEASUREMENTS AND CALCULATIONS

Thermal transmittance represents one of the single largest performance criteria applied to building materials. The introduction of the new Part L of the Building Regulations (DLTR, 2002) has increased the relative importance of thermal performance by reducing the required values for the heat conductivity of building components. To measure the thermal conductivity of ETFE Foil cushions a set of standardised thermal transmittance tests were carried out. The configuration and size of cushions has a large impact on the thermal transmittance and it was not possible to test more than one size of component. Hence, the results from these physical tests were used to validate the ability of a Finite Element Analysis model ANSYS to calculate the thermal conductance of ETFE Foil cushions in built examples.

The configuration of the ETFE foil cushions enables them to provide thermal insulation. The heat conductivity of air is quite low if convection movement is restricted. In the ETFE Foil cushion system the air is trapped between the layers of foil and the result of this is a restriction of convection movement. Therefore, the air in between the foils acts as an insulator and provides the system with a relatively low thermal transmittance (U- value measured in W/m^2K).

The physical test carried out at the BBA (2000) measured the thermal performance of an ETFE Foil cushion sample using the guarded hot box method. The test conformed to British Standard BS 874 (1987). In this test the transfer of heat from one chamber to another is measured using the ETFE Foil sample as the only bridge. The sample tested was clamped in an aluminium frame the dimensions of the sample were $2103mm^2$ with the frame and $1964mm^2$ with the frame excluded. This test sample does not reflect the size of cushion which is usually used in buildings; however, the dimensions of the sample were limited by the capacity of the guarded hot box (Figure A7).

The sample is placed in a test panel between a hot chamber and a cold chamber, the heat in the hot chamber passes through the sample to the cold side of the chamber until the temperature reaches equilibrium. The test panel consists of the sample and a

150mm thick expanded polystyrene surround. During the test heat is supplied to the hot side of the chamber to bring it to the correct temperature.

The total heat flow through the test panel is determined by the measured energy input into the hot chamber and the derived energy loss through the hot chamber walls into the guard space around the hot chamber. The heat flow through the surround panel is determined using a calibration panel. The heat flow through the sample is calculated by deducting the derived heat flow through the surround panel from the total heat flow through the test panel. The measurements collected using this equipment are accurate to within ±10%.

The sample consisted of three layers of ETFE foil, an outer layer 150μm thick a 50μm interstitial layer and an internal layer of 100μm, these layers of ETFE Foil were welded together and clamped into a standard size proprietary aluminium frame. The sample was tested in two configurations, with the frame exposed so that heat transfer occurred through both the fame and cushion, and with the frame insulated to minimise the impact of heat transmission through the framing. The test chamber which contains the sample can be rotated so that the effect of orientation can be measured. With the frame insulated the sample was tested in the following positions: horizontal, 20° to the horizontal and vertical, it was subsequently tested with the frame exposed in a vertical position. These tests were carried out so that there would be enough information to investigate the effect of convection inside the cushions. Subsequently this information was used to validate the finite element model of the cushion.

Table A3: The results of the guarded hot box test by the configuration of cushions.

SAMPLE NAME	CONFIGURATION	U-value W/m^2 K	TRANSMISSION W/K
Test 1	Vertical	2.59	10.0
Test 2	Horizontal	2.73	10.5
Test 3	20° to the horizontal	2.69	10.4
Test 4	Vertical with frame exposed	3.00	11.1

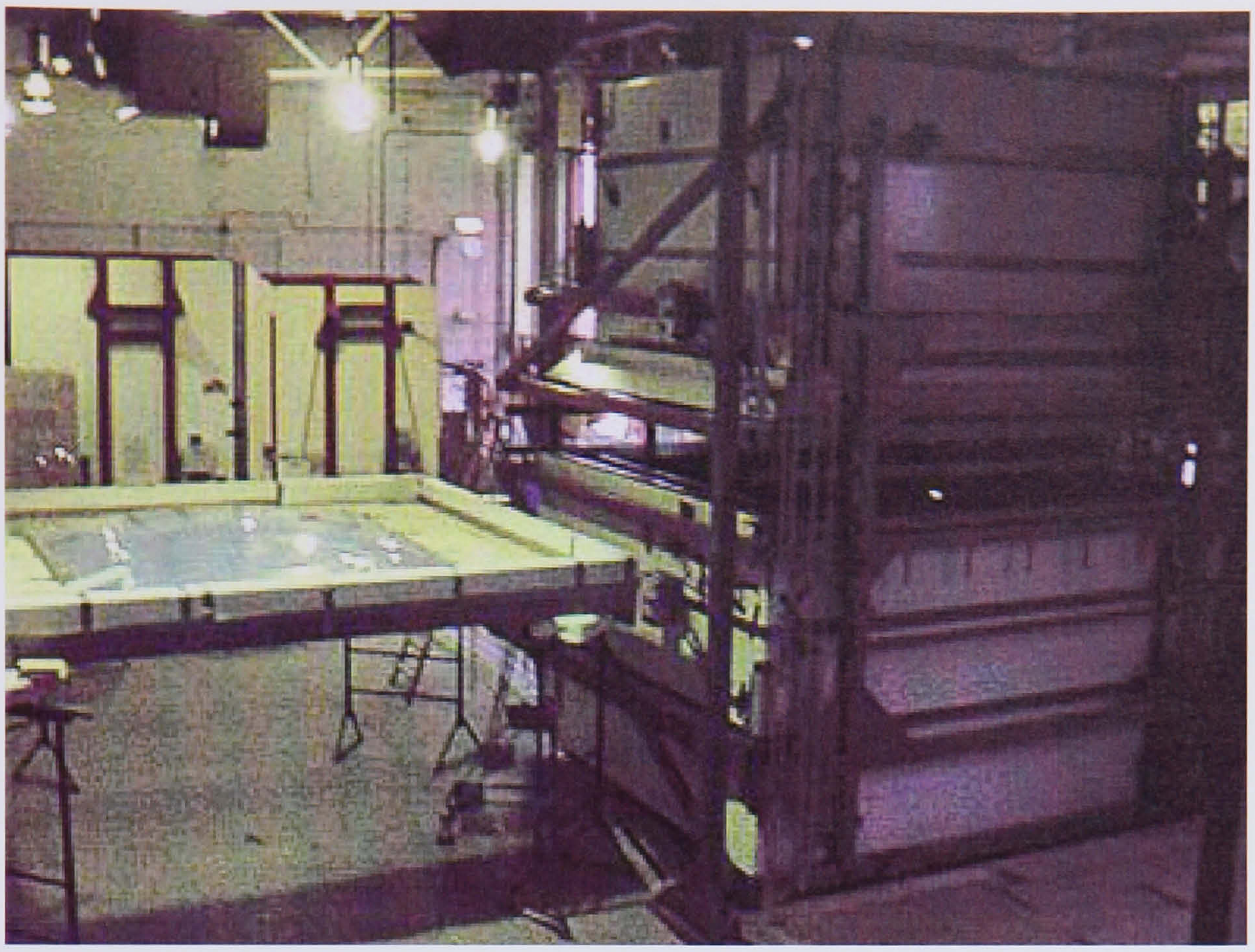

Figure A7: The hot box equipment at the British Board of Agrément.

The test results from the guarded hot box test are presented in Table A3. These tests show that thermal transmission in the ETFE Foil cushion is a function of orientation. The U-value in the horizontal position is worse than that in the vertical position, which is probably due to greater area available for convection movement through the cushion when the cushion is horizontal. These results also show that the thermal transmission through the frame has a large impact on the overall U-value of the cushions. In a live building situation steps should be taken to reduce the thermal transmittance of the metal framework by providing thermal breaks. However, this effect is magnified in the test situation, due to the high ratio of frame to cushion. In built examples the cushion-to-frame ratio is likely to be much larger, however the larger cushions have greater internal volume and centre depth. This would the increase thermal transmittance by the convection mechanism.

Since the foil cushions have a complicated configuration, the calculation of the U-value can not be approached by standard methods such as those proposed by BS 6993:1989. Nevertheless, the guidelines specified by BS 6993 were followed in the Finite Element Analysis (FEA) which was employed to solve this problem.

A FEA of ETFE foil cushions was carried out by Wang (2000) to analyse the usefulness of FEA as a tool for evaluating the U-value of complex ETFE configurations. This validation of the ANSYS FEA software was required because the FEA technique has a limited ability to take into consideration convection inside the layers of the cushions. During the validation of the model the cushion that was modelled had the same dimensions and composition as the cushion that was used in the guarded hot box tests.

This cushion considered in these tests consisted of three layers of ETFE foils inflated with air. The internal convective heat transfer of air and radiative heat exchange between bounding foils were simplified as conductive heat transfer with equivalent thermal conductivities which are derived below.

The equivalent thermal conductivity K_c by convection is defined as

$$K_C = N_u \cdot \lambda \qquad \text{(A- 1)}$$

where:

λ is the normal thermal conductivity of air

$N_u = C(G_r P_r)^n$, is the Nusselt Number

and where:

C and N are constants which depend on the orientation of cushion; Standard values C = 0.16 and n = 0.28 were adopted for the horizontal air gap with the direction of heat flow upwards, and C = 0.035 and n = 0.38 for the cushion in the vertical position with the heat flow horizontally. P_r is Prandtl number (For air, P_r is normally equal to 0.71).

G_r is the Grashof number defined as:

$$G_r = (gS^3\Delta T)/(T_m v^2) \qquad \text{(A- 2)}$$

where:

g is the gravitational acceleration (9.8 m/s^2)

S is the mean width of the space gap (m) the mean width S was assumed to be 125mm for the current case.

ΔT is the temperature difference over gap (K)

ν is the kinematic viscosity of air.

T_m is the absolute mean temperature (K)

For foil cushion in the horizontal position which covers the interior environment underneath as in a roof situation, the equivalent thermal conductivity K_c by convection was found to be 0.24 W/(mK) from equation (A1-1). For a foil cushion in the vertical position, the equivalent thermal conductivity K_c by convection was found to be 0.27 W/(mK). This means that foil cushions transfer more heat by convection in the vertical position than in the horizontal position.

In addition to the convective heat transmission across the cross-section, there is also radiative heat transmission between foil layers. According to BS 6993, the radiation conductance h_r across air space is given by the equation:

$$h_r = 4\sigma \left[\varepsilon_1^{-1} + \varepsilon_2^{-1} - 1\right]^{-1} T_m^{\ 3} \qquad \text{(A- 3)}$$

where;

σ is Stefan's constant

ε_1 and ε_2 are the effective emissivities of bounding foils

T_m is the absolute mean temperature

The normal emissivity of clear 200μm ETFE layer was measured to be 0.954 at Pilkington Technology Centre. Following the guidance given by BS 6993, the effective emissivity of clear ETFE was set at 0.89. The absolute mean temperature T_m was specified as 283K (the average temperature of both environmental temperatures on either side). The interior and exterior environmental temperatures were assumed to be 20°C and 0°C respectively in the analysis. Therefore, the radiation conductance $h_r = 4.125\ W/(m^2K)$. This value is independent of the orientation of a foil cushion.

With the assumption of average thickness of air gap is 125mm, the equivalent thermal conductivity for radiation was found to be 0.52 W/(mK). By a comparison of magnitudes of both equivalent thermal conductivities generated by radiation and convection, it can be seen that the heat loss through the ETFE foil cushion itself occurs mainly by radiative heat transfer between bounding foils. This implies that the heat loss through an ETFE foil cushion can be considerably reduced if the emissivity of the material can be lowered, perhaps by the application of low emissivity coatings. The thermal resistance of foil the itself can be ignored due to the extreme thinness of the material (approximately 200 μm).

The internal and external surfaces of the foil cushion will exchange the heat with the interior and exterior environments by radiation and convection. According to BS6993, the normal value of the exterior heat transfer coefficient $\mathbf{h_e}$ is standardised to 25 $W/(m^2K)$, and the interior heat transfer coefficient $\mathbf{h_i}$ is standardised to 10 $W/(m^2K)$ for the purposes of comparison in the horizontal position. These coefficients are the sum of both convection and radiation coefficients. $\mathbf{h_e}$ is standardised to 16.7 $W/(m^2K)$, and $\mathbf{h_i}$ is standardised to 8.3 $W/(m^2K)$ for a foil cushion in the vertical position.

The symmetry of the cushion allowed for the modelling of one quarter of an ETFE foil cushion to represent the whole. Before further modelling was carried out, the actual shape or radii of curvature of the foil cushion had to be determined. The radii of curvature of a cushion is dependent on the inflation pressure and the mechanical properties of the foil. The first model used a reasonable approximation of the curvature that was based on the assumed maximum thickness of the cushion.

Based on the above derived parameters and the designated dimensions, a steady-state heat transfer analysis was carried out by using a general purpose finite element programme ANSYS (Kohnke 1998). The thermal element SOLID70 of ANSYS was selected. SOLID70 has a three-dimensional thermal conduction capability. The element has eight nodes with a single degree of freedom, temperature, at each node. In total 20 SOLID70 elements were used in the modelling of one quarter cushion.

The results of the physical tests and the modelling can be compared in order to validate the modelling process. In the model an average heat flux density through the cushion was finally found to be 54.6 W/m^2 for a foil cushion in the horizontal position. Therefore, the typical U-value for a three layer ETFE foil cushion under study should be:

$$U = 54.6\,(W/m^2)\,/\,20\ K = 2.73\,W/m^2K \tag{A-4}$$

This value is equivalent to the BBA test result, 2.73 W/m^{2}K.

For a foil cushion in the vertical position, an average heat flux density through the cushion was finally found to be 50.65 W/m^2. Hence, the U-value for the cushion in vertical position should be:

$$U = 50.65\,(W/m^2)\,/\,20\ K = 2.53\,W/m^2K \tag{A-5}$$

This value correlates very well with the BBA test result 2.59 W/m^{2}K.

Although for a foil cushion in the vertical position, the standardized heat transfer coefficients are lower compared with these in the horizontal position, the convective heat transfer by air is higher than it in horizontal position. Therefore, the difference of U-values between the two orientations is as big as was initially anticipated.

In conclusion, the U-values of a foil cushion in the vertical and horizontal position is slightly better than the standard U-value 2.8 W/m^{2}K of a typical double glazing window unit. It should be noted the size of the sample tested and modelled is smaller than those used in actual projects, and the U-value is for a foil cushion only (without the contribution of the frame).

A2.3 CASE STUDY

This section describes a case study comparison between an ETFE Foil roof and a glass roof with the same site conditions and dimensional area. The rooflight is for a six storey building in central London. The rooflight opening is 7m by 15m. The case study is based on a section of a building designed in 2002, which is currently under construction.

A structural steel member can span 7m, both the glazing and the ETFE must span between the structural members. Hence, the first design item which must be determined is the structural grid of the roof. ETFE is capable of spanning between 3 and 4 metres in its smallest dimension and up to 30m in length. This spanning distance would be unsuitable for a glazed rooflight, which must be further broken down into smaller units.

A balance between the size (in square meters per pane) and the thickness of the glass determines the unit size of overhead glazing. As the thickness of the glass must be increased to carry the wind loads resulting from larger panes, this increases the weight of the glass, which in turn increases the size of the supporting members. Overhead glazing must be safety glazing (reference), in case of fracture, thus it is acceptable practice to specify a pane which is of a size that can be toughened in a toughening oven. This places a further restriction to the maximum size. On average, a pane which is $4m^2$ with no dimension larger than 2.5m can easily be sourced and procured (Glaverbel 2003) both in the UK and across Europe.

This leads to a development of a 3m structural grid for the ETFE and a 1.5m structural grid for the glass, which is further broken down into three panes; two 2.3m panes and a single 2.4m see Figures A8 and A9:

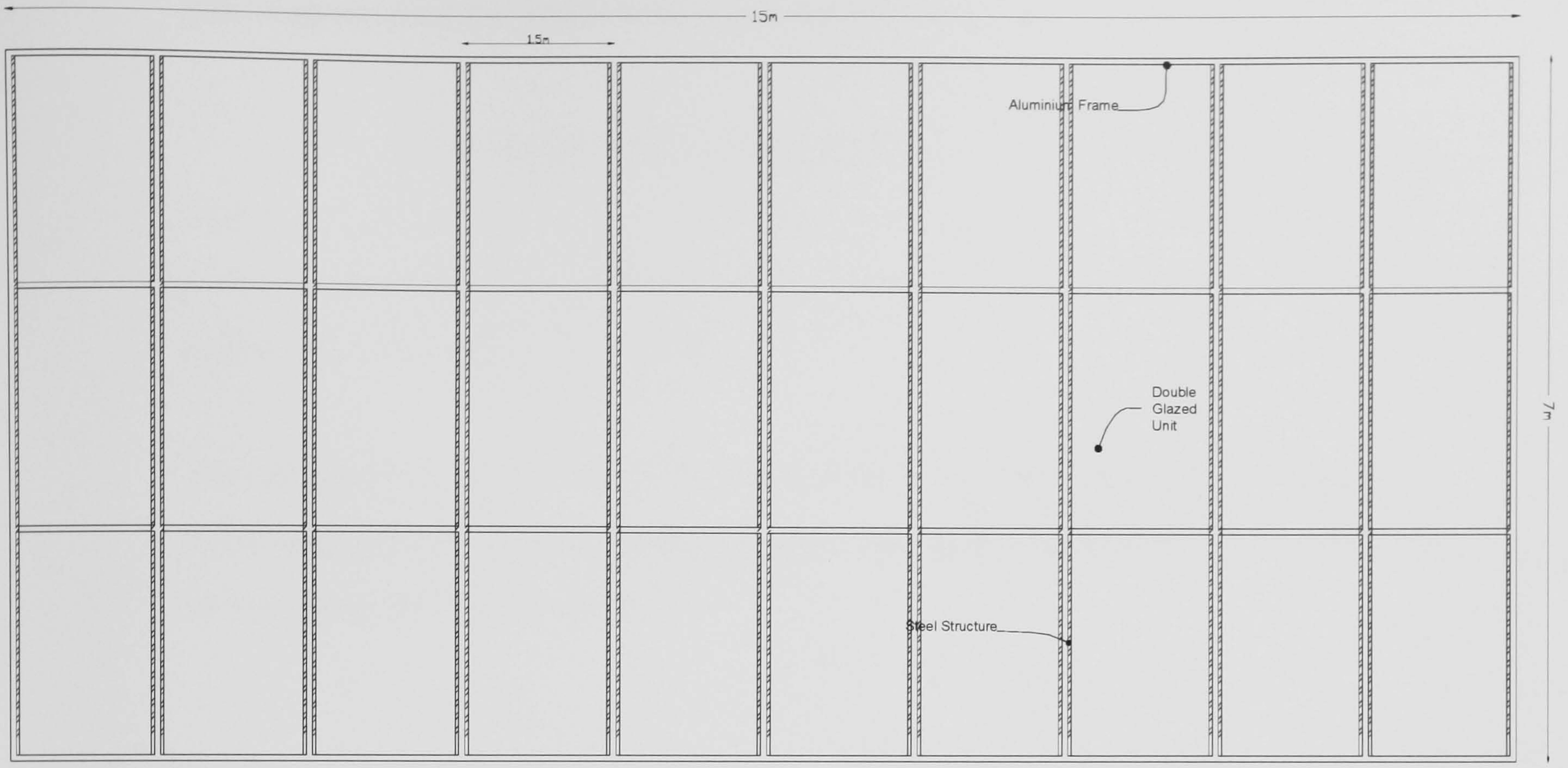

Figure A8 Plan for the double-glazed rooflight.

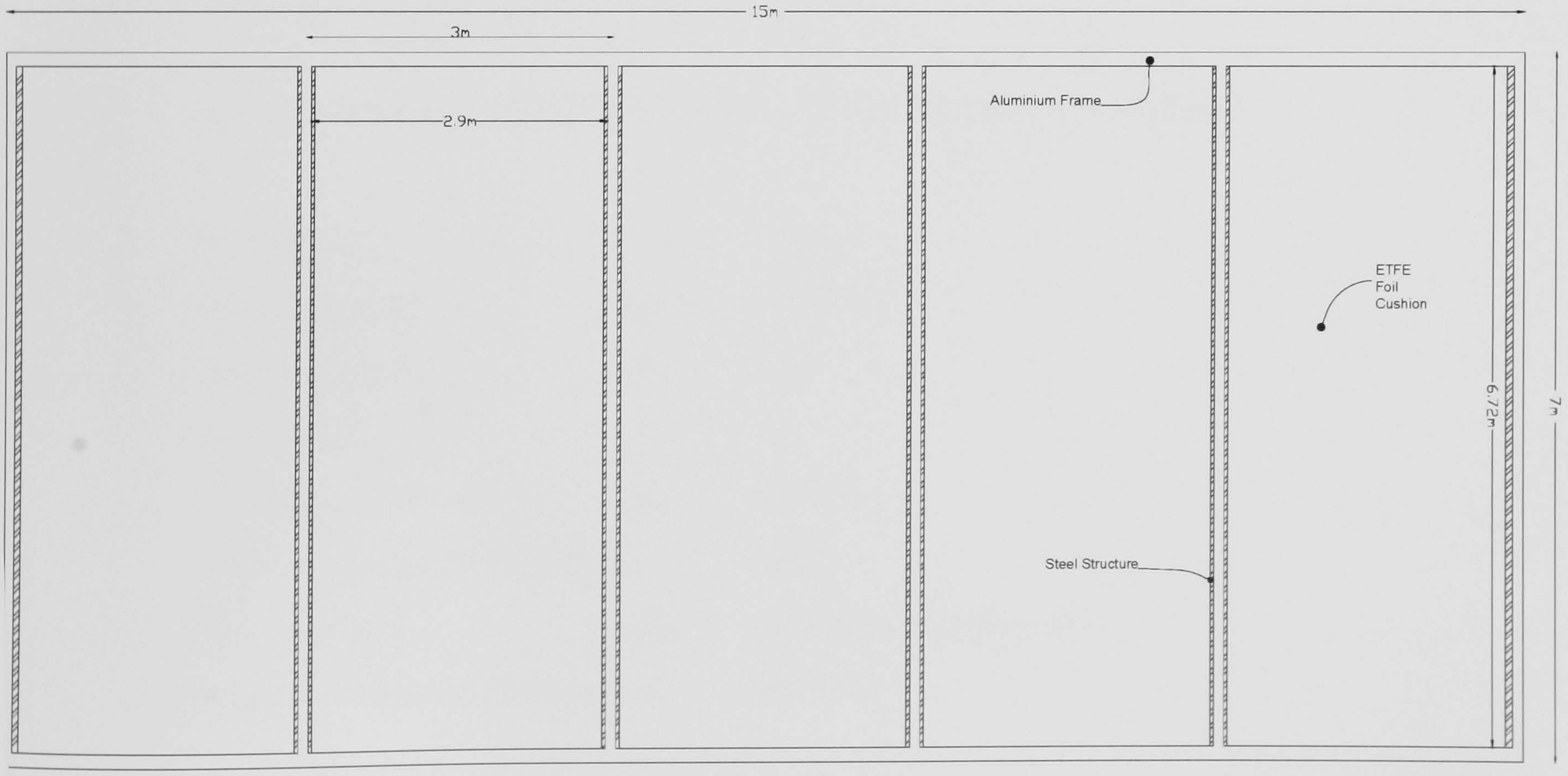

Figure A9 Roof plan for ETFE rooflight.

The glass thickness is determined using guidance in BS 5516:1991. Using the following equation the design load is calculated:

$$\text{The design load} = 2.6(p_s + p_{di}) \qquad \text{(A-6)}$$

where:

p_s design snow load.	750 N
p_{di} Design dead load.	357 N

The calculated design load of 2878 N/m^2 results in a recommended glass thickness of 6mm toughened and 8.4mm laminated glass. This glass is supported on four sides by two mullions and two transoms.

Structure

The structure for the rooflights is a series of simply spanning beams, rafters, which span the 7m from one side of the void to the other. The spanning steelwork members have been sized using the following information:

A wind pressure of + 1.0 kN/m^2 and – 1.2kN/m^2 based on the following:

Wind Speed		37m/s.
Dynamic pressure	q_b	300 N/m^2.
Altitude Factor	S_a	1.1.
Directional Factor	S_d	1.0.
Site Dynamic Pressure	q_s	330 N/m^2.
Effective Height of Building		22m.
Terrain Factor	S_b	3 (50 Km from the sea).
Effective Dynamic Pressure	q_e	990 N/m^2.

The dead load is developed from the self-weight of the steel, aluminium frame and glass or ETFE. The snow loading is a nominal figure based on the location of the site, BS 5516: 1991, 0.75 kN/m^2. The uplift wind load is the dominant loading and is in the order of 0.87 kN/m^2. A self-weight for the glass and ETFE along with supporting structures has been calculated at 0.6 kN/m^2 and 0.5 kN/m^2 respectively.

The beams have been sized using a limit state code BS EN 10210 Part 2 (1997) using deflection limit of 20mm. The size of the beams required for both roofs is similar: 168mm x 10mm circular hollow section with a mass of 39 kg/m for the ETFE and 193.7mm x 6.3mm circular hollow section with a mass of 29.1 kg/m for the Glass. However, the higher quantity of beams required results in a heavier structure for the glazed roof at 2.24 tonnes in comparison to 1.64 tonnes for the ETFE foil roof, an increase of 36%. The increased weight of steel is also translated into an increase in the structure required below the rooflight to support it.

Weather

The rainwater is removed from the roof by having an angle of 6° from one side of the void to the other, this directs rainwater through the channels in the aluminium mullion systems for the glazing. The simplistic aluminium framing system used for ETFE does not create a drainage channel, but relies on the angle of the roof to draw the water down into a gutter.

Sound

The ETFE foil roof has a high sound transmittance with a weighted sound reduction of 8dB Rw (Hoechst 1991) in comparison to 33dB Rw (Pilkington 1997a) for the glazed roof. The high sound transmittance would make this type of roof unsuitable for spaces where the transmission of external noise is an important design issue, an office beside a busy street for example. However, in instances where the internal noise levels are likely to be high and there are noise pollution concerns this feature can be an advantage. In this case is likely to present a small advantage, the high sound transmittance of the roof will lessen the sound of footfall at the base of the atrium, and there is not likely to be excessive external noise.

Thermal

The new Building Regulations Part L2, introduced in April 2002 place higher restrictions on the permitted heat transmission through rooflights and atria than was previously the case. Conservatories, atria and similar sunspaces (DTLR 2002) should be treated as an integral part of the building where no separation occurs and if there is separation, i.e. walls with the same U-value as external walls, it is suggested that such spaces are unheated and un-cooled or have their own on/off controls. In this instance, the rooflight would be treated the same as an integral part of the building, that is required to meet a U-value of 2.2 W/m^{2}K for a metal framed window and 2.0 W/m^{2}K for a PVC or Wooden frame.

U-value for a multi-part façade element is calculated using the following equation:

$$U_{Total} = \frac{A_i U_i + A_f U_f}{A_i + A_f} \qquad \text{(A-7)}$$

Where :

A_i is the area of the infill element

A_f is the area of the frame

U_i is the U-value of the infill element

U_f is the U-value of the frame

U_{Total} is the U-value of the roof

The U-value for this size of cushion in a three layer configuration was calculated using ANSYS at 1.83 W/m^{2}K (Wang 2000). The U-value for the frame can be calculated from Table A3, using the U-value of the test cushion with and without frame. Using this method the U-value of the ETFE framing system is 5.8 W/m^{2}K. Using the frame to cushion ratio of this roof design, the overall U-value of the ETFE Foil roof is 2.15 W/m^{2}K, which is just below the recommended limit in Part L2 of the Building Regulations.

The U-value of the glass roof was calculated in the following manner, a value of 2.3 W/m^{2}K was taken for the framing system. This is based on a typical curtain-walling section, widely used in the UK and Europe (Shüco 1998). The double glazed glass with low-e coating has a horizontal U-value of 1.9 W/m^{2}K (Pilkington 1997b). With the configuration shown in Figure A8 the glass roof light has an overall U-value of 1.94 W/m^{2}K.

These results show that there is little difference in U-value between the two types of roof. The poor U-value of the ETFE framing section is compensated for by the large infill to frame area ratio. However, It also presents an opportunity for an improvement of the thermal transmittance of ETFE foil cushion roofs. A curtain wall mullion is well developed with a system of thermal breaks and an internal box structure. If a similar approach was taken to the thermal bridging in an ETFE foil roof profile leading to an improvement of the thermal bridging through the frame to something akin to a curtain wall, which after all is a similar structure for a similar purpose, this would result in a reduction in this overall roof U-value to 1.86 W/m^{2}K. This small improvement in U-value (13.5 %) will become important as the Building Regulations become more stringent with respect to thermal transmittance.

Lighting

The light transmittance through a roof light is important because it can aid daylighting in a building and the transmittance through the cushion can increase the external load, through solar gain, into the space below. Light transmittance through glass roofs is well characterised (Pilkington 1994). However, the light transmittance through the single layers of ETFE foil can be combined to give the light transmittance of a combination of ETFE layers, as shown in Table A4.

Table A4 Light transmittance through ETFE and glass rooflights.

		ETFE Foil [a]	Glass [b]
Light	Transmittance	0.78	0.72
	Reflectance	0.20	0.16
Solar	Direct Transmittance	0.80	0.51
	Reflectance	0.18	0.13
	Absorbtance	0.02	0.36
	Total transmittance	0.81	0.63

Source: (a) Pilkington 1999, (b) Pilkington 1994.

The light transmittance through the ETFE foil cushions is similar to that through double-glazing; however, the ETFE has a higher solar transmittance. This will lead to larger solar gains through an ETFE roof when compared to a similar glass roof. There is also less structural framework and no intermediate transoms, therefore the view through is clearer and less obstructed.

The conclusion from this must be that an ETFE roof can provide similar internal conditions to that of a glass roof. In addition if the structure is designed specifically for ETFE the large spans which can be achieved offer the potential for savings in the quantity of primary steel structure, which can reduce both the cost and environmental impact of the scheme. The use of ETFE has been particularly popular where large transparent roofing areas are required with a low weight and relatively unobstructed views, such as the Eden project, see FigureA2. However, this case study shows that ETFE can be applied to smaller atria and roof lights in office buildings.

CHAPTER A3 ENVIRONMENTAL PERFORMANCE

The previous chapter discussed the physical properties of ETFE foil cushions and presented a case-study comparison between an ETFE and a glass roof. As mentioned before, ETFE is a co-polymer of polyethylene and tetrafluoroethylene and therefore a plastic material. The use of plastics presents some environmental questions, for example persistence in the environment is a useful feature of plastics during use, but can cause problems during disposal. It must not be forgotten the plastic industry is based on the consumption of non-renewable organic resources. The change from coal to oil for fuel production has both helped to increase the availability of plastics and reduced their cost.

The use of plastics in the construction industry is a small part of overall plastics consumption, 28% (Mulder 1998). Yet, the environmental performance of construction materials is an important criterion to assess product suitability. If an existing material is to be substituted with another material it is important to ensure that the substitute material does not have greater environmental impact. The life cycle phases of ETFE Foil cushions are discussed in this chapter in terms of their impact on the environment and where applicable comparisons are made with glass and other materials.

Manufacture

ETFE is manufactured from fluorspar, hydrogen sulphate and trichloromethane (CaF_2, H_2SO_4 and $CHCl_3$). The fluorspar or fluorite is the largest natural store of fluorine; it is found all over the world and is often mined in conjunction with limestone. These raw materials are used to make Chlorodiflouromethane, a Class II substance under the Montreal treaty on ozone depleting substances (which does not contribute to global warming). This undergoes pyrolysis at 700°C to give $CF_2{=}CF_2$, which can be polymerised using a method described in US patent No. 4016345. The tetrafluoroethane is polymerised in an aqueous reaction in the presence of a dispersing agent (fluorinated carboxylic acid or fluorinated carboxylate) and in the presence of an inorganic persulfate initiator. The reaction is carried out at a temperature of between 95°C and 125°C, the initiator is added continuously until 50 - 85% of the polytetrafluoroethene is formed. The resulting resin is coagulated and dried. The by-products of this process are calcium sulphate $CaSO_4$, hydrogen chloride HCl and hydrogen fluoride HF. The calcium sulphate and hydrogen fluoride are used to make more fluorspar and the other waste products are incinerated.

Ethylene is produced from the cracking of naphtha and hydrogenation of long chain polymers from the petrochemical industry. The feedstock has a mixture of paraffinic, naphthenic and aromatic hydrocarbons of varying molecular weights and it is possible that the composition of naphtha feed stocks vary from one batch to the next. There are fugitive emissions from the pyrolysis of naptha and volatile hydrocarbons, although they are hard to quantify. The waste from the caustic solution is used to scrub the polymers during the compressor stage. The ethylene monomers are co-polymerised with the PTFE monomers using a “free radical polymerisation” process.

Processing
ETFE is sold by manufacturers as granules; it is heated to its softening temperature of ≈ 170°C in the hopper of an extruder. The extrudate is then blow moulded into large sheets between 50μm and 150μm thick. The sheets of ETFE are transported from the materials manufacturers to smaller façade contractors. There the sheets are cut to size and heat welded together to form the three layer cushions. The pneumatic cushions are fixed into either aluminium or steel frames. Transporting the finished cushions ready for installation to site requires one tenth of the energy to transport a similar construction in glass due to its much lower density.

The float glass process is well documented (Pilkington, 1969). However, its most important feature is the very high heat input needed to cause the raw materials to combine. There are also very significant gaseous by-products, principally CO_2, SO_X and NO_X, implicated in global warming, acidification and nitrification respectively. There is virtually no solid waste in the process due to the recycling of solid waste material created during the process. The energy aspects of this are addressed through the embodied energy data presented in Table A5.

Embodied Energy

This is a concept that takes into account the amount of energy used to produce material and includes the energy associated with mining, mineral purification and processing. The embodied energy (ee) values for sheet glass and ETFE are presented (Table A5). The embodied energy for ETFE resin is based on data from the manufactures and values presented are for ETFE per m^2 based on a typical three layer configuration of 150μm, 50μm, 250μm sheets. The embodied energy values for glass are based on average data from the UK (West, 1994). It can be seen from Table A4 that although the values of embodied energy per tonne of material is similar, Table A4, it is very different when a suitable functional unit is compared, such as area covered by roofing material.

Table A5 Embodied Energy values for ETFE and Glass.

EMBODIED ENERGY		ETFE FOIL CUSHION	6mm FLOAT GLASS
EE	GJ/tonne	26.5	20
EE per m^2	MJ/m^2	27	300

Resource Consumption in Use

ETFE has a low friction constant, anti-adhesion and water/oil repellence which means that roofs and atria need to be cleaned less frequently than similar glass roofs. This leads to a reduction in the cost to the owner of the building, but also a reduction in the use of detergents and water used to maintain the building.

Higher daylight factors due to greater transmittance of light can lead to a reduction of artificial light used in buildings. This directly reduces the energy consumption of the building and improves the atmosphere inside buildings.

A good U-value decreases the amount of heat lost through the roof, directly reducing the burden placed on the heating system of the building. However, care is needed in the design to avoid overheating. For glass there is no energy needed in use. ETFE foil cushions are kept inflated by using an electric fan and this uses a small amount of energy, approximately 50W per $1000m^2$.

Recycling

The process used to manufacture the three layer cushions does not require any additives to the co-polymer system and other products are not mixed. The cushion can be directly removed from its aluminium frame and washed. Once the material is clean it can be recycled by heating it to its softening temperature. The softening temperature of ETFE is low so this is not a very costly operation; the recycled ETFE can be added into the hopper with virgin ETFE. Due to the novel nature of ETFE being used in buildings there is as yet no mechanism for the retrieval and recycling of ETFE from buildings.

Glass is also very recyclable, and bottle glass is very often re-used or recycled. However, the float glass process is very sensitive to any impurities, which can result in catastrophic failure, so that in practice float glass is not recycled into float glass. The fixings and frames used in glazing cause contamination, particularly those made from aluminium, because aluminium causes inclusions and bubbles to form inside the molten glass that cannot be removed. Because of the high specifications for float glass there is a very low tolerance of visual imperfections.

Fire By-Products

Some PTFE based roofing materials have been implicated as fire hazards (Purser, 1994) because of the production of "super toxic" compounds under certain fire conditions. ETFE is not implicated in this manner because ETFE has a much lower melting point than PTFE 260°C. This means that in a fire situation ETFE is much more likely to vaporise. While the by-products of burning and incineration of ETFE are toxic fumes including CO and HF (Dupont, 1992) these are not the super toxic compounds involved with the incineration of PTFE. On a small scale these fumes would occur in a tiny amount; so for example the ash and fumes created by a building fire would be very insubstantial. Test have been carried out (FEDRA, 1998) which show that in the event of a fire beneath an ETFE Foil cushion roof the polymer would recoil from the flames and vent the fire. However, when using incineration as a disposal method special precautions have to be taken to avoid the discharge of fumes and the contamination of water by waste.

Glass does not burn under building fire conditions, so there are no issues relating to its by-products, although if the fire is intense enough the glass will shatter so there are design issues relating to safety of overhead glazing in fire conditions.

Landfill

Due to the inert nature of ETFE: a foil roof which was disposed of would create very little contamination although there is a slow release of HF gas from the foils. Glass is also very inert after production and will remain in the ground for thousands of years. In most situations reuse or recycling is a preferable environmental option to landfill. However, in the case of ETFE there is little commercial or legislative imperative to recycle the polymer at the end of a building lifecycle. Architectural glass, in particular safety glass such as is used in overhead situations, with the inclusion of coatings and polymer inter-layers is technically difficult to recycle or use as cullet. The pressures on glass manufactures to recycle architectural glass are both financial, the inclusion of ground glass or cullet in glass manufacture reduces processing costs, and legislative, the reduction in the quantity of energy used during the processing of float glass would help to reduce the amount of carbon emissions associated with float glass. Thus it is likely that the technical problems associated with the recycling of float glass will be overcome in the near future.

Conclusions

The use of both ETFE Foil and Glass in buildings can be beneficial as studies have shown improving daylight in buildings and linking lighting to building management systems can result in energy savings (Lynes 1990, Leslie 2003). If only energy consumption during manufacture is considered ETFE has a fraction of the environmental impact that glass does, approximately 10%. However, a view of the other stages of the building lifecycle and a widening of the definition of environmental impact requires a reassessment of this analysis. The other impacts associated with ETFE manufacture, in particular the release of fugitive emissions of Hydrogen Fluoride must be weighed against those emissions associated with glass. Although it can be argued that the smaller quantity of material used to span the same distance results in a smaller environmental impact. This is particularly the case when considering the reduced amount of steel that will be used in an ETFE foil roof. As steel has a large embodied energy (24- 59 GJ/tonne) and associated environmental impacts from its manufacture. The reduction in the weight of steel in the roof whilst maintaining the structural integrity of the roof is a distinct advantage.

During the deconstruction of a building the roofing materials will be removed, all metals used are likely to be stripped from the site and recycled because the metal scrap has financial value. However, although it is technically possible to recycle both glass and ETFE at the moment it is unlikely to happen in practice. Both the ETFE and glass will be sent to landfill.

A triple layer ETFE foil cushion roof has lower embodied energy and is likely to require less cleaning during its lifetime yet performs the same function as a glass rooflight. However it must be noted that there is a lifetime energy consumption associated with the use of an ETFE Foil when used in place of a glass roof.

CHAPTER A4 PART A SUMMARY, DISCUSSION AND CONCLUSIONS

Part A of the portfolio presented work which was carried out into the use of ETFE Foil cushions in buildings. This part of the portfolio examined both the effects of ETFE manufacture and its use in buildings. This study has considered performance both in terms of fitness for purpose and in comparison to glass; the common alternative. Chapter A1 discussed the application of transparent materials to roofs and atria (which is their main application in buildings) as well as the use of polymers in these applications. Chapter A2 presented the physical properties of ETFE and tests carried out and a case study. In chapter A3 the environmental impacts of ETFE foil cushions and glass were discussed. The main findings can be summarised as follows:

Lighting

ETFE and glass transmit a similar range of frequencies, providing similar daylighting opportunities. However, the picture rendering through ETFE Foil cushions is poorer than that through glass, because the surfaces of the cushion are curved. The impact of this would depend on the external view; although lettering would appear distorted, it is easy to see clouds below an atrium roof.

Solar control

Transparent materials admit daylight, but, if this is uncontrolled glare and overheating could result. However, this is a similar problem for both glass and ETFE foil cushions and measures should be taken to eliminate glare and optimise the transmission of solar radiation inside buildings. A poor estimation of the quantity of solar gain can lead to the under/over sizing of HVAC equipment.

Sound Transmission

ETFE Foil cushions are, in effect, non-existent when it comes to sound; they transmit practically all sound. This can be viewed in different ways for different design questions. If the building is a library beside a motorway or train station this could be a problem, but if it is a leisure centre in a field this is a good solution as internal noise is transmitted out rather than reflected back into the building. In an atrium, footfall is not reflected around so the internal space can be very quiet, but conversely rain is easily audible.

Thermal Insulation

The thermal properties of a building are an important consideration, they impact on the thermal performance and ultimately the energy cost of the building. A well insulated building will be both easier to heat and easier to cool than a badly insulated building. The U-value is an index measuring the heat flux through an element per unit of surface area and temperature difference. A three layer ETFE Foil roof will have a similar insulative value to a low-e double glazed roof.

Environmental Implications

There are some adverse environmental impacts that result from ETFE manufacture. However, these must be balanced against the adverse environmental impacts from the use and manufacture of glass. Using ETFE can reduce the overall embodied energy of a structure and provide similar thermal conductivity as double-glazing. The use of ETFE instead of double-glazing can provide energy consumption reductions due to the improved U-value. The low density of the ETFE foil cushions also results in reduced steel structure.

Discussion of the Methodology

The work presented in Part A of the portfolio was carried out at the beginning of the candidate's doctoral programme. At the time that the work was carried out little was known about ETFE and there was little information in the public and academic domain, which discussed it's use as a building material. The work presented here which was both carried out by the candidate, and others where mentioned, helped to raise the profile of ETFE foil and in the years which have followed the material has been more widely used in buildings.

However, there is scope for a widening and deepening of the research presented in this part of the portfolio. There are two main areas for further research which would improve the information presented here.

- A comprehensive building survey which monitored the internal conditions in both ETFE and Glass atrium buildings.
- A lifecycle analysis of ETFE Foil with a similar scope and system boundaries to that which was later carried out on architectural float glazing.

At the time this work was carried out the number of ETFE foil buildings in the UK was limited, less than 20 buildings. The form of these building was varied and ETFE was incorporated into these few buildings in varying quantities. The buildings as well as having varying forms also housed varying functions which made internal comparison between glass and ETFE buildings less than useful. At that time the candidate did not have access, either through the academic institution or the work placement, to long-term monitoring sites.

The candidate researched the environmental impacts associated with the use of ETFE foil cushions, but this research could have been furthered by a comprehensive lifecycle analysis, which could only have been undertaken with the cooperation of one of the two main ETFE manufacturers. Although one of the ETFE manufacturers was approached to discuss such an option, ETFE for use in buildings has such a small share of the total ETFE market that the ETFE manufacturer did not see such a study as a high priority. However, if the use of ETFE foil in building continues to grow this study could be carried out in the future.

Overall Conclusions

ETFE Foil is an appropriate technology for certain building applications, particularly leisure venues, office atria and agricultural buildings, where the volume of space to be enclosed is large and high light levels are important. The physical characteristics of the material used enable this approach to be used in a variety of situations where a large expanse of glass is not suitable. Further, it allows the weight of the structure to be greatly reduced whilst providing the same level of stability. ETFE Foils can improve the environmental performance of a building from two points-of-view; there is the opportunity to reduce the overall environmental burden incurred from the construction process itself and there is also the opportunity to reduce the burden of the building during its lifetime. This is all dependent, however, on the ability of architects and engineers to take advantage of both the flexibility and limitations of ETFE Foil cushions.

PART B

LIFE CYCLE ANALYSIS (LCA)
OF
ARCHITECTURAL FLOAT GLASS

PART B: LIFE CYCLE ANALYSIS OF ARCHITECTURAL GLASS.

This part of the portfolio documents the Life Cycle Analysis (LCA) of Pilkington float glass. This was a "cradle to gate" LCA which considers the environmental impacts of glass manufacture, and which focuses on the embodied energy and environmental impact calculated in Eco-Indicator 99 eco-points. Chapter B1 is an introduction to the project together with a description of the glass-making process. Chapter B2 describes the LCA methods chosen for this study while chapter B3 presents the methodology for the analysis. Chapter B4 presents the results, and conclusions are drawn in chapter B5.

CHAPTER B1 INTRODUCTION

As mentioned in the executive summary the construction sector accounts for 46% of the greenhouse gas emissions in the UK (CIBSE, 1999a). This sector also has a large impact on resource depletion and is cited as one of the most environmentally-polluting industries (Chatfield, 1998). Buildings use 30% of the UK energy production in heating, cooling and lighting during their lifetime (DTI, 1997).

In order to reduce the energy consumption of buildings, the UK Government has focused on improving the design of building systems and structures. Primary production has also come under scrutiny and there has been research carried out into the intrinsic energy value of construction materials (Atkinson, 1996). Some materials provide large benefits despite their impact on the environment, but with most materials the question over the benefits that they provide and their environmental impact is less clear. Glazing has a major effect on the environmental performance of buildings. Orientation, light transmission levels, solar gain and thermal transmission of glass are all major contributors to the environmental impact of a structure. In the EU 6.9 million tonnes of float glass were produced in 1997 and approximately 75% of this was used in the building industry (European Commission, 1999).

Pilkington plc. is the largest glass manufacturer in the UK, in recent years architects have begun to express an interest in the environmental impact of their products. This led them to collaborate with the candidate to try to assess the environmental impact of their main product, which is 4mm float glass. This product is used in the majority of residential double-glazing and forms the main constituent of the most widely used laminated glass (8.8mm, two leaves of 4mm glass and 0.8mm polyvinyl butyral). The results of the study have discussed with Pilkington plc. and has been used to develop their environmental procurement policy.

B1.1 ENVIRONMENTAL ANALYSIS OF BUILDING PRODUCTS AND COMPONENTS

It is possible to view the construction project as a solution to multiple product-specific functional constraints, with a series of viable solutions (Chevalier, 1996). If a building is viewed in a "product oriented" rather than "process oriented" manner, it becomes possible to analyse the environmental impact of a building within the context of the performance specification demanded by user requirements. This conceptual framework is important because the performance parameters of materials are linked. For example meeting a higher thermal transmission requirement by improving the thermal insulation in a wall will be more costly, but will probably result in reduced acoustic transmission, which is an unforeseen benefit. The tendency in the past has been to select materials on performance criteria which did not include environmental performance. However, requiring higher environmental performance has a large impact on both the actual environmental performance of a product and the other materials properties'associated with that product.

While it is widely acknowledged that buildings need to be assessed from an environmental stand point, it is not always obvious which methods of environmental assessment will provide the desired results, i.e. to achieve building solutions which meet the requirements of the relevant stake-holders (e.g. occupants, owners and the wider community) whilst having the lowest feasible impact on the environment. Environmental assessment methods fall into two groups mono-criterion and multi-criteria assessment methods.

Mono-criterion methods, like a fixed requirement for embodied energy, or the emphasis on thermal insulation values in Part L of the building regulations (DTLR, 2002) have the advantage of being easily understood. It is clear whether or not a criterion is achieved or improved and there is a fixed target to aim for. However, this type of environmental analysis can have the disadvantage of causing "pollution shifts". This is because the improvements on the criterion under study are almost certainly at the cost of deterioration in another criterion.

Multi-criteria analysis systems are more complex and require the assessment of various criteria simultaneously. Some multi-criteria methods of environmental assessment consist of scoring methods which mark specific parameters according to a defined set of bench marks. This provides an "environmental friendliness" score. Examples of this type of tool include:

- BREEAM or Building Research Establishment Environmental Assessment Method; developed in Britain, and has been extended for use in Canada and Hong Kong (Prior, 1993).
- Eco-Profile; a method developed in Norway.
- Leadership in Energy and Environmental Design (LEED); developed in the USA.

This type of tool has the advantage of a defined set of criteria which is useful for benchmarking. However, one of the disadvantages of this type of tool stems from the fact that definitions of "good" and "bad" in environmental terms are predefined by the developer of the tool (Chevalier, 1996). This method does not allow the user to see the biases and priorities of the tool developer.

The descriptive method of environmental assessment does not set standards, but rather describes the system in detail and uses the information gained to highlight areas for improvement, monitoring or further investigation. Life Cycle Analysis (LCA) is one of the most widely used descriptive environmental analysis tools. LCA is a method which has developed from "net energy analysis" (Ayres, 1995) a method developed during the 1970s.

This work presents an in-depth LCA of clear float glass in order to quantify the environmental impacts of the material and indicate ways of reducing them. This will have a direct effect on the reduction of a buildings' environmental impact. Before the LCA work carried out is presented, the following section describes the glass making process to provide an understanding of the components involved.

B1.2 DESCRIPTION OF GLASS MANUFACTURE

Figure B1 presents a diagram of the float glass manufacturing process. This process produces optically flat glass between 4 and 20 mm thick for use in architectural and automotive applications. The glass is based on silica from sand (appropriate carbonates are added to the sand to form the soda-lime silica glass). The feedstock is heated to remove the water from the system and allow the decomposition of carbonates, sulphates and nitrates. This results in a very viscous liquid full of bubbles, which is heated to approximately 1600°C. The bubbles are removed with the addition of chemical refining agents and the glass is slowly cooled as it progresses toward the end of the melting furnace.

At approximately 1000°C the molten glass is poured from the furnace into the float bath, which is a chamber filled with molten tin. The atmosphere in the float bath is closely controlled to prevent oxidation of the tin, which could mark the surface of the glass. The glass floats in a ribbon on the tin at a consistent thickness; which is controlled by the speed of the ribbon of glass. It is possible to produce parallel sided glass with a good surface finish using this process. The glass is annealed at the glass transition temperature (T_g) in the Lehr to remove any internal stresses that build up due to the differential cooling rate between the surface and interior of the glass. The ribbon of glass is checked for faults, which are marked and removed. The resulting clear glass is cut to the required size, packed and stored on site ready for sale.

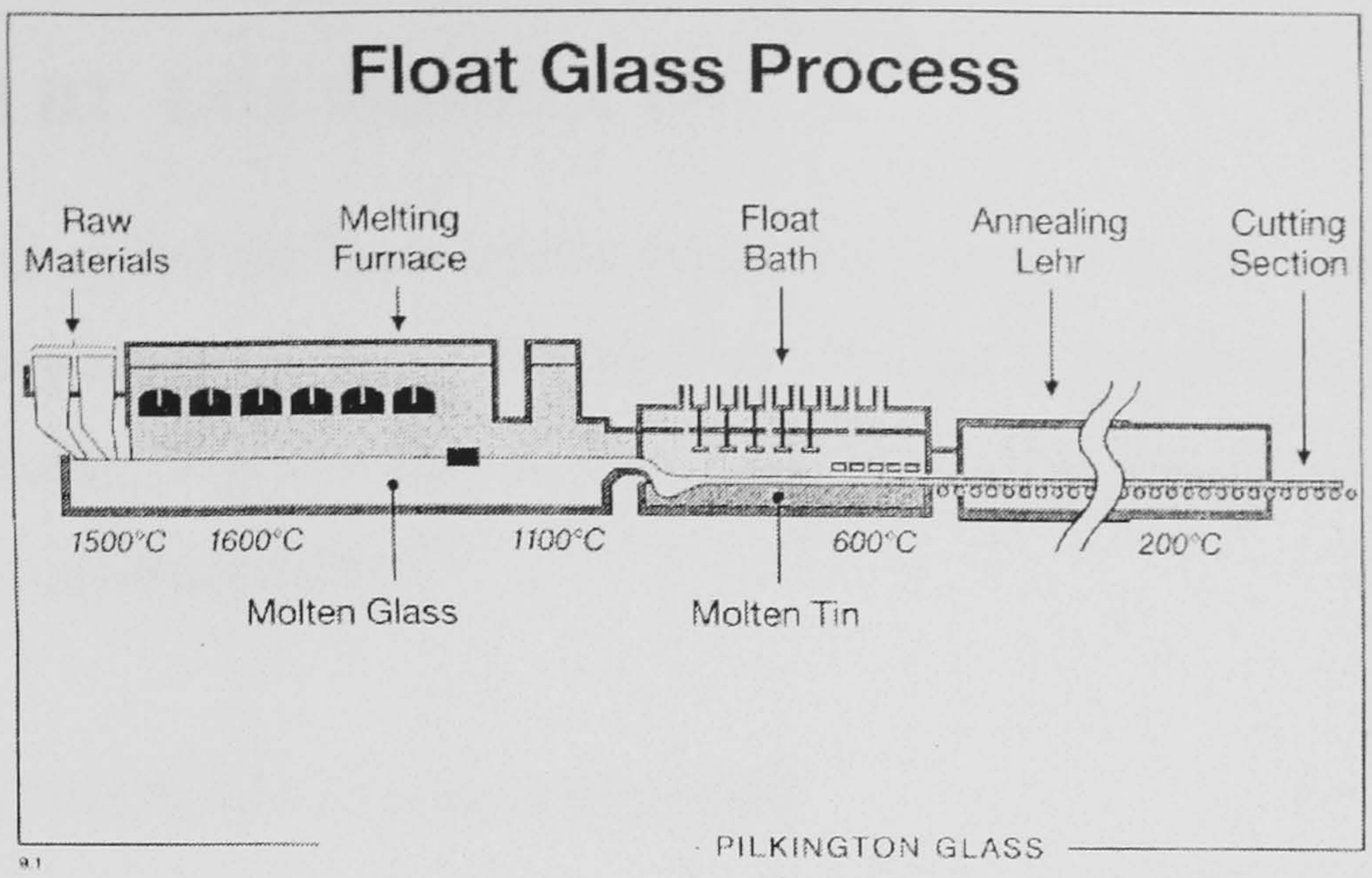

Figure B1: The Float Glass manufacturing process.

CHAPTER B2 LCA MODELLING

This chapter describes the basis of the lifecycle analysis concept. There are several methods of carrying out an LCA and one method, the ECO-Indicator 99 method, is described in detail. The selection of a suitable LCA tool is described and the details of the chosen tool are presented.

B2.1 LIFE CYCLE ANALYSIS CONCEPT

The LCA concept addresses the environmental impacts of the system under study in the areas of ecological health, human health and resource depletion (Consoli, 1993). LCA uses a simplified model of a physical system to determine where the environmental impacts occur; part of the decision making process when carrying out an LCA is defining the boundaries and level of detail employed in an LCA study. LCA is a flexible method of environmental assessment whose various stages can be tailored to suit the system under scrutiny.

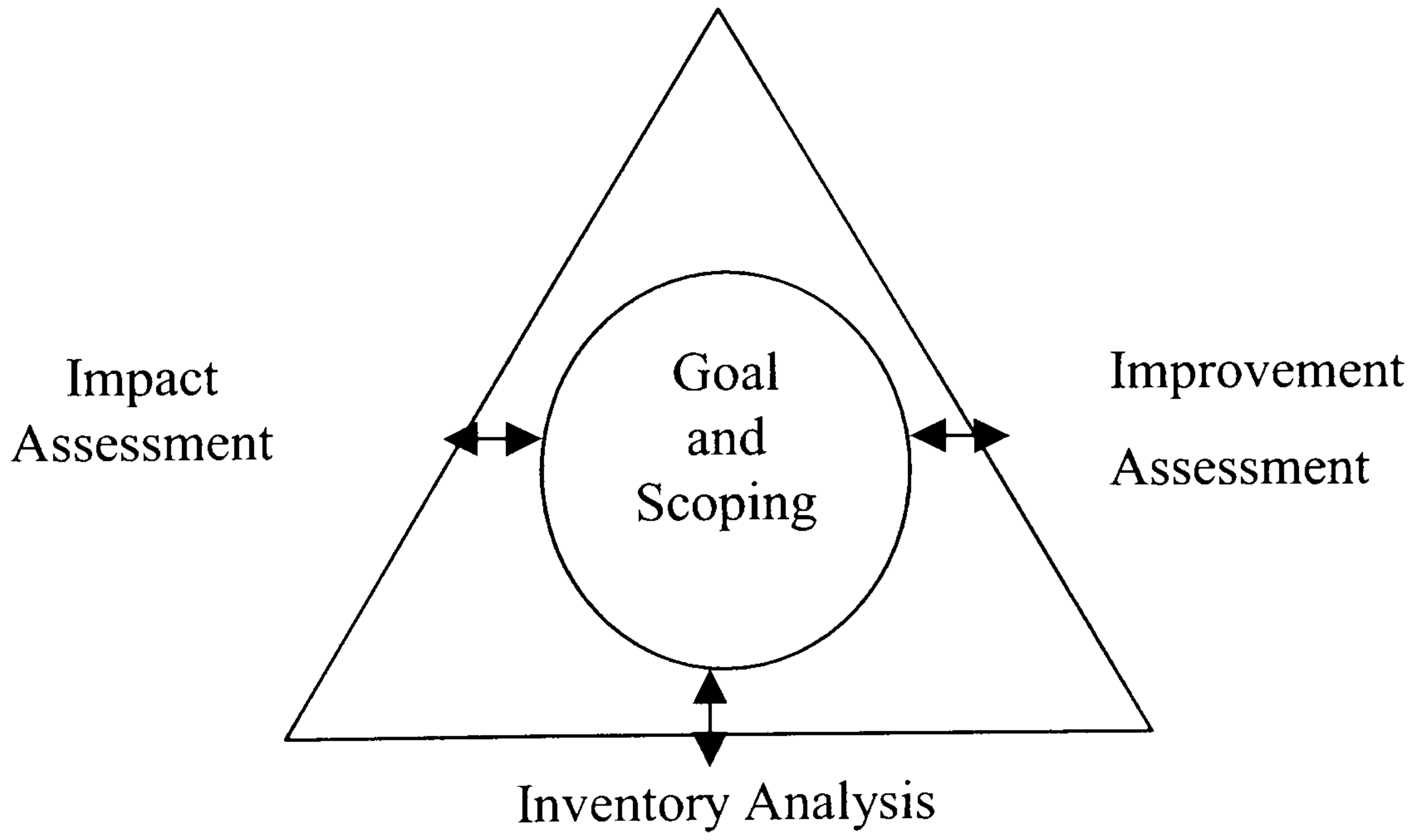

Figure B2: The SETAC LCA interdependencies diagram.

LCA is one in a long line of systems that evaluate products by way of their energy use, waste and resources. It has come to prominence in the last ten years, partially as a result of the extensive work carried out by the Society of Environmental Toxicology and Chemistry (SETAC) and due to some innate advantages it has over other methods of environmental analysis. LCA methodology has the advantage of being multifaceted and able to assess complex models, by stages if necessary. SETAC have produced a diagram (Figure B2) to show the way that the different parts of an LCA interact.

It was originally envisaged that LCA would be used as a tool to facilitate an iterative processes, which could improve the environmental impact of products and services with improvements in the design of products and services feeding into the LCA, thus creating a virtuous cycle.

As depicted in Figure B2, an LCA has several distinct stages (Consoli, 1993):

- Goal Definition and Scoping.
- Inventory Analysis.
- Impact Assessment.
- Analysis and Interpretation.

Goal Definition and Scoping

This part of the process sets out the boundaries of the LCA, because typically LCAs are performed in order to answer a specific question or investigate a specific problem. The problem investigated is set out clearly so that the aim of the work is transparent. The boundaries of the study are also defined, which sets out what information will be included or excluded from the study. It is possible that two or more smaller LCAs can be linked together in order to provide information about a complex product i.e. a building.

Inventory Analysis

Once the boundaries of the study have been defined, it is possible to look at the steps involved in the product or service. Any product or service under study is referred to as the "system". The system is broken down into a number of smaller less complicated steps the "sub-systems". The inputs and outputs to the sub-system are listed and they become known as the system flows. The inventory is simply a list of all of the individual flows in a system. An inventory is a statement of the quantity of material used and produced by a process and contains relatively little of use by itself.

The information in the inventory must be analysed in order to make an effect assessment of any effects that the system has on the environment.

Impact Assessment

During the inventory analysis flows are grouped together and the effects, known as impacts, are summed so that the total impact on the environment can be calculated. There are two effective stages, the classification and characterisation of the flows from the inventory and then the valuation of those flows.

The raw data collected from the inventory is classified into impact categories. An impact category classifies the impacts according to the sphere of the environment where the impact occurs i.e. water, air, land, human health etc. A particular flow may have environmental effects which correspond to more than one impact category and in this case it will appear more than once in the impact classification categories.

The classified data is characterised, so that it can be usefully compared. The characterisation involves the measurement of the intensity of a flow against a base flow with a known environmental impact and thus all the contributions to this area can be quantified. This information is used to create a value for the total effects which occur in that area of the environment. Although there has been a consensus agreement about the classification categories there are several methods of impact characterisation, which use different bases for their comparison. A broad classification of categories is as follows:

- Resource Depletion.
- Ozone Depletion Potential.
- Global Warming Potential.
- Eutrophication.
- Acidification.
- Human and Eco Toxicity.
- Embodied Energy.

Analysis and Interpretation

An important step for the interpretation of LCA results is the valuation of the classified and characterised data. Valuations allow a number to be developed which expresses the total environmental load of a product or system. This enables the comparison of impact categories; otherwise evaluating two impacts of a similar magnitude which affect different parts of the environment would be a great challenge. Traditionally LCAs use 10 or more impact categories to rate the total impact a product has on the environment. Each impact category is valued separately and the score is combined to give a total rating. This evaluation allows the seriousness of negative impacts to be taken into account. The valuation adds a value judgement to that of the scientific judgements already made when the impacts were classified and categorised. While this enables the environmental impact of a particular product to be given a single environmental score, it must be highlighted that the ISO 14040 (1997) states:

"There is no scientific basis for reducing LCA results to a single overall score of number, since trade-offs and complexities exist for the systems analysed at different stages of their lifecycle." (4.1 Key features of LCA)

However, this step is often used because by valuing the environmental effects of products, it is possible to compare the impacts of several different products which have qualitatively different impacts. This makes the full results of an LCA easier to interpret and can provide a useful basis on which to carryout comparisons.

B2.2 BASIC ASSUMPTIONS

There are several basic assumptions which underly the LCA concept. These assumptions give an indication of the limitations of this methodology:

- Time stability.
- Separability.
- Precision.
- Continuous, idealised world model.

The LCA method uses information from a particular time frame. This "snap shot" does not take into account variations in the system over time. For example it is general practice to make assumptions about the "end of life" of a product which may be 10 years hence. Accepted practice for disposal or reuse of a product at the time of the LCA may vary widely from the fate of that product in 10 years time.

In order to simplify the system under study the LCA technique assumes that the system under study is a closed system; hence, there is no interaction between the system and the "environment". This assumption affects the ability to reflect realistically the environment, however, it is necessary in order to reduce the unmanageable expansion of the system.

The LCA process assumes that a particular flow can have only one accurate value. This is a feature of the averaging of all of the values which has been discussed. For example it is typical practice for annual energy and material's consumption figures to be divided by annual output figures to give average consumption per unit. However, there may be very large variations in this value. The nature of LCA means that it is difficult to give supplementary information, such as the standard deviation from the mean environmental impact value.

The continuous idealised model utilised in the LCA process causes some anomalies in the impact valuation process. In order to simplify the system under study the impacts resulting from the use of materials etc. are separated into their effects in different spheres of the environment. This method ignores any impacts that are interdependent. There is little treatment of the locale of the environmental impacts, all effects are assumed to be local.

The selection of the appropriate valuation methods for Life Cycle Analysis has been widely discussed (Powell, 1997 and Notarnicola, 1998). These studies, although thorough, are not recent enough to cover the currently-available valuation methods. However, it is possible to apply the techniques used to assess the LCA valuation methods described in these studies. Valuation methods have been based on four main approaches:

- Distance to Target Techniques.
- Environmetal Cost Controls.
- Evironmental Damage Costs.
- Scoring Approaches.

The *distance to target* methods use the extent to which an actual environmental performance deviates from a standard or target. This method means that the method ranks impacts as more important the further away from a standard a particular impact is. However, there are several difficulties with this method, the targets or standards used to define the resulting weighting are often set by governments or political organisations. The targets set often reflect achievability rather than levels which are scientifically environmentally desirable. This method also assumes that all targets are equally important.

In the *environmental cost control* methods the weighting factor is based on the financial amount required to remediate the impact. This is based on the idea that there is an environmental standard which can be reached. This aspect of this method links this method to the distance to target methods and this has the same inherent drawbacks.

The *environmental damage costs* method utilises the theory of the willingness to pay (WTP) to avoid the impacts. This method differs form the environmental cost control methods in that it is based on the willingness to pay in order to avoid environmental harm rather than the cost of remediation. This methodology has a tendency to anthropomorphise environmental impacts. The weighting factors are usually based on sets of questionnaires in which a selection of the general public are asked to place monetary values on endangered species and environmental impacts. There are two inherent drawbacks, firstly the public perception of money values is highly subjective and secondly this method tends to favour animals and environmental impacts which have the highest public profiles i.e. those which are campaigned for, or have a good public image.

Scoring approaches offer an alternative to the valuation methods. In this instance the weighting factor is developed by a group of experts or a cross section of stakeholders. This method requires a two-stage valuation; a valuation of the individual flows relative to reference flows and the valuation of the reference flows to rank them in order of importance. The success of this method is highly dependent on the transparency of the decision making process and selection of the interested parties.

Powell (1997) argued that the selection of a valuation method is dependent on the aims of the study being carried out. Powell uses a selection of methods to value the environmental assessment methods:

- Transparency, this refers to the extent to which a method is easy to understand and replicate.
- Practicality, includes the availability and cost of using a particular method.
- Comprehensiveness: the approach must be capable of deriving weights for the most important impacts in the study.
- Goal consistency: the goals must be clear and the weights must be consistent with the goal.
- Goal acceptability: there must be some social acceptability in the way in which the goals are formulated.

The valuation method that has been selected for this study is the Eco-Indicator 99. This method was developed by two Dutch companies in 1995 (DUIJF consultancy BV and PRé Consultants) and has since been updated to produce the Eco-indicator 99 indices (Goedkoop 1998, Goedkoop 2000). The original work was funded by the

National Reuse of Waste Research Programme in Holland and the methodology has been developed in conjunction with some of the leading members of the LCA field.

The methodology used by the Eco-indicator developers is based on the scoring method. A set of flows are collected, these are then broken down to their constituent elements. The individual flows are characterised using a reference chemical and the characterised values are weighted. This method enables the user to interrogate the methodology at two points.

Firstly, during the valuation of the flows with regard to a reference chemical, it is possible to include new flows with your own toxicological data to this method. Secondly, the weighting used to score the classified flows is visible, thus it is easy to see a particular bias in the weighting process. A general approach to weighting flows in different spheres enables this method to be applied to any life cycle where you can procure the correct level of detail in the inventory data. The weighting has been developed in consultation with both members of the public and environmental professionals, using this method it has sought to address the criteria of social acceptability. The software is easily available (it can be downloaded and trialed from the internet) and widely used. However, the accuracy of this method is dependent on the incoming information including the inventory produced by the user and the toxicological data used to characterise the flows. This means that the eco-indicator 99 method satisfies Powell's criteria.

B2.3 ECO-INDICATOR – 99

The Eco-indicator method reduces the environmental flows in the inventory using 10 indicators as presented in Table B1. The resulting Eco-99 indicators are then weighted using a reduction factor. This reduction factor is associated with the seriousness of the significant harm caused by the environmental impact.

Table B1: Eco-Indicator 99 environmental flows

Method Name	*Unit*	*Year*	*Sphere of Impact*
Acidif and Eutrop damage	PDF*m2*yr	1999	Ecosystem
Ecotoxic emissions damage	PDF*m2*yr	1999	Ecosystem
Land occupation damage	PDF*m2*yr	1999	Ecosystem
Carcinogenic effects	DALYs	1999	Human Health
Climate change damage	DALYs	1999	Human Health
Ionising radiation damage	DALYs	1999	Human Health
Ozone layer depletion effects	DALYs	1999	Human Health
Respiratory effects	DALYs	1999	Human Health
Fossil fuels extraction damage	MJ	1999	Resources
Mineral extraction damage	MJ	1999	Resources

The Eco – indicator 99 indices (E) are calculated as follows:

$$\mathrm{E} = \sum W_e \times E_{e,i} \times m_i \qquad \text{(B-1)}$$

where for the compound i, m_i is the mass of the compound, $E_{e,i}$, is the characterisation factor of the compound i to the impact e, and W_e is the weighting factor for the environmental impact.

This reduction of the inventory flows to the final eco-indictor scores is depicted in Figure B3. The 10 indicators are grouped by the sphere they affect into impact categories and there are three separate impact categories which are weighted:

- *Damage to Human Health,* measured in DALYs (Disability Adjusted Life Years) an indicator developed by the World Health Organisation.
- *Damage to Ecosystem Quality,* specifically effects on diversity measured in PDF (Potentially Disappeared Fraction). This contains the acidification and

eutrophication damage, eco-toxic emissions damage and land occupation damage indicators.

- *Damage to Resources*, this category looks at the surplus energy required to extract lower quality mineral resources and includes the depletion of agricultural and bulk resources.

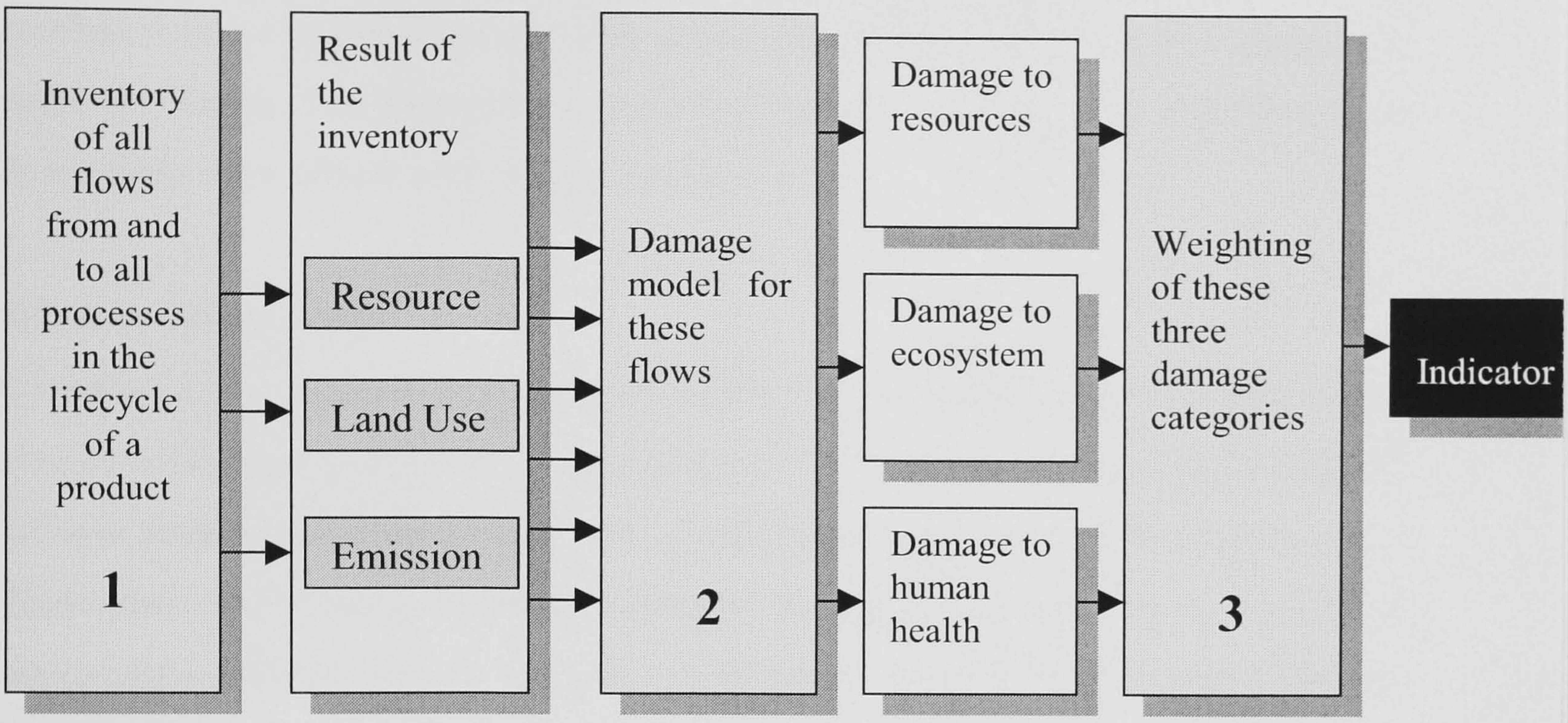

Figure B3: Diagrammatic representation of the eco-indicator 99 LCA analysis process

The characterisation factor ($E_{e,i}$) is calculated differently for each of the different types of impacts as described below:

Damage to Human Health

A fate analysis method, see below, models an emission from source to a sphere in the environment which is used to link an emission to a temporary change in concentration. Exposure analysis links this change in concentration to a dose. The effect the dose analysis has on a number of known health risks is calculated, e.g. numbers and types of cancers or respiratory effects. Damage analysis is carried out which calculates the number of Years of Life Lost (YLL) and Years Lived Disabled (YLD) from this dose.

Damage to Ecosystem Quality

A fate analysis model (see below) is used within the software to trace where a chemical from an inventory output will find its way into the environment. The length of time that the chemical substance will remain in the environment and how long it will accumulate is dependent on both the substance and the compartment of the environment; air, water and soil. The calculated concentrations of the chemical substance give a measure of how much substance is absorbed by people, plants and other life forms. The exposure is used to calculate the types and frequencies of disease and other effects used to measure the impacts.

Damage to Resources

Extraction of resources decreases the available stocks of that resource for the future as well as the quality of the remaining resources. The quality of the stocks is reduced because people always mine the most economic and easily accessible reserves first. This means that future generations will have to expend more energy to extract the remaining mineral resources. This effect is taken into account in the resource impact.

The increasing use of the earth's surface for man's activities has reduced the amount of habitat left for the propagation of non-human species. In some instances the destruction of habitat has led to the extinction of species, which makes this an important issue to address correctly. In eco-indicator 99 both local and regional impacts of land use are taken into account. The overall impacts of land use are not limited to the reduction of habitat, this is the local impact. In addition, the impact of the removal of habitat impacts on the surrounding natural habitats. The decrease of this natural resource increases the pressure on the remaining resources as well as decreasing survival mechanisms of species, such as the ability to migrate from one area to another.

Fate Analysis Method

An LCA has a lack of spatial and temporal information. The LCA specifies a release of a substance without specifying where and at what rate the mass is released. Therefore only the quantity of the emission is known, without knowing when and what the background concentrations of the substance are. A procedure is required to convert the discrete releases (in mass) of a substance into concentration. Fate models are so called because they model the flow of a substance and establish a link between a flow and a concentration of that substance. This is important as substances degrade or are transferred to areas regarded as sinks in the environment. A sink is the substance's final destination.

A fate model must overcome the flux-pulse problem, which can be defined by looking at this example. Suppose that a factory produces 1000 widgets per hour and has an emissions rate of 1kg of sodium bicarbonate per hour. To model the impact of one widget it is possible to say that a widget is responsible for 1g of sodium bicarbonate per hour, or 1 kg per 3.6 seconds , or 1/24 grams per day. However, this becomes more complex as more flows are added, intermittent use of electricity to the plant for example. It is also likely that some of the emissions from the process, i.e. the emission resulting from the widget after it is sent to landfill are likely to take place at some unknown time in the future, as described in Figure B4. So it is assumed that the mass specified in the inventory table is released into the environment in the form of a pulse. The product of flow and time period is equal to the mass.

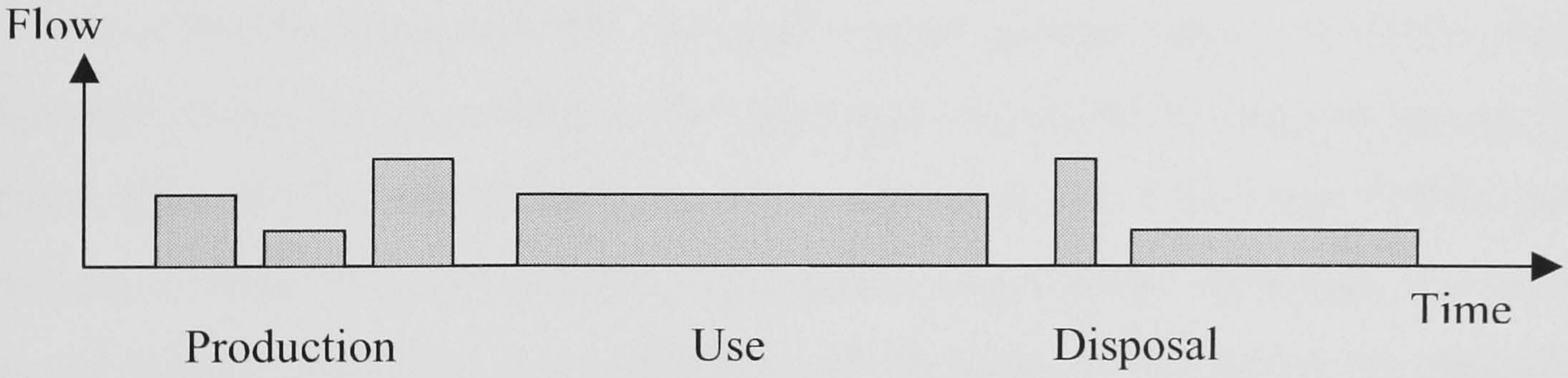

Figure B4: A literal representation of substances released into the environment.

All damage models link a steady state concentration to a steady state damage. Figure B5 shows that a mass loading is only responsible for a temporary change in concentration, it is also deemed to be responsible for the damage during a certain period of time.

Assuming that the concentration of the substance in the environment remains the same, by ignoring when it was emitted it is possible to say simply that a particular life cycle was responsible for the flow for a specific length of time. This is the pulse attributed to this product; the pulse is not the actual concentration of the substance in the environment, but rather it is the result of arranging all of the small pulses that a product creates over its whole life cycle. Because the model is linear the time and height of pulse are not important, what is important is the product of the height and duration, i.e. the mass.

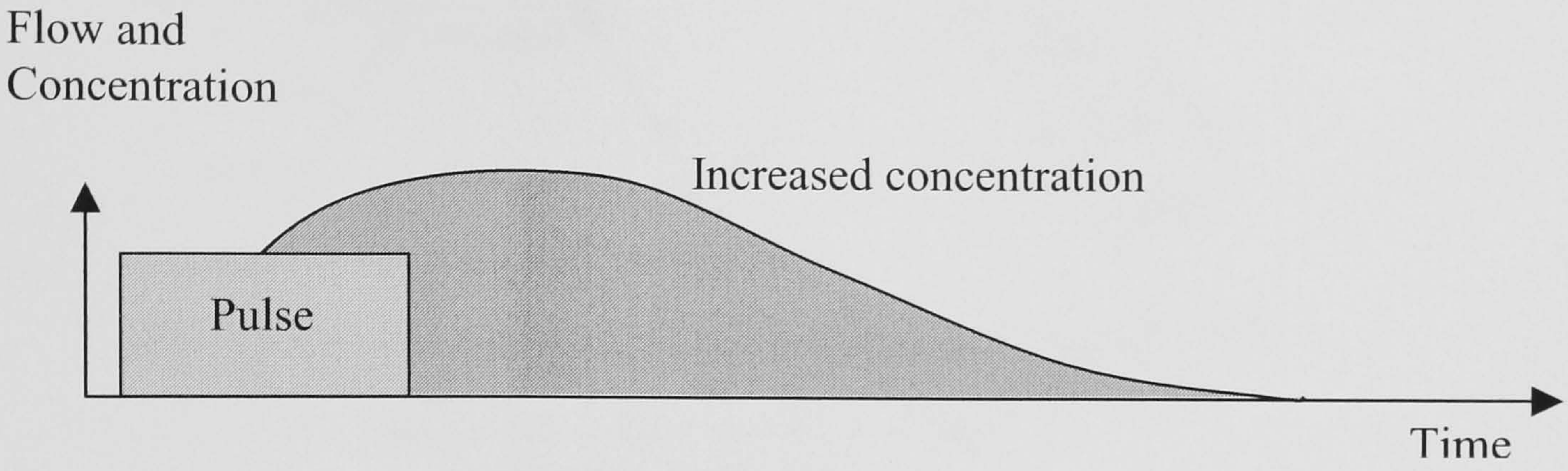

Figure B5: The figurative representation of a release of a substance in the environment.

Weighting Factors

In order to develop the weighting factors LCA interest groups were questioned about the value of the damage categories. Average weightings were taken from these value judgement responses. A second set of questions was asked in order to reduce the societal bias of the respondents based on the work of Thompson (1990) and Hofstetter (1998). This information was used to develop the weighting factors in response to three indicators of significant harm. By limiting the number of categories to be assessed, the eco-indicator 99 methodology is more reliable than the previous eco-indicator 95 methodology (Goedkoop, 2000). The result of the survey was that damage to human health and eco-system quality were viewed as similar, while damage to resources was considered approximately half as important. The contributory flows to an impact category are multiplied by the weighting factors to produce eco-indicator values measured in points (pt). Figure B6 shows the average weighting factors used in the Eco-indicator 99 method.

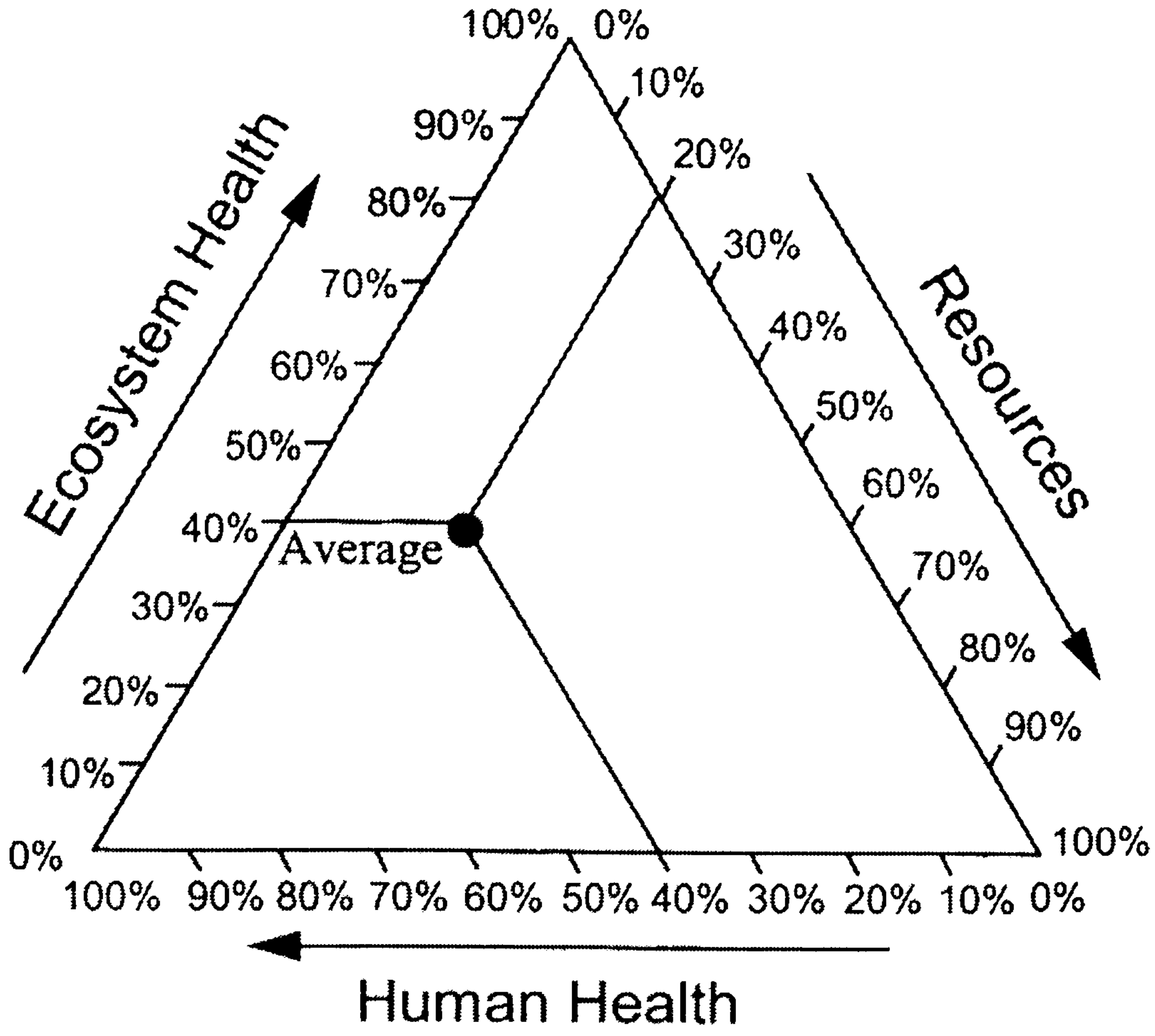

Figure B6: A representation of the weighting factors used in the Eco-indicator 99 method.

B2.4 SELECTION OF AN LCA MODELLING TOOL

There are several computer-based programs which can be employed when carrying out an LCA. These tools are a combination of a database of environmental information, from various sources, and a spreadsheet which calculates the total impact from the inventory supplied. It is then possible to select a method of inventory analysis and organise the data into impact categories.

Criteria for tool selection

The main criteria for choosing a suitable LCA assessment tool for this study were:

- Usability.
- System Requirements, i.e. operating system.
- Data Availability.
- Interoperability.
- Impact Assessment Methodology.
- Representation of Results.
- Sensitivity Analysis.
- Consistency of approach i.e. units.

Several LCA tools are paper based and not very useful for the analysis of complex systems. To carry out a sensitivity analysis would require a recalculation of all the initial data. The addition of the ability to input a graphical flow diagram of the system under study has added to the usability of LCA tools. Windows-based systems have the largest take up as those LCA tools which rely on UNIX or DOS systems are less popular. While the popularity of a tool is not necessarily an indication of the accuracy of the tool, it does indicate an advanced level of tool development, and wide applicability.

Environmental impact data is available from a wide selection of sources. It is important that a tool has the capability to export and import data from various sources. While it is not unexpected that the tool should require a particular type of formatting, data should not always need to be input manually. Some of the flows associated with existing projects can be rather cumbersome to input manually.

The representation of results in both a tabular and graphical form can help to reduce the time spent in data analysis. There are tools which require the transposition of all data to a second data analysis program and this would require access to the second program. The ability to carry out a sensitivity analysis as part of the pre-programmed procedure is a useful addition which would help to save time when carrying out an analysis. A study was carried out by Rice (1996) which used a set of criteria to evaluate the suitability of 12 LCA tools to implement various LCA tasks. Table B2 presents the result for the four most widely used LCA Tools.

Table B2: Comparison of various Life Cycle Analysis software.

Model	**Boustead**	**Team**	**Sima Pro 3.1**	**PEMS 3.0**
Developer	**Boustead**	**Ecobilan**	**PRé**	
Volume of data	V high	V high	High	high
UK appropriate data	Yes	Yes	Yes	Yes
Windows™ Based	Yes	Yes	Yes	Yes
Network Capability	n/s	No	No	Yes
Impact assessment		Yes	Yes	Yes
Graphical impact assessment		Yes	Yes	Yes
Graphical inventory analysis	Via Excel	Yes	Yes	Yes
Auto sensitivity analysis	No	Yes	No	Yes
On line help	No	Yes	Yes	Yes
Flow diagram capability	no	Yes	Yes	Yes
Restriction to input / output	n/s	No limit	No limit	24
Demo Version	No	Yes	Yes	Yes

Based on the criteria previously specified and the comparison of tools mentioned above the Team™ software (Ecobilan, 1997) was selected. The study carried out by the University of Surrey (Rice, 1996) cited Team™ as a package that was particularly capable of representing industrial processes with a high standard of UK appropriate input data.

Team™ Produced by Ecobilan

The Team software is aimed at an expert user, with both graphical and tabular input methods. A useful feature of this software is "encapsulation" which means that descriptions of a system or sub-system can be moved altered and reused in other LCAs. The software also allows both graphical and tabular representation of results, which can be externally exported for analysis using other suitable software. The software runs on the Windows™ operating system with a minimum of a 486 processor and a 16Mb memory. The software is supplied with an extensive database which covers the following:

- Plastics.
- Steel.
- Aluminium.
- Glass.
- Pulp and Paper.
- Energy.
- Transport.
- End of life.

This environmental analysis data is supplied in modules which can be used in any analysis carried out. The information is transparently available as is an indication of data quality and scope. The information contained in the software is from reputable sources and the data tends to be site-specific rather than industry-average data from trade associations. This leads to a higher data quality overall. The following chapter details the methodology employed in this study.

CHAPTER B3 METHODOLOGY

This chapter provides a detailed description of the assumptions and premises on which the life cycle analysis of Pilkington architectural float glass is based. The scope, functional unit, system boundaries and data quality restrictions are detailed.

B3.1 LCA SCOPE AND FUNCTIONAL UNIT

A full LCA would consider the float glass from the raw materials to the eventual end processes involved with the disposal of the float glass at the end of its life. Float glass is a particularly hard product to trace to the end of its life as it is used in a variety of building and other applications where the lifetime of the product is more dependent on the vaguaries of the construction industry than the design life of the glazing. The life time of any glazing system is limited by other components rather than the glass itself. As a consequence this chapter considers float glass from the batch materials to the factory gate where it is ready to be delivered to contractors, as shown in Figure B7.

The system being considered involves the following steps:

- The extraction of raw materials.
- The transportation of these materials to the plant.
- The construction of the plant.
- The processing of the raw materials.
- The energy consumed by the plant.
- The use of by-products from other processes and production of waste.
- The preparation of the glass for sale.

One of the differences between LCA and other methods of environmental assessment is the requirement for a clear functional unit, i.e. a unit of measure that relates to the product function rather than per quantity in weight or other physical measure. In this case it would be the ability of the glass to provide a view and light into a space. This means that the glass must be measured in area (m^2) rather than weight. This study is based on information gained from the running of the UK6 Greengate float glass

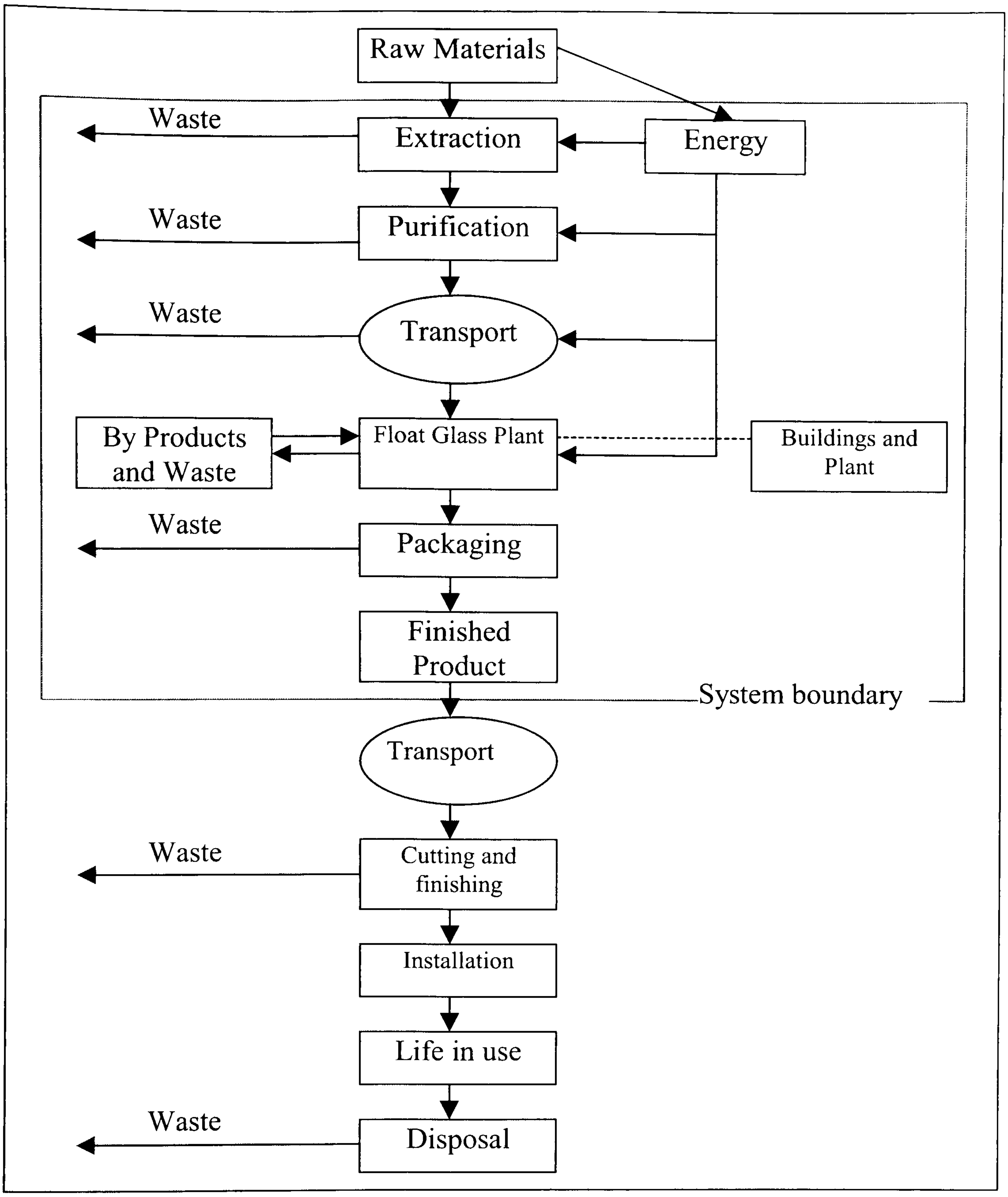

Figure B7: Diagram of the boundaries of the Architectural glass LCA.

plant, which is based in the north of England. This plant was chosen because float glass is the only product that is made on this production line. There are several thickness of glass ranging from 4mm to 20mm produced at the plant according to the requirements of clients. The operating parameters and resource consumption vary slightly with the thickness of glass produced and these changes affect the operating efficiency of the plant. The base product of a float glass plant is 4mm float glass: this thickness is determined by the size of the furnace and tin bath and the viscosity of the melt. Changing the thickness of the glass affects the following process parameters:

- Quantity of raw material per m^2.
- Processing time.
- Volume of glass per metre.
- Energy input to the Lehr.

These differences in production make it difficult to assess the environmental impact of a particular product, e.g.. 12mm float glass, so this chapter considers the general behaviour of the plant as a whole. It has been estimated that differences in thickness contribute an error of approximately 3 – 4% to the values used for this study. This chapter assumes an average production level of 164,000 tonnes per annum. The amount of glass produced (by the square metre) per annum varies according to the orders placed in any given year and the degree of stoppage for cleaning, maintenance or change of products on the production line.

B3.2 INVENTORY COLLECTION

The inventory is a list of the inputs and outputs to the system under investigation. Each inventory represents some simplification of the real system. It is important when assessing the results to understand the assumptions that have been made and the way that calculations have been carried out. The quantities of material used are based on information from the manufacturer and the inventory data about the materials used are presented in Table B3. The following sections explain the assumptions made while collecting the data for the inventory.

Table B3: Data Sources for inventory data.

SOURCE	DATA	DATE
ETH Zurich	Transport	1998
ETH Zurich	Energy	1998
ETH Zurich	Metals	1996
BUWAL 250	Raw Materials	1996
Various	Miscellaneous inc. P.E.	

Raw Materials

The batch materials described in the Raw materials sub system are included as a result of information received from the manufacturer. The weight of batch material per m^2 of saleable glass X, is based on the following calculation:

$$\frac{W_m}{W_{sg}}(\rho v) = X \tag{B-2}$$

where W_m is the weight of materials per annum, W_{sg} is the weight of saleable glass per annum, ρ is the density of glass and v is the volume of glass per square metre. The density of glass is assumed to be 2.4 Mg/m^3 (Ashby, 1997).

The distance that the raw materials are assumed to have travelled is based on deposit sites in the areas outlined by the manufacturer. All the measures of transport were calculated using an average km.kg value which describes how far each kilogram of material has travelled to get to its final destination. This method was used because assumptions made about the type of vehicle used to transport materials and the percentages of load per journey are not very accurate. Where the raw materials have travelled within the UK it has been assumed that they have been transported by road. Where materials were transported by sea it was assumed that the journey to a UK port was made by sea with the remainder of the journey by road.

Table B4: Origin of materials used in architectural glass production.

MATERIAL	PLACE OF ORIGIN	PROPORTION OF MATERIAL	DISTANCE/ km
Sand	Chelford Cheshire	100%	55
Dolomite	Warmsworth Yorkshire	66%	150
Dolomite	Euigi Spain	33%	1445
Limestone	Buxton Derbyshire	100%	105
Soda Ash	Cheshire	100%	43

Building

This considers the factory building where the manufacturing process takes place. A typical building lifetime can be assessed in many different ways:

Functional service life:	10 – 20 years.
Technical Service life:	60 – 75 years.
Economic service life:	30 – 35 years.

The true life of a building is a combination of these considerations (Llewellyn, 1998). The functional life of a material is the length of the guarantees that are given for the building components, whereas the technical life is the life that the building might achieve with refurbishment. The actual economic service life of a building is the lifetime which it is likely to achieve and be in economic use and this is often at a mid point between the functional and technical service life. The materials that have been used in the construction of the float plant are considered in the light of this. Where it was possible to replace an item such as electric wiring the functional service life has been considered over the limiting factor. Where it is not possible to replace an item without replacing the building as a whole this has become the limiting factor of the building life. In some cases this would mean that other building components would not have needed to be replaced at this time, but this is accepted. Thus the lifetime of the building is limited by the economic service life of the steel framework and the structural concrete.

The energy inputs into the float glass plant have not been treated separately from the process energy. The heating requirement for a float glass plant is negligible due to the large amount of heat given off during the production of the glass melt. Pilkington are unable to determine the proportion of electrical energy which is consumed by the process and that which is used to fulfil the factory's lighting requirements. However, the artificial lighting requirement in the factor will be low due to the large window area and low number of staff working in the plant.

Process

All energy use and emissions from the float glass process, including those made which actually occur at other parts of the process, were added in this sub system. This is to enable process inputs to be easily altered. The process covers those activities that take place from the batch mixing to the cutting of the glass sheets. The process inputs were calculated from the annual values provided by the manufacturer using equation B-2.

Preparation

The materials in the preparation sub system dealt with the additions made to the glass once it has been cut from the float line in order that it might be made saleable. The major addition at this stage was Lucite dusted on the surface of the glass to stop it from sticking to other materials. The quantities of Lucite used were calculated using equation B-2.

Data Quality

Data quality is cited as one of the major criteria which affects the quality and usefulness of LCA results (Ayres 1995, Krozer 1998, Finnveden 1998). There are several factors which can be used to define the quality of the data:

- Time.
- Geography.
- Type e.g. technology and representativeness.
- Allocation.
- System boundaries.

In this study data which was not more than five years old were used and data specific to western Europe or the UK was selected. This was to ensure that modern representative data were used, although this could not guarantee that there had not been process improvements since the collection of the data, however, the likelihood of this was limited. Single supply data were avoided and data which was representative of a particular technique were chosen instead, this was to avoid the impact of one poor sample being taken and this skewing the LCA results. Using average data has its drawback, but this must be taken into consideration when reviewing the results of this work. There are a limited amount of data available which discuss the exact allocation methods and system boundaries of LCA data from commercial sources, however, where these data were available the boundaries which most closely matched those of this survey were selected.

B3.3 IMPACT ASSESSMENT

In this LCA the embodied energy of the material is of particular interest. Calculating the embodied energy of construction materials is a method of accounting for the energy input into the materials in order to transform them into a useable state. It can be defined as the energy used to produce and transport and install building products. Using the data collected from the LCA inventory it is possible to calculate the embodied energy (ee) of this system and hence this material. The embodied energy calculation has been carried out according to the principles laid out in the British

Standard 14040:1997. The delivered energy values provided by Pilkington have been converted into primary energy consumed; this is used together with estimated values for the transport factors. The embodied energy values are also calculated in CO_2 levels per tonne using the fuel mix present in the process.

The analysis and interpretation stage of the LCA carried out is discussed in the next chapter.

CHAPTER B4 RESULTS AND DISCUSSION

A full inventory analysis was carried out and the resulting 356 flows, both outputs and inputs, associated with the system under study are available in Appendix B1. The individual flows associated with the float glass process are useful for calibrating the system and investigating any opportunities for improvements. However, it is difficult to evaluate the results in this format, hence, the flows were used to produce two types of results, the embodied energy of the system and the eco-points rating. These two analysis methods allow the raw data to be compared with other systems and express the results from the LCA in more familiar units.

B4.1 EMBODIED ENERGY

The embodied energy of Pilkington float glass has been calculated from the inventory input data. The embodied energy of flat glass calculated by the BRE can be used for comparison, shown in Table B5. The calculated figure for Pilkington Float glass is 13.4 ± 0.5 GJ/tonne, slightly above the BRE average value of 13 GJ/tonne. The embodied energy of other common building materials are also shown in order to provide a comparison with glass.

The BRE have based their embodied energy figures on data collected from an industrial survey. There were a wide range of responses, the industrial organisations that responded to the BRE estimated that the embodied energy of their float glass was between 10 and 30 GJ/t. The widely differing estimations of embodied energy are dependent on the system boundaries imposed and the distances raw materials have travelled which affects the embodied energy values. The BRE data includes the process and the transport of the raw materials to the factory site, but does not consider contributions from the construction of the factory buildings. The BRE used the mean value of 13 GJ/t to calculate a value for the associated carbon dioxide emissions.

There could be several explanations for the small difference between the embodied energy associated with the Pilkington process and the BRE average for flat glass. The use of the name "flat glass" would suggest that not all of the processes included in the survey were float glasses; for example rolled glasses, such as types of safety glass may have been included. The removal of the energy requirement for the float bath process may reduce the embodied energy of the systems under investigation. The use of different minerals in the process, such as anthracite, or the use of the same minerals in different proportions would affect the total embodied energy that is consumed by the glass manufacturing process.

Table B5: Embodied Energy of Glass.

Material	Indicative (ee)		Associated CO_2 emissions	
	GJ/t	MJ/m^2	Kg/t	Kg/m^2
Pilkington float Glass	13.4	128.47	1059	10.2
(Process only)	10	96	722	6.4
BRE flat glass values[a] (average)	13	125	1100	10.6
(range)	10 - 30	96 - 288		
ETFE (three layer cushion)[b]	26.5	27		
Steel (steel sections)[a]	24 - 59	-	1434 - 3522	-
Aluminium (virgin)[c]	191	-		
(recycled)	8 - 27	-		
Cement[a]	4.3 – 7.8	-	257 - 465	-

Source: (a) Atkinson 1996, (b)Bishop 1997, (c) Baird 1983.

In Table B5 the embodied energy of some construction materials have been included for reference. ETFE is another façade material used mainly in roofing as an alternative to glass, as discussed in Part A of the portfolio. As a bulk material it has a similar embodied energy to glass, however it is used in smaller quantities hence it has a much reduced embodied energy per square meter. The embodied energy of steel is similar to the embodied energy of glass, because the steel manufacturing and glass manufacturing processes are similar. The production of steel and glass manufacture both requires large amounts of fuel to melt the raw materials and create the resulting new microstructure.

Cement production requires extraction, refinement of the raw materials. The raw materials are then heated in a kiln to form clinker which is combined with gypsum to form cement. Aluminium is produced by smelting alumina in an electrolytic process. Although pure aluminium has a melting temperature of 660.32°C, a large amount of electrical energy is required to separate the aluminium from its oxide, hence, the embodied energy of aluminium is nearly tenfold that of steel and glass. However, the embodied energy of recycled aluminium is considerably lower, and bring aluminium in line with steel and glass. In the construction of a façade the relative thickness of framing material or cladding is dependent on the design and can vary widely so embodied energy per m^2 has not been calculated.

Table B6 shows the contribution of each subsystem to the total embodied energy of the float glass process. In each subsystem the significant contributory flows (i.e. all flows that contribute more than 0.05 %) have been included so that both the small and large contributors to the embodied energy total are easily visible. Figure B5 shows that the three major contributors; natural gas, soda ash and electricity.

Table B6: Embodied Energy by subsystem of the float glass process.

Subsystem	Embodied Energy MJ/ tonne	Embodied Energy MJ/ m^2	Contribution to Total %
Building	**47.1**	**0.5**	**0.4**
HDPE	20.6	0.2	0.2
Copper	1.3	<0.01	<0.1
Concrete	4.9	<0.01	<0.1
Steel	20.4	0.2	0.2
Process	10008.8	**96.04**	**74.8**
Hydrogen	7.5	0.07	<0.1
Tin	0.03	<0.01	<0.1
Electricity	944.3	9.0	7.1
Heavy Fuel	146.5	1.4	1.1
Natural Gas	8906.4	85.5	66.5
Raw	**3119.7**	**29.9**	**23.3**
Limestone	134.1	1.3	1
Dolomite	183.1	1.8	1.4
Sand	194.3	1.9	1.5
Salt Cake	72.4	0.7	0.5
Soda Ash	2528.8	24.26	18.9
Transport	**207**	**1.9**	**1.5**
Road	207	1.9	1.5
Total	13386.57	128.47	-

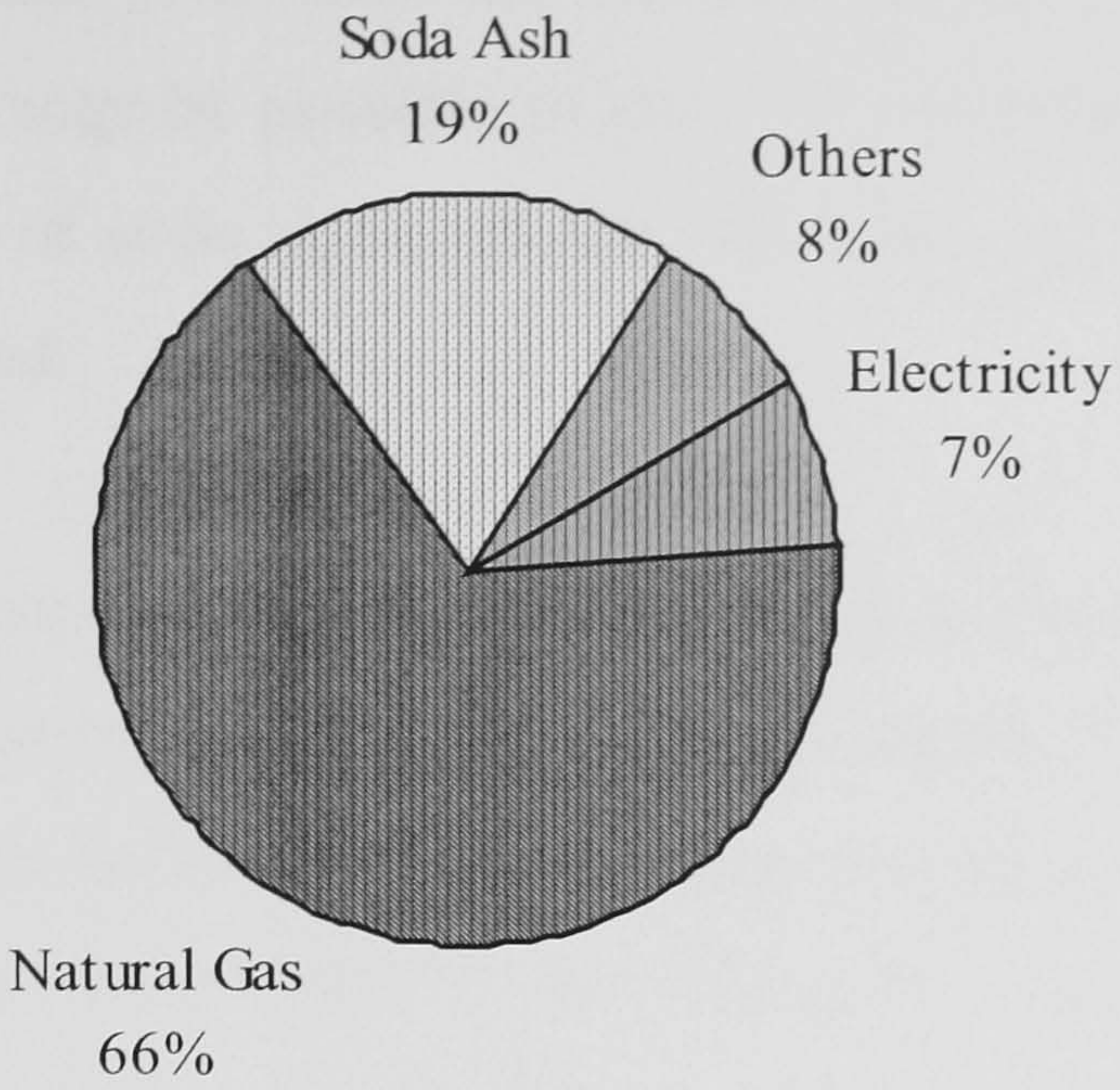

Figure B8 The contributory flows to the embodied energy of glass.

In the building subsystem, High Density Polyethylene (HDPE) and Steel both make a visible contribution of 0.2% to the total embodied energy of float glass. This shows that the longevity of the structure which houses the float glass plant can have a small contributory effect to the total embodied energy of the glass produced.

The process subsystem is by far the largest contributor to the total embodied energy of the system, 74.8% of the embodied energy associated with this part of the process. The laws of physics govern the minimum quantity of natural gas that can be used in the furnace. However, through improving the thermal efficiency of the plant it must be possible to reduce the energy used until it become closer to the theoretical amount of energy required. .

The electricity consumed by the float glass process includes both the energy sometimes used to augment the furnace and that consumed by the other automated processes in the plant. There may be opportunities to reduce the amount of electricity used in the plant.

The mining, extraction and preparation of raw materials for the glass manufacturing process contributes 23.3% of the total, but this is heavily dominated by the amount of energy required to produce soda ash (Figure B5). Soda ash is manufactured from salt, ammonia, CO_2 and lime using electrolysis and as with other electrical manufacturing processes this has an inherent inefficiency, and requires large amounts of energy. It may be possible to alter the composition of the melt mixture, to reduce the amount of soda ash used and still retain the high quality of the float glass which is produced.

The transport subsystem includes the transport of all raw materials to the factory site, this accounts for approximately 1.5% of the embodied energy in the system. Materials sourced from within the UK were transported to the factory by road and materials sourced from outside the UK are transported to the nearest port and then transported by road. Any increased efficiency that can be made will help to reduce this impact on the environment. While transport contributes little to the impact per tonne of glass manufactured, transport of raw materials to the site results in the emission of 56,000 kg of CO_2 to the environment every week. Any opportunity to reduce distances travelled by the raw materials to the Pilkington site or the method of transport should be taken.

B4.2 Eco-Points

The contributory flows in the Pilkington float glass system resulted in 243 ±11 eco-points per tonne and 2.4 eco-points per m^2 of glass, (one eco-point is equivalent to a thousandth of the annual environmental load of the average European inhabitant). Table B7 shows the total eco-points in each indicator category. This shows the places where the float glass process had the largest impacts.

Table B7: Distribution of eco-points across damage indicators.

Indicator	**Impact Damage**	**Normalised**	**Weighted (millipoints)**	**% of Weighted millipoints**
Damage to Eco-systems	**PDF*m^2 *yr**	**5.13E+03**	**400**	
Acidification and Eutrophication damage	6.20E+01	1.21E-02	4.83E+00	1.8%
Eco-toxic emissions damage	9.64E+00	1.88E-03	7.52E-01	0.2%
Land occupation damage	2.00E-01	3.92E-05	1.56E-02	-
Damage to Human Health	**DALYs**	**1.54E-05**	**400**	
Carcinogenic effects damage	2.92E-05	1.90E-03	7.59E-01	0.3%
Climate Change damage	2.97E-03	1.93E-01	7.73E+01	28.6%
Ionising Radiation damage	5.29E-08	3.44E-06	1.38E-03	-
Ozone depletion Effects	1.07E-07	6.96E-06	2.79E-03	-
Respiratory Effects	5.87E-03	3.81E-01	1.52E+02	56.5%
Damage to Resource Levels	**MJ**	**8.41E+03**	**200**	
Fossil Fuels extraction damage	1.41E+03	1.68E-01	3.36E+01	12.5%
Mineral extraction damage	8.06E-01	9.58E-05	1.92E-02	-
Total	**1487.22**	**7.58E-01**	**243493.6**	

Table B8 shows a breakdown of the four largest indicators into the contributions from subsystems. All flows that contribute more than 0.1% have been included.

Acidif and Eutrop Damage	**By %**	**Climate Change Damage**	**By %**	**Respiratory effects**	**By %**	**Fossil Fuels Extraction Damage**	**By%**	**Total eco-points millipoint**
6.5	0.1%	303	0.4%	-	-	9.31	0.3%	744
2.4	-	6.6	-			5.63	0.2%	517
0.3	-	132.0	0.2%	-	-	-		-
2.0	-	118.0	0.1%	-	-	-	0.1%	153
-	-	-	-	-	-	-	-	-
3740.0	78.7%	48600	62.9%	25900	17.0%	2615.4	77.7%	78436.2
1.1	<0.1%	32.1	-	12.7	-	0.7	-	45.9
57.6	1.2%	3920.0	5.1%	537	0.3%	116.7	3.5%	4569
22.4	0.5%	776.0	1.0%	289	0.2%	52.1	1.5%	1210
222.0	4.7%	38300.0	49.6%	1310	0.9%	2448.7	72.8%	39933
3440.0	72.3%	5520.0	7.1%	23100	15.5%	-	-	27160
995.6	20.9%	30797.6	35.2%	125722	82.5%	803.17	23.9%	154733.7
19.7	0.4%	695.0	0.9%	13600	8.9%	46.5	1.4%	14406
4.3	0.1%	904.0	1.2%	1570	1.0%	59.2	1.8%	2484
2.8	0.1%	810.0	1.0%	37000	24.3%	51.8	1.5%	37766
945.0	19.8%	24400.0	31.6%	73200	48.0%	622.1	18.5%	99474
23.8	**0.5%**	**404.0**	**5.0%**	**35.2**	**0.2%**	**23.5**	**0.7%**	**822.6**
13.2	0.3%	1202.4	1.6%	514	0.3%	75.23	2.2%	1957
4.8	**0.1%**	**42.4**	**0.1%**	**40**		**-**	**-**	**94.8**
3.4	**0.2%**	**1160.0**	**1.5%**	**474**	**0.3%**	**75.23**	**2.2%**	**1862.7**
4760	-	80900	-	158710	-	3364	-	243493.6

in the Pilkington Float Glass system.

The impact damage indicators are normalised in order to reduce all of the values to a figure without a unit. This figure is then weighted to give the scores in eco-points. The figures used to weight the normalised values convert the indicators into millieco-points (mpts). This was done because several products and services have values so small that they are not significant when valued in eco-points (pts). In this case it is useful because it is possible to see that the smaller flows do make some contribution, however insignificant, to all of the impact categories. However, Table B7 shows that approximately 56% of the eco-points in the Pilkington Float Glass process are associated with respiratory effects. Climate change damage contributes approximately 29%, mineral extraction damage contributes 12%, acidification and eutrophication damage contributes a small amount (2.1%), with less than 0.5% contribution in the spread over the other impact categories.

Closer inspection of the origin of the two largest contributory flows to the total eco-points indicators is required, and is shown in Table B8. The acidification and eutrophication, climate change damage and respiratory effects indices are allocated to the subsystems where they originate and the significant contributory flows are identified. The contribution of the sub-system to the total eco-points assessment is included for comparison.

Arranging the eco-points attributed to the Pilkington float glass process by sub-system (Figure B9) shows that the preparation and transport subsystems make a very small contribution to the eco-point indicators. The building subsystem has a small contributory effect on the total eco-points providing only 0.3% of the damage due to climate change and 0.3% of the total eco-points. This is mainly due to the energy used to produce the copper wire, concrete and steel, with small contributions from the other building materials. The energy requirement is so small that it has no significant impact (0.1%) on the acidification and eutrophication index which is also linked to energy use.

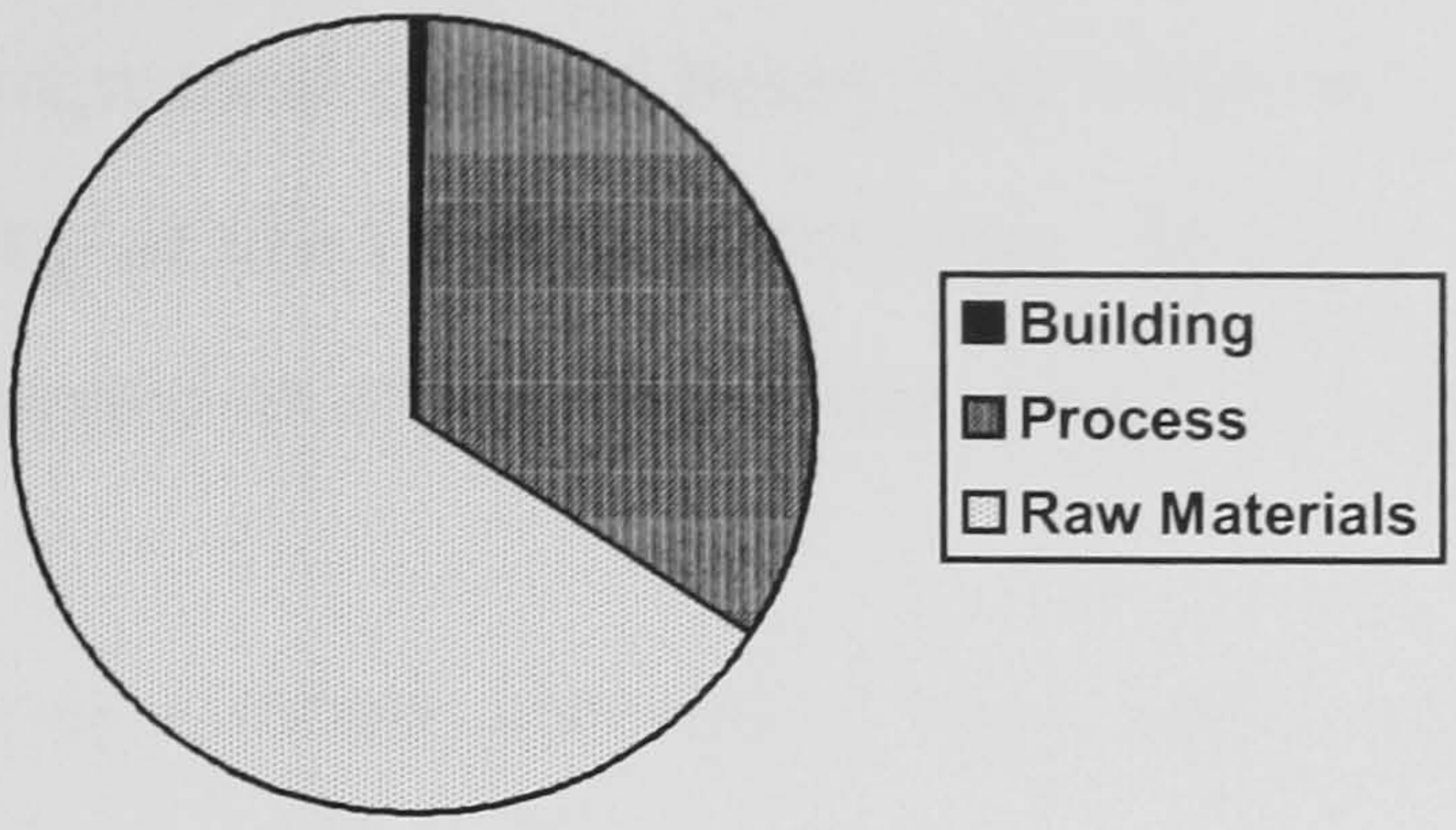

Figure B9: Eco-points by subsystem.

The process and raw materials subsystems have a large impact on all of the eco-point indicators (Figure B6). The value of the acidification and eutrophication index is directly related to the amount of NOx and SOx emitted in the manufacturing process. Climate change damage is as a result of greenhouse gases. Particulates and the emission of heavy metals into the atmosphere are largely responsible for respiratory effects, while NOx and SOx do play a small part. In order to examine the origin of the contributory flows to the eco-points indicators, it is best to examine each indicator separately as follows:

Acidification and Eutrophication index

The acidification and eutrophication index monitors the flows of ammonia, NOx and SOx into the environment. The release of the latter two chemicals causes acid rain and an increase in the amount of nitrogen in the aquatic environment. The emission of NOx and SOx is directly related to the combustion of fossil fuels and flows that contribute are represented in Figure B10.

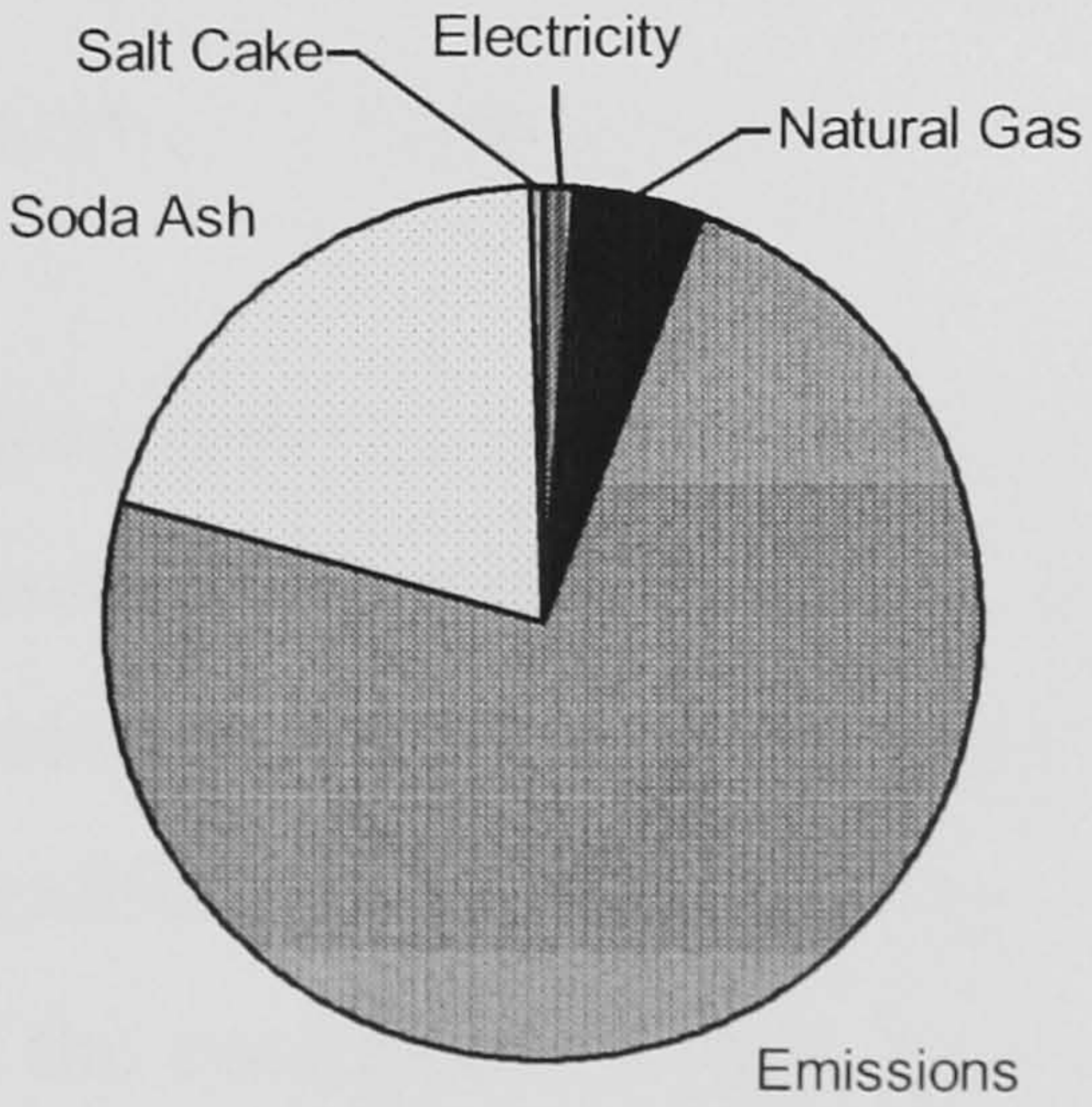

Figure B10 Acidification and Eutrophication

Emissions from the furnace are responsible for 72% of this index. This is caused in part by the combustion of natural gas and heavy fuel oil in the furnace to produce the conditions for the melting of the feedstock minerals. It is also due to the release of sulphates and nitrates trapped as impurities in the feedstock minerals.

Soda ash contributes a significant amount to this index. This is due to its high embodied energy. Similarly salt cake provides a large amount to this index considering the small quantity of salt cake in the melt. This is because both soda ash and salt cake are produced using electricity. Electricity production is the largest source of NOx and SOx in the UK. The production of natural gas contributes a small amount to this index because energy is consumed in the mining and transport of natural gas. There is also energy embodied in the production of electricity, hence the small contribution of electricity to the acidification and eutrophication index.

Climate Change Damage Index

The climate change index monitors greenhouse gases, carbon dioxide, halons, methane and nitrous oxide. This index is directly related to energy use and the combustion of carbon-based fuels and flows that contribute are represented in Figure B11.

The combustion of natural gas is the largest contributor to this index, due to the carbon dioxide emitted as the gas is burnt in the furnace. It would be difficult, as has previously been mentioned, to reduce the amount of CO_2 associated with the combustion of natural gas in the furnace. Indeed the combustion of natural gas is more efficient than some fossil fuels; coal for example. The contribution from the heavy fuel oil, although smaller is similar in nature.

Sand, salt cake and limestone both contribute a little to the index, this is due to the small amount of energy used in the mining, refining and preparation of the natural mineral resources into useable feedstock. The amount of energy used is so small that it had no impact on the acidification and eutrophication index, where the emissions from the furnace dwarfed the contributions from the use of electrical energy. This was exacerbated by the fact that ratio of carbon dioxide to NOx and SOx emitted during the production of electricity is 140:1.

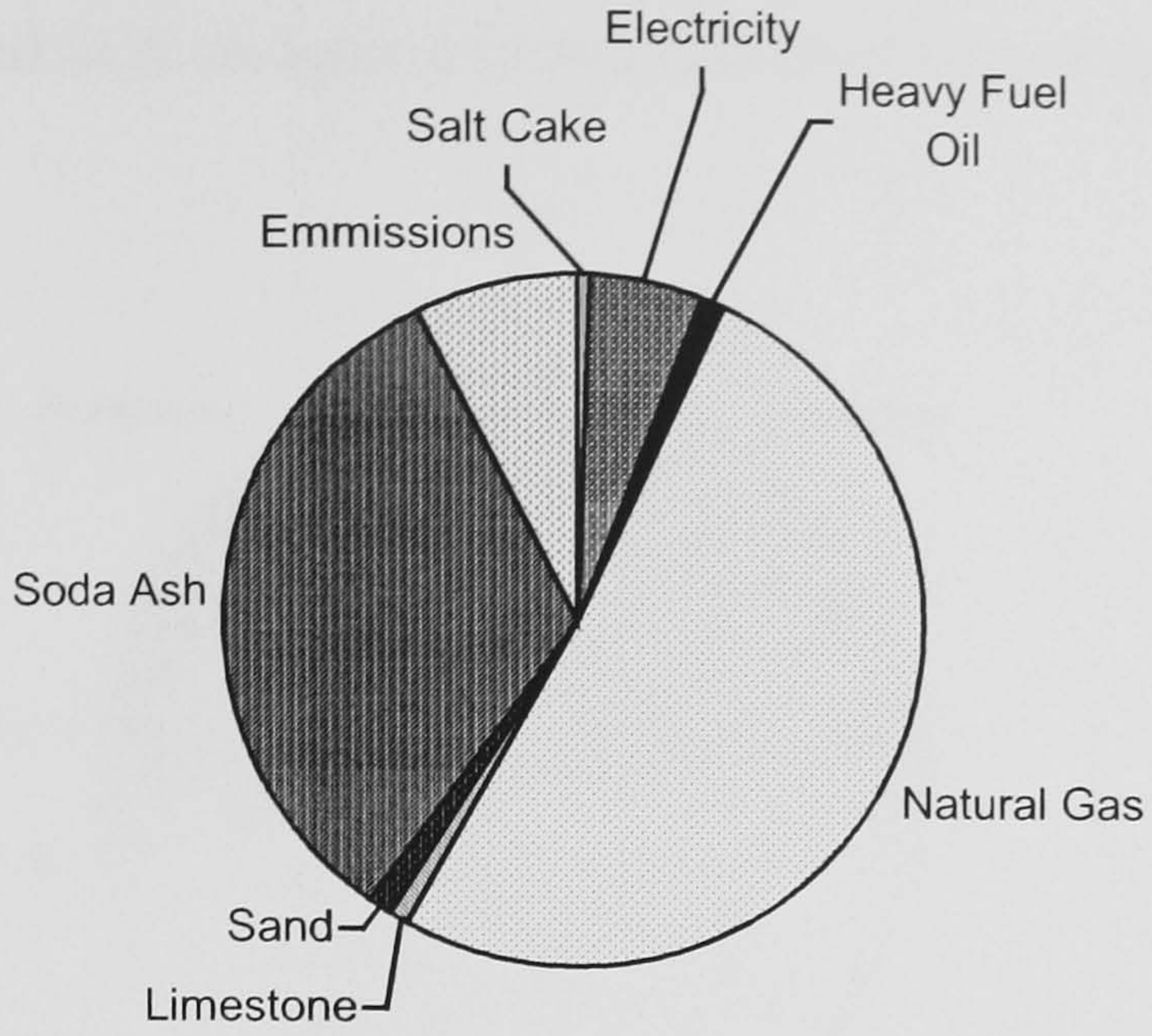

Figure B11 Climate Change Index.

Soda ash contributes a large amount, more than 30%, to this index because as has previously been mentioned a large amount of electrical energy is used in its production. They are therefore the areas to promote in efforts to reduce this environmental impact from this process.

Respiratory Effects Index.

The respiratory effects indicator measures the amount of volatile organic compounds, NOx and SOx and particulates that are released into the atmosphere.

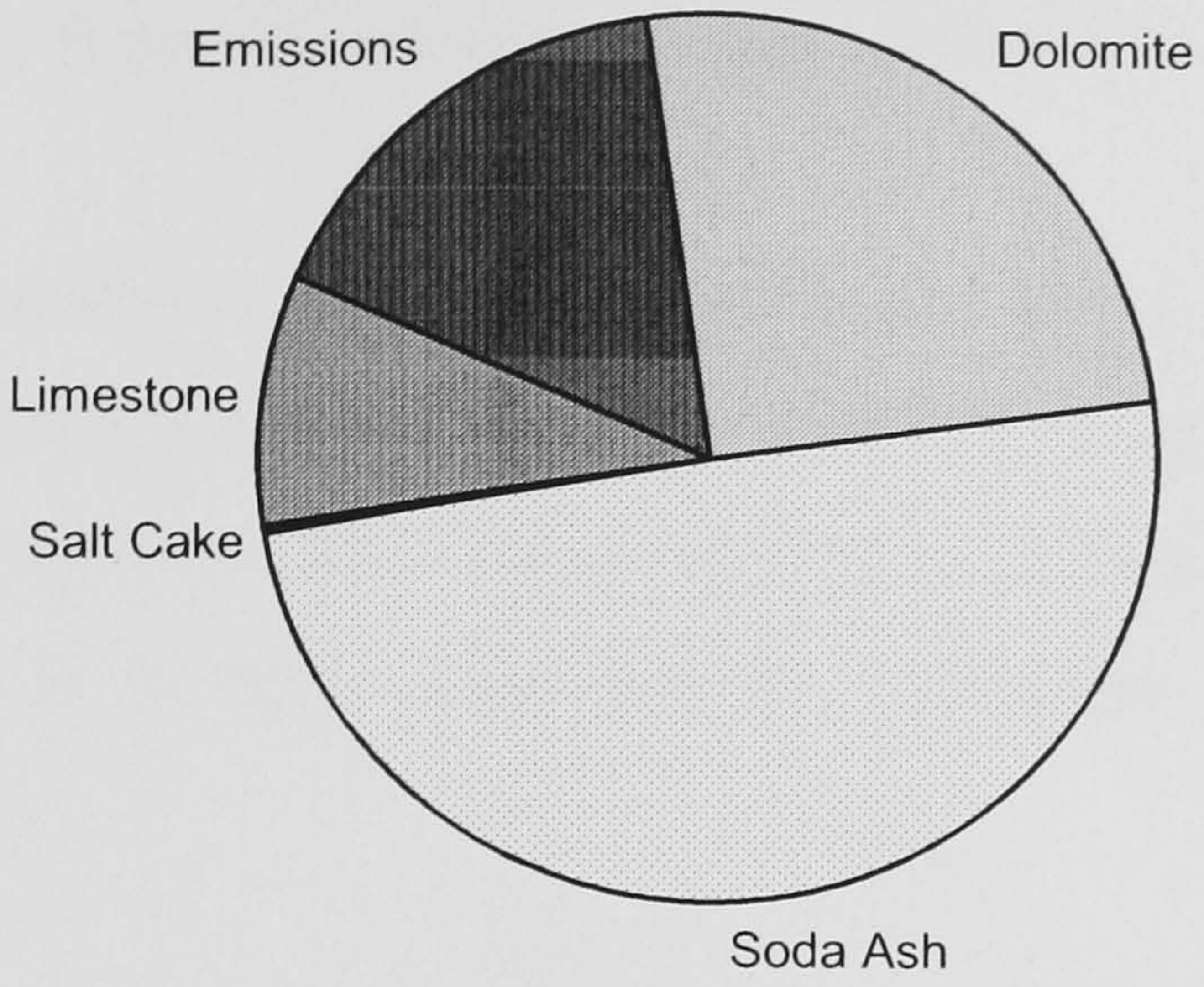

Figure B12 Respiratory Effect Index.

The emission of these pollutants has been cited as one of the causes of respiratory diseases. The major flows are represented in Figure B12. Soda ash constitutes 48% of this index, a small part of this is due to the emissions associated with the electrical energy required for soda ash production. However, the large contribution of soda ash is due to two other flows in its manufacturing process, the particulates released and the escape of ammonia which occurs during soda ash production.

Dolomite makes the second largest contribution to this index, this is largely due, to the particulates which are emitted from Dolomite. The part of the index contributed by limestone is also due to the particulates that emanate from the mineral, during processing.

Emissions from the furnace are responsible for 15.2% of the contribution to the index. The large contribution of the emissions to the acidification and eutrophication index shows the relative quantity of NOx and SOx emitted in this part of the process. However, these emissions, although included, are not a very important part of this index, which is reflected in the small contribution that the emissions make to this index.

Fossil Fuels Extraction Damage

The fossil fuel extraction damage index takes into account the damage to the environment from the reduction and extraction of fossil fuels. This index measures the amount of coal, natural gas and oil. The contributory flows are shown in Figure B13. The index gives a larger weight to oil and natural gas and this can be seen when the contributory flows represented diagrammatically.

Natural gas contributes 70% of this index, as the index weighs the environmental impact of natural gas at 6 times that of coal it is unsurprising that natural gas makes the largest contribution. Heavy fuel oil is directly shown in this index, but the small use of fuel oil in the float glass process translates to a small percentage in this index.

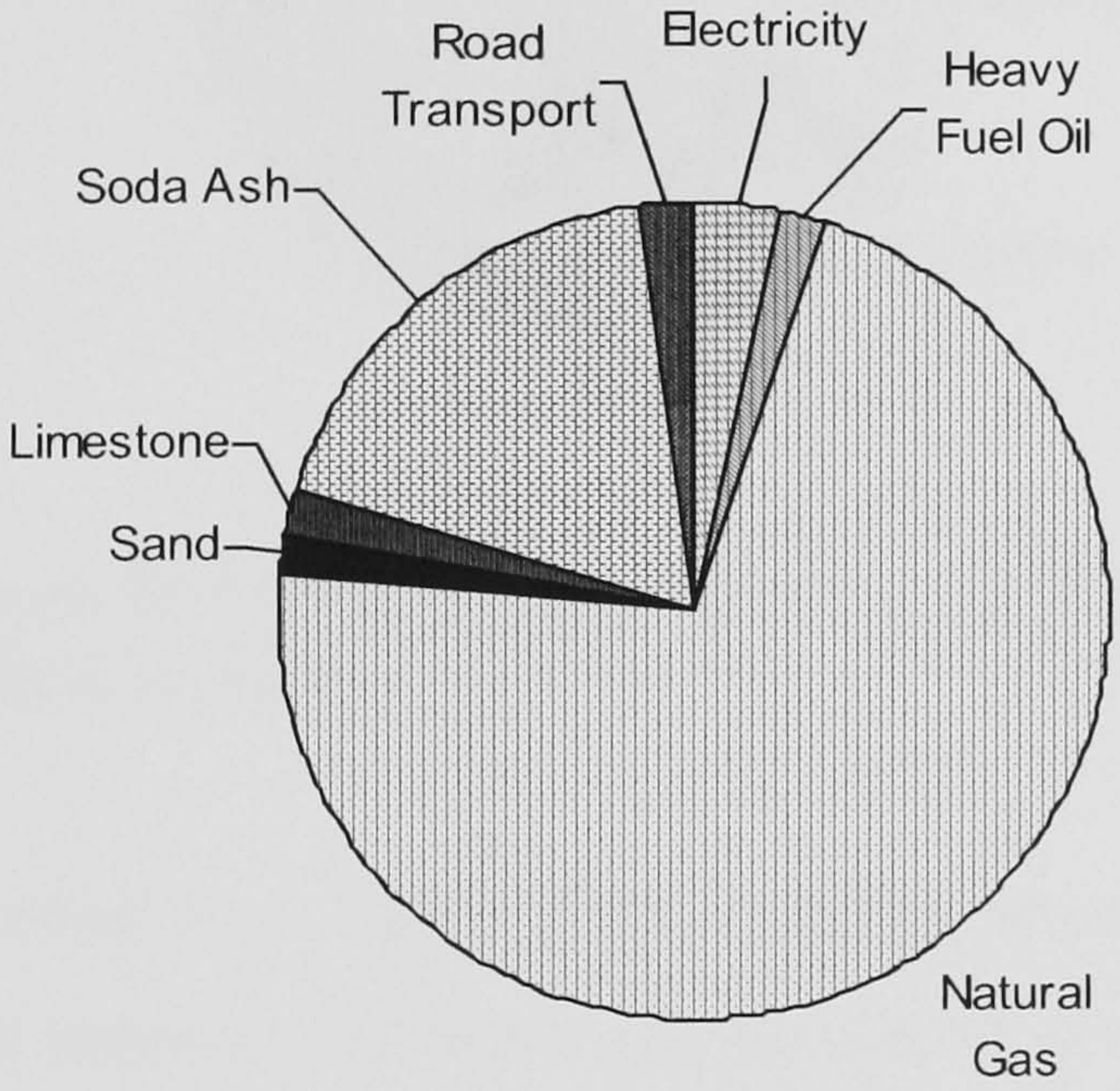

Figure B13 Fossil Fuel Extraction

The production of soda ash uses a large amount of electricity and the electricity is produced using a combination of oil, coal and gas, hence the large contribution shown. The remaining contributory flows are limestone, sand and road transport, contributing 1.3%, 1.7% and 2% respectively. A small amount of energy is consumed in the extraction of both sand and limestone, but sand and limestone become significant flows due to the quantity of these raw materials used in the production of float glass. Road transport uses a derivative of oil, hence its appearance on this index.

Summary Of The Eco-Points Assessment

In summary, if the contribution of all the flows (greater than 1%) to the eco-points for Pilkington float glass are reviewed (Figure B14) it becomes obvious that soda ash, natural gas, dolomite and emissions make the largest contribution to the eco-points. Electricity and limestone make a significant contribution to the total, but less than 10% each.

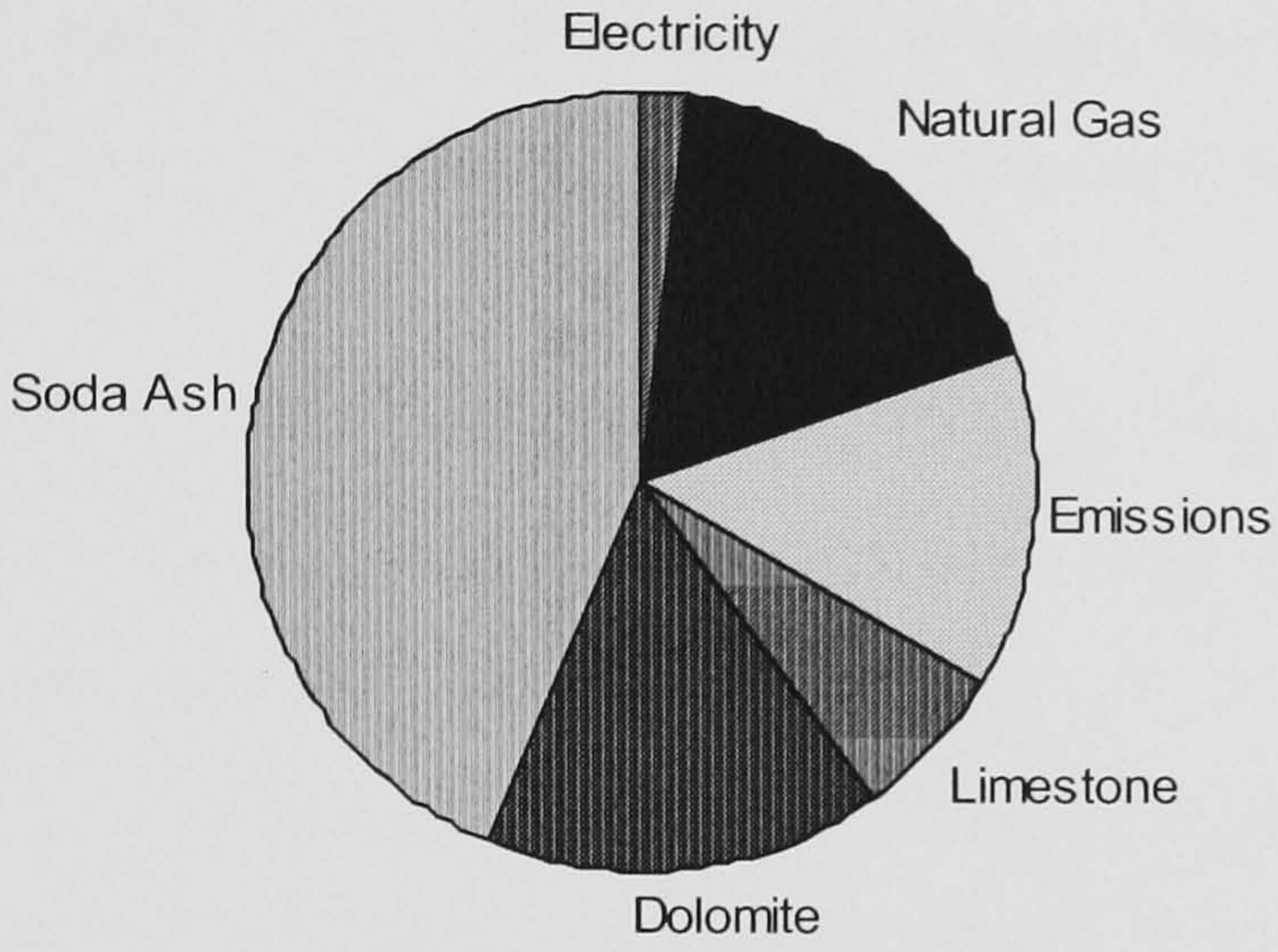

Figure B14 Contributory flows to the Eco-indicator points.

The emissions exist as a result of the combustion of gas in the furnace. Hence a reduction of the amount of natural gas and heavy fuel oil used in the furnace could reduce the contribution of both the natural gas and the emissions. The temperatures required in the furnace are due to the make up of the feedstock. If the amount of gas used was decreased and the melt temperature remained the same this would lead to an increase in the use of electricity and it is likely that the overall environmental impact of the float glass process would increase rather than decrease.

Dolomite and limestone are used as part of the raw materials for the production of glass. Their inclusion gives glass the required properties. Any alteration of the proportions of raw materials in the melt should take account of the environmental impact of salt cake, limestone and dolomite, and particularly the respiratory effects associated with the use of dolomite.

Soda ash is responsible for the largest single contribution (40%) to the total environmental damage. Hence, eliminating soda ash from the process, or using a less environmentally-harmful production method could reduce the total eco-points attributed to this system to 144 eco-points per tonne. Discussion of the results with Pilkington Glass revealed that the soda ash from the UK could be replaced in the process by natural soda ash mined as a by product of other mineral production. The mined soda ash would reduce the environmental impact associated with energy production, i.e. both climate change and acidfication and eutrophication, but it would have an impact on the Mineral Extraction Damage index. A further assessment of the environmental implication of this change is being discussed with Pilkington Glass and this should lead to a further research into this area in near future.

Several methods for reducing the environmental impact of Pilkington float glass have been mentioned including: altering the proportions of the raw materials, particularly soda ash and dolomite. It should be mentioned that increasing the amount of cullet in the feedstock would reduce the environmental impact of glass manufacture. This would reduce the temperatures required in the furnace, and hence reduce the amount of natural gas, heavy fuel oil and electricity consumed by the process, thus reducing the emissions of NOx and SOx and CO_2. However, this has not been implemented because there is a shortage of cullet in the UK. The unique constituents of float glass and the high standards applied to the finished product make it difficult to use waste glass from other products, i.e. glass bottles. The shortage of cullet could be solved by finding a way to effectively recycle float glass.

Comparison of glass with other materials

Comparing the eco-points of the Pilkington float glass with the production of other raw materials can be useful for bench marking. Little data is available to cover alternative glazing components or other transparent roofing and window materials. However, materials widely used in the construction industry have been selected and shown in Table B9.

Table B9: Eco-points for common construction materials.

Eco-Points for production of raw materials (pts per tonne)		
Material	Indicator	Description
Pilkington Float Glass	253	-
Steel (low alloy)	910	93% primary iron, 5% scrap, 1% alloy metals
Steel (high alloy)	110	71% primary iron, 16% Cr, 13% Ni
Aluminium	780	100% primary material
Cement	20	Portland Cement
HDPE	330	High density polythene
EPDM	360	Vulcanised with 44% carbon, including moulding

Source: Goedkoop (2000)

The number of eco-points associated with steel manufacture varies widely depending on the composition and quality of the steel. Aluminium has a high eco-points score, which is due to its large amount of energy used in the smelting process. The 94% of the points are split equally between resource depletion and damage to human health (a large part of the damage to human health is in the climate change index). Cement has a low eco-points score, 70% of this is due to the emissions during the process, which are hazardous to human health. Both the polymeric materials high density polyethylene, used in pipes, and etheylene-propene-diene Rubber, used to manufacture gaskets for use with glazing systems, have similar eco-points scores. They have a similar embodied energy, which is high because of the energy required to crack large hydrocarbons. It is also possible that they both involve the release of volatile hydrocarbons.

Influence of Research on Pilkington Glass

Pilkington Glass is the largest manufacturer of glazing for buildings and the automotive industry in the UK. As the awareness of the environmental impact of buildings has increased they have come under pressure to reduce the environmental impact associated with their products. Pilkington had never before agreed to an investigation of this nature into their products. Pilkington agreed for this study to be carried out so that they would be able to use it to provide their customers with greater information about their products and to meet the enquiries of building professionals such as Architects.

Pilkington Glass were primarily interested in the embodied energy value, because the embodied energy of building products is seen as a guide to their overall environmental impact (West 1994). However, this measure is more widely used in the construction industry. The approach taken by this study introduced a new method of analysing the environmental impact of products to Pilkington plc. There is the pervasive air within Pilkington that the environmental effects of the float glass process are so large that other than increasing the energy efficiency of that process there was no way of reducing the environmental impact. However, the results of this study demonstrated that although the influence of the process itself was large it was possible to reduce the environmental impact by altering the way that the raw materials were sourced.

Pilkington Glass has decided to use this study as the basis for a series of further investigations, which will look primarily at the following:

- The influence that increasing thickness of the glass has on the environmental impact.
- The inclusion of other subsequent processes such as: toughening, coating and laminating.
- The addition of the materials required to produce a double glazed unit.

CHAPTER B5 PART B SUMMARY AND CONCLUSIONS

This study was carried out in order to investigate and understand in depth the environmental impact of façade materials and systems through their life cycle. It focusses on the Life Cycle Analysis (LCA) of Pilkington UK6 float glass plant in the UK. This was a cradle to gate LCA which considers the environmental impacts of glass manufacture, as measured using embodied energy and environmental impact calculated in Eco-Indicator 99 eco-points.

After briefly discussing methods of environmental impact analysis of building products and components and a description of the glass making process (Chapter B1), some background information on LCA is given, including basic assumptions and definitions for parameters used (Chapter B2). A discussion on available LCA modelling tools in included in chapter B3 where the tool selected for this study (TEAM^{TM}) is described together with the required input and outputs.

Chapter B4 presented and discussed the results of the two types of analysis carried out on the inventory data:

- Embodied energy calculation
- Eco-indicator 99 points assessment

These two assessment methods allow the environmental impacts associated with the production of glass at the particular Pilkington plant to be evaluated. It was calculated that the Pilkington float glass has an embodied energy of 13.3 ±0.5 GJ/tonne and 243 eco-points per tonne. Both of these indicators suggest that the environmental burdens associated with this plant are in line with those that would be expected by a plant of this type in the UK. The small difference between the Pilkington float glass and the average flat glass value from the BRE is easily explained, most notably by slight differences in the LCA boundaries.

Embodied Energy

The contribution of four subsystems to the total embodied energy of the float glass process was calculated; building, process, raw materials and transport. From these process and raw materials make the highest contribution to embodied energy; 74.8%

and 23.3% respectively. The building subsystem contributes 0.4% while transport 1.5%.

Eco-points

The contribution of three indicators were calculated; damage to Eco-systems, Damage to Human Health and Damage to Resource Levels. It was shown that approximately 85% of the eco-points are associated with the Damage to Human Health Indicator, 12.5% with Damage to Resources and 2% with Damage to Ecosystems. From the 85% of the Damage to Human Health eco-points approximately 56% are contributed to respiratory effect and 28% to climate change damage.

Arranging the eco-points attributed to the Pilkington Float glass process by sub-system, it was calculated that the building contributes 0.3%, Process 33.2%, Raw Materials, 65.6% and transport 0.8%. Building and Transport contribution are small as in the embodied energy index but the affect of process and raw materials is inversed. This is mainly due to respiratory effects of raw materials (in particular soda ash) which are included in the calculation of eco-points.

The comparison of the eco-points attributed to other primary processed materials shows that Pilkington Float glass is comparable to the use of steel, and highly preferable to the use of aluminium as a cladding panel. In order to evaluate the true environmental cost of glass in buildings other issues must be discussed. These include the benefits to the building space, such as natural light, a connection with the external environment and warmth. There would also be issues regarding the thermal insulation provided by glazing and the prospect of overheating during the cooling period, particularly an issue in buildings with large areas of glazing. These issues and the environmental impacts of various other cladding types are addressed by the research described in Section C of the portfolio.

PART C

FAÇADE CONCEPT DESIGN TOOL

PART C: FAÇADE CONCEPT DESIGN TOOL

This part of the portfolio describes the rationale and methodology for developing a concept design tool for evaluating the effect of the façade design on the building's internal thermal and lighting conditions as well as energy demand and environmental impact in office-type buildings in the UK. The need for and use of concept design tools is discussed in chapter C1. The building model used for the development of the tool is presented in chapter C2. Chapter C3 discusses the three simulation models used for the creation of the database. The main features of the developed tool are detailed and a set of sample results are presented in chapter C4 to show how the tool may be applied and how to interpret the predictions. Finally, chapter C5 presents the results of a parametric analysis of the tool database.

CHAPTER C1 INTRODUCTION TO CONCEPT DESIGN TOOLS

There is a wide range of building strategies that the energy-conscious designer can implement in the design of a building. However the choice of façade affects, and is effected by, the overall building services and structural strategy for a building (Gibb, 1996).

An example of the complex nature of the façade design options can be illustrated in the decision to use daylighting as a method of providing the required lighting in a building. The use of daylighting and combination on/off controls can reduce the electrical energy consumption of lighting by approximately 85% (Lynes, 1990). Increasing the window size in a façade would increase the amount of daylight available and should be able to reduce the requirement for artificial lighting during the day. However, this is an over simplification of what is likely to happen in practice; a daylighting strategy must include provision for the cooling load from solar gain and some treatment of the distribution of the light as well as overall amount of light provided. External shading must be considered; it reduces glare and makes it less likely that people will pull down the blinds and turn on the lights, although it also reduces the light transmittance and average daylight factor. So if large amounts of fenestration are provided for daylighting purposes, solar gain must be addressed, as must internal and external shading.

The importance of considering facades and building envelopes in general in the early design process is indicted by the results of the Annex 32 of the International Energy Agency research programme (Svendsen, 1999 and Baker, 2000). This was a four year international research programmed concluded in 2000. The difficulties of choosing the optimum façade solution can summarised by the following three questions:

- Which combinations of façade type, shading, etc. will provide the best performance in terms of internal conditions, environment, energy and cost performance?
- If more stringent restrictions were imposed on one of the parameters, i.e. the environmental performance, which façade would give the best performance?
- If most of the parameters are fixed by the site, which options will fit within the performance constraints required by the client / brief?

The facade typology and building geometry are developed at a very early stage of the construction process: Indeed it is often the basis for the award of the contract to a particular firm of architects or developers. Typically, a detailed energy analysis of the facade, along with the whole building, is carried out during the detailed design phase when the servicing strategy is being developed. It is possible to employ detailed energy analysis at an early design phase, but this is impractical for the following reasons:

- Detailed energy and environmental analysis is time consuming. At the early stages of design there are often several iterations of a design, or several facade options which all require investigation. This relegates energy simulation to the later stages of design.

- Detailed analysis requires detailed information about the building, which may not have been decided at an early design stage. This restricts detailed energy analysis to the latter stages of design.

However, during the final design stages changes to the external appearance of the building are severely restricted. The overall facade typology is "locked" into the design at an early stage by the plans submitted to the planning authorities. This means that the designer can make only small variations in order to optimise the design. The greatest opportunity to evolve an environmentally-efficient facade design is at the earliest stages of the design process.

Recently a number of concept design tools have been developed. Some focus on one technology such as night ventilation for cooling (Kolokotroni, 1998) and others on the integration of two or more environmental condition provisions in generic or specific types of buildings. For example the LT method (Baker, 1999) and Office Design Tool (Bunn, 1999) are two concept design tools developed in the UK. The LT Method is a generic tool and can be applied to a variety of non-domestic buildings. It is an energy design tool, which allows the designer to predict the energy consumption for a proposed building, at the early stages of the design. It is sensitive to parameters such as building plan and section, orientation and glazing ratio, and provides an output for annual primary energy use and CO_2 production under the end uses of heating, lighting and cooling. The Office Design Tool, on the other hand, is directly applicable to office-type buildings and has embedded thermal and daylighting modelling algorithms based on the CIBSE admittance method (CIBSE, 1999b) and BRE (Littlefair, 1988) calculations. The tool can then be used to model thermal and lighting conditions for a 'typical' day or for a typical CIBSE weather year. Benchmark energy requirements are included as default values. Both tools treat the building façade as a combination of solid and open (glass) areas and do not consider the façade design in detail.

Through an extensive literature review no single concept or simplified design tool was identified which would address the impact of various façade types of non-domestic buildings in terms of the provision of thermal and lighting conditions as well as energy demand and environmental impact. Two concept design tools exist which are aimed towards the optimisation of thermal impact of facades in residential buildings; RESFEN (University of California, 1999) and OPTI (Gratia, 2002). Both tools have been developed by using advanced dynamic thermal simulation tools; RESFEN includes USA weather data and is restricted to energy predictions whilst OPTI includes Belgian weather data and outputs, and include internal thermal and lighting conditions as well as energy demand estimation. For façade systems suitable for non-domestic buildings a simplified tool exists (Aarons, 2001) to assess the feasibility of double façade systems. For this tool, an energy model was used to calculate internal comfort, lighting levels as and energy demand. This project focuses on the development of a concept design tool for a number of generic office-building façade designs. This research project focuses on offices because they are the service sector building type which consumes a high percentage of delivered energy (17%), (DTI, 1997). This is comparable to retail establishments (18%) and the catering sector (17%). Office building types and their energy consumption, defined by building type and function, are well documented in the UK, moreover, occupants of office buildings are both more permanent and more stable, hence the opportunity to influence the operational energy consumption is high.

In general, concept design models can be divided into two categories:

- Results are extracted from built-in databases derived from advanced modelling for a specified number of cases (in the form of parametric analysis) and weather data (usually country restricted).
- Results are calculated from built-in (usually energy and thermal) simplified or fast-to-run algorithms and appropriate databases for other variables of interest such as lighting and acoustics.

It was decided to develop this tool using the 'database' approach because:

- The results would be based on detailed and advanced modelling and therefore more accurate.

- User misinterpretation of results would be more difficult as the selection of cases is restricted by the development of the tool.

The tool presented in this part of the portfolio was developed by using three simulation models listed below, Figure C1 shows diagrammatically how the simulation models were used.

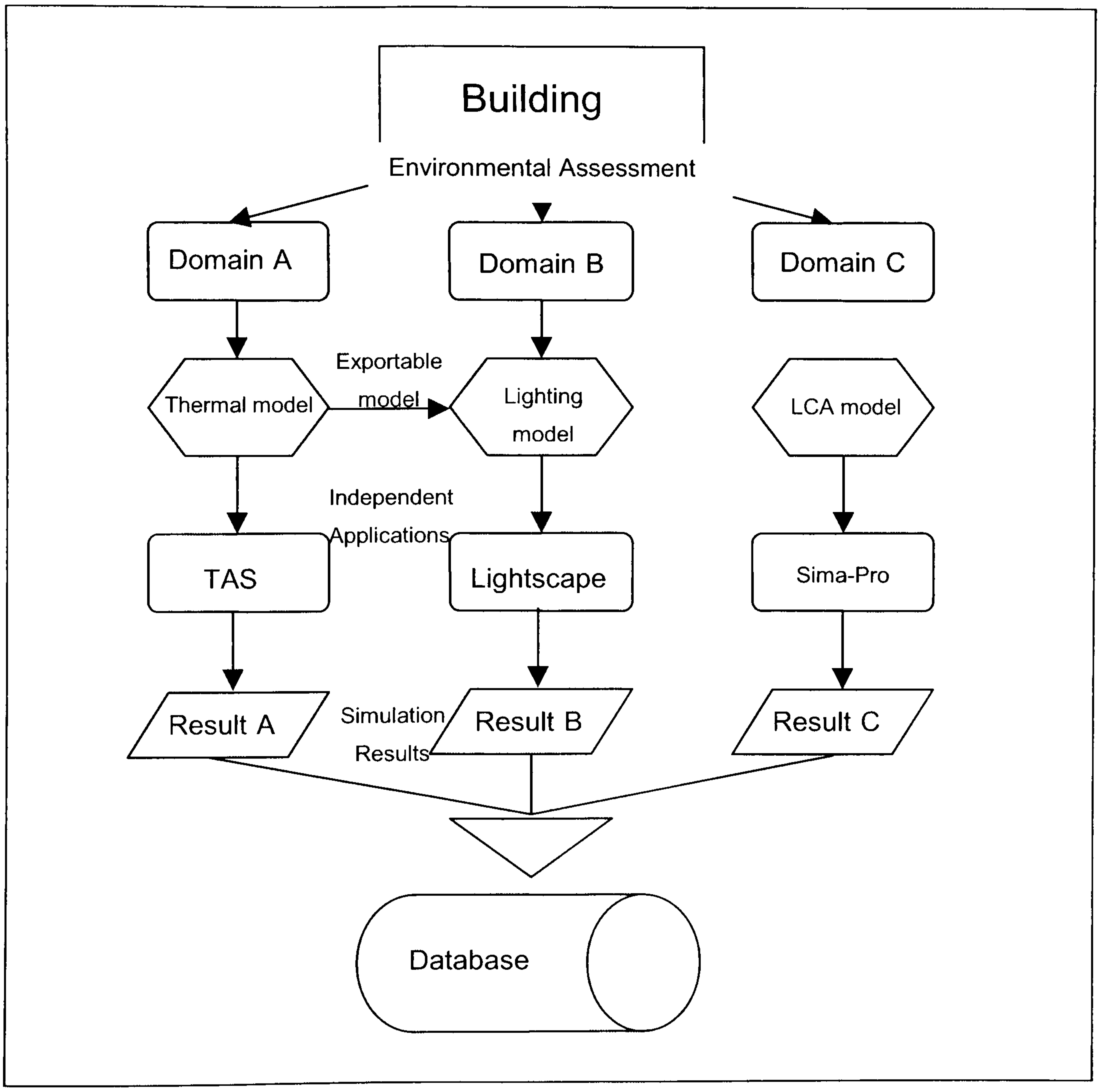

Figure C-1 Diagrammatic representation of the method used to build

- A dynamic thermal simulation model (Tas), provided energy demand and internal thermal conditions data.
- A steady-state lighting simulation model (Lightscape) calculated the lighting environment based on the optical properties associated with the facade. The lighting model shared a common model format with the dynamic thermal modelling tool.
- A Life Cycle Analysis (LCA) accounting tool (Sima-Pro), calculated the impacts associated with the construction and use of the building based on information about the construction and energy use in the building over a fixed time (Llewellyn 1998). The LCA methodology Eco-Indicator 99 was employed and the computer tool used in this part of the work is similar to that described in Part B of the portfolio.

The data from the three tools were combined in a façade selection tool. Visual Basic programming was used to create a user-interface to enable the user to interrogate the data base. A beta version of this tool is included with this portfolio on a CD-Rom.

CHAPTER C2 DESCRIPTION OF THE BUILDING MODELS

This chapter describes the building models which were used to carry out the parametric analysis, the results of this parametric analysis was developed into the datasets to be used in the concept design tool. A large number of building energy simulation codes exist, which can be used to analyse building systems in varying levels of detail (Hong 2000). However, as there were a large number of independent variables to be considered a large computational effort was required. This was overcome by the use of an idealised model. An idealized model of the facades under investigation allowed different façade types to be compared consistently.

The inputs required for the three modelling tools were defined on the basis of a comprehensive literature review and experience gained from visits to existing buildings and façade manufacturing plants. The following parameters were required to define the model:

- Office type
- Facade type
- Shading type
- Internal environmental conditions and energy practice
- External conditions
- Life cycle data.

These variables are discussed in more detail in the following sections.

C2.1 OFFICE TYPE

Two building types have been modelled; the building types have been developed from the information provided in Leighton (1990), DETR (1998) and Saporito (1997). A large database of office buildings in the UK was used to develop four office building typologies that are described in detail in the three publications in terms of construction and operational details. This study has used the two building types, which most adequately reflect the construction typical in urban locations as described below:

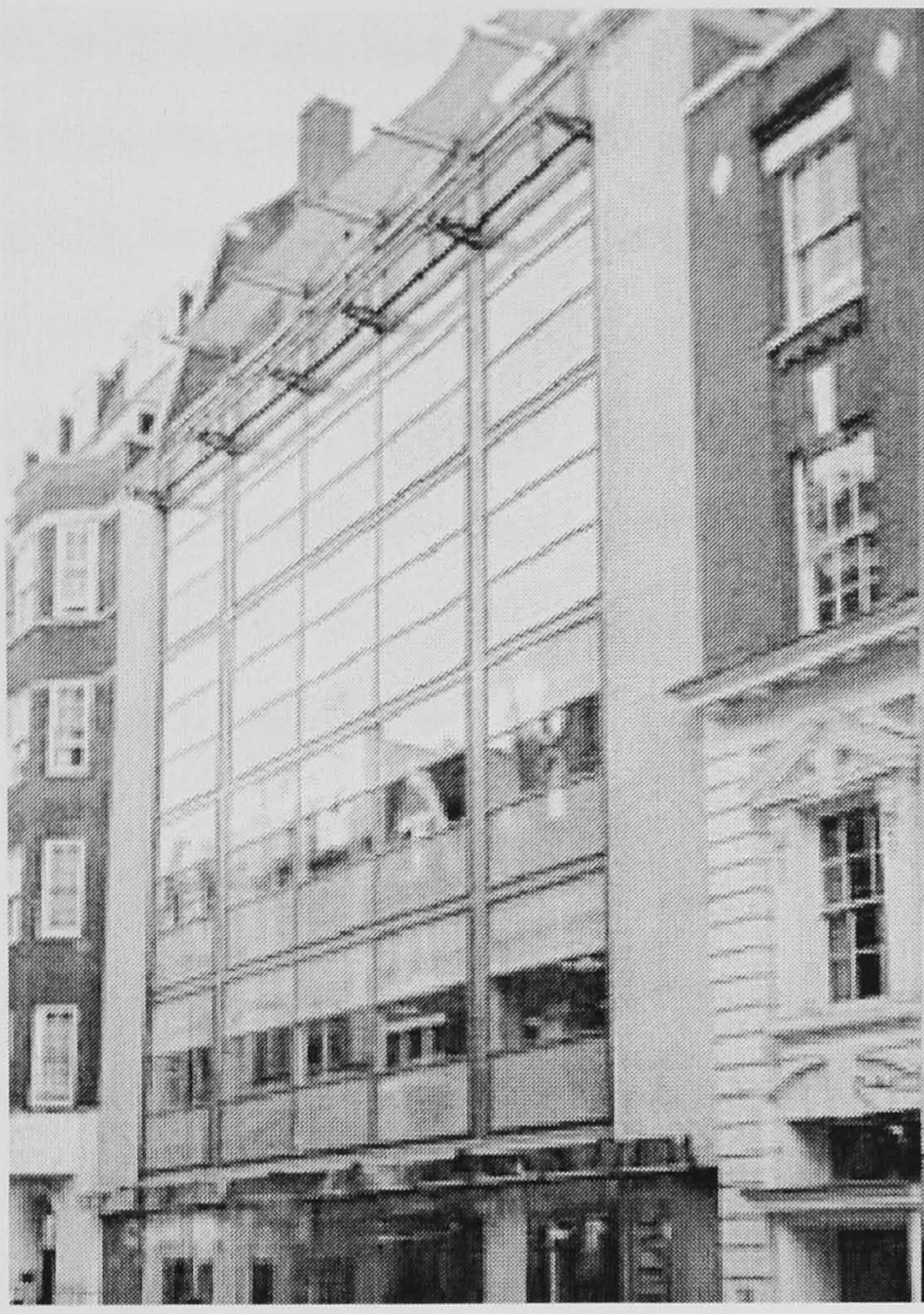

Figure C2 Building Type 1.

Figure C3 Building Type 2.

Type 1: *naturally ventilated open-plan building type.* This is based on the traditional structure prevalent in UK cities, which is often refurbished to provide modern office space (Figure C2). This type of office building can range from 600 to 4000m^2, is typically open plan, but with some areas closed off, such as meeting rooms. This building has a high thermal mass and is likely to be less than five stories high with medium internal heat loads.

Type 2: *Air Conditioned Prestige Building Type.* This type of building is usually a national or regional head office and the typical size ranges from 4000 to 20000 m^2 (Figure C3). This building usually has low thermal mass, is more than five stories high and tends to have high internal heat loads.

The development models are based on a single office space (6 m deep, 10 m long and 3 m high), with a single face (10 m x 3 m) as an exposed facade. This office form has been used in various energy simulation experiments in the UK (e.g. Kolokotroni, 1997). All surrounding buildings are considered to be of similar heights, with a city aspect and a ground solar reflectance of 0.2. The building orientation can be rotated through the cardinal points to 0°, 90°, 180°, 270°. The construction of the floor/ceiling slabs is used to change the thermal response of the building. The Type 1 building has three floors and the test office is on the central floor, whereas in the Type 2 building the test office is on floor three out of seven floors.

Exchange with the external environment is through this façade. Although this study was carried out before the introduction of the new building regulations with regard to the design and development of the thermal and solar performance of facades, the facade typologies were developed with regard to the future introduction of the legislation. Part 1.7 of the document states that standard U-values for solid wall area of 0.35 W/m^{2}K and a standard U-value of 2.2 W/m^{2}K for window glazed in metal frames. These U-values should be adhered to in the following proportions for places of assembly, offices and shops windows may comprise 40% of the area of exposed wall. However, it is possible using a trade of in the U-value of standard elements to use larger proportion of window area to solid as long as the suitable compensating measures are taken, i.e. the overall U-value is not greater than a wall of the standard U-value and proportions. When trading off U-values the poorest acceptable U-value for parts of exposed solid wall or floor is 0.70 W/m^{2}K. Using equation A-7 the average U-value can be determined for the exposed elevation of the test building if it conformed to the standard construction areas and U-values set out in Part L2 of the building regulations at 1.1 W/m^{2}K.

Part L2 of the building regulation s also state that buildings should be constructed such that occupied spaces that rely on natural ventilation should not overheat when subjected to a moderate level of internal heat gain. A method of achieving this for spaces with only one external façade is to restrict the maximum allowable area of glazing.

Table C1 Maximum allowable area of glazing to avoid overheating.

Orientation of Opening	Maximum allowable area of opening in %.
N	50
NE/NW/S	40
E/SE/W/SW	32
Horizontal	12

Source: Table 4, pg. 17 (DTLR 2002)

As it is unlikely that the areas of glazing will vary so dramatically from elevation to elevation in a façade Part L2 allows for the application of shading to meet the overheating criterion. In this study the maximum glazed area for a north elevation was used as standard, with the view being that the tool developed would allow the user to investigate the effects of various shading types on other elevations.

However, the case of highly glazed curtain wall facades must be dealt with separately. A standard curtain wall façade, such as the one investigated in this study is difficult to employ on a building, as it is unlikely to meet either the U-value requirements of the new regulations of the solar overheating requirements. It has been included, because it is currently one of the most popular types of façade used in offices in the UK.

C2.2 FAÇADE TYPES

The facade types were determined, in part, by the building structure. Inherent buildability, suitability and the type of ventilation system had an impact on the façade type selection. Table C2 lists the facade types according to building structure and ventilation system. It can be observed that only the façade of the last category 5 is different for the two structures considered. Therefore, six different façade types are considered in total.

Table C2 Façade types described by building structure and ventilation system.

	Heavy weight masonry structure with natural ventilation	**Lightweight steel framed building with air conditioning**
1	Lightweight Cladding with 50% glazing ratio.	Lightweight Cladding with 50% glazing ratio.
2	Heavyweight Cladding with 50% glazing ratio.	Heavyweight Cladding with 50% glazing ratio.
3	Internal Weatherseal Double skinned façade	Internal Weatherseal Double skinned façade
4	External Weatherseal Double skinned façade	External Weatherseal Double skinned façade
5	Traditional Masonry wall with 50% glazing ratio.	Curtain Walling

A description of the façade types used for this study follows. In all cases two systems can be defined; a standard system (SS) and a high quality system (HQS). This is achieved by altering the glazing properties and/or the U-value of the cladding panel. These changes will influence the thermal properties and infiltration rate of the façade.

Response factors for the materials are specified, these are a measure of the thermal response of a material, the higher the response factor the heavier weight the building is. A response factor (F_r) below 6 is considered lightweight (Leighton, 1990). All internal surfaces are surrounded by other offices or corridors having the same internal temperature as the office being considered. So there is no net heat flow through the internal surfaces. No account is taken of internal doors, the surface resistances of the internal walls do not change. The ceiling of each floor is considered to be the same construction as the floor above.

Table C3 Detailed description of façade constructions.

Element Name	Construction	U-Value W/m^{2}K	Solar Trans.	Light Trans.	F_r
Floor Type 1 Building	Lightweight concrete, screed.	1.4	-	-	3.1
Floor Type 2 Building	Precast concrete plank.	1.7	-	-	7.2
Internal Walls	Plasterboard, concrete, plasterboard.	1.5	-	-	1.2
SS Lightweight Cladding	metal, insulation, metal	0.5	-	-	1.3
HQS Lightweight Cladding	metal, insulation, metal	0.3	-	-	1.3
SS Heavyweight cladding	concrete, insulation, concrete	0.5	-	-	7.5
HQS Heavyweight Cladding	concrete, insulation, concrete	0.3	-	-	10.8
SS Masonry cladding	brick, air cavity, insulation, block, plaster.	0.5	-	-	5.2
HQS Masonry Cladding	brick, air cavity, insulation, block, plaster.	0.3	-	-	5.5
Metal Spandrel panel	aluminium, insulation and plasterboard	0.3	-	-	3.5
SS Glazing	8mm toughened glass, 12mm air cavity, 8.4 mm laminated glass (low-e), with a metal framing system.	1.7	0.4	0.78	-
HQS Glazing	8mm toughened glass, 12mm argon filled cavity, 8.4mm laminated glass, with a metal framing system.	1.5	0.4	0.79	-
Double-Skinned Façade Glazing (internal)	12 mm toughened glass, 0.2m cavity, 8mm float glass, 12 mm argon, 8.4 mm laminated glass	1.1	0.3	0.71	-
Double-Skinned Façade Glazing (external)	12 mm toughened glass, 0.8 m cavity, 8 mm float glass, 12 mm argon, 8.4 mm laminated glass.	1.1	0.3	0.71	-
Curtain Wall Glazing	10 mm toughened glass, 12 mm air cavity, 10.6 mm laminated glass (low-e) with a metal framing system.	1.6	0.4	0.7	-

Lightweight Cladding

This type of cladding element can be manufactured from various materials, as listed below:

- Metal, typically steel or aluminium
- Glass fibre reinforced cement (GRC)
- Glass fibre reinforced polyester (GRP)
- Fibre Cement
- Terracotta

In office buildings, lightweight cladding is often used to fill large areas that do not require daylight or natural ventilation, or as a cladding in conjunction with fenestration. The advantages of this type of cladding include: ease of construction, low cost, relatively high performance and a range of finishes (CIRIA, 1992c). In this study a metal cladding panel has been modelled. This cladding typically comprises an outer sheet of metal, thermal insulation, some form of isolation of the fixings if required to prevent cold bridging and an inner sheet of metal or a metal lining tray.

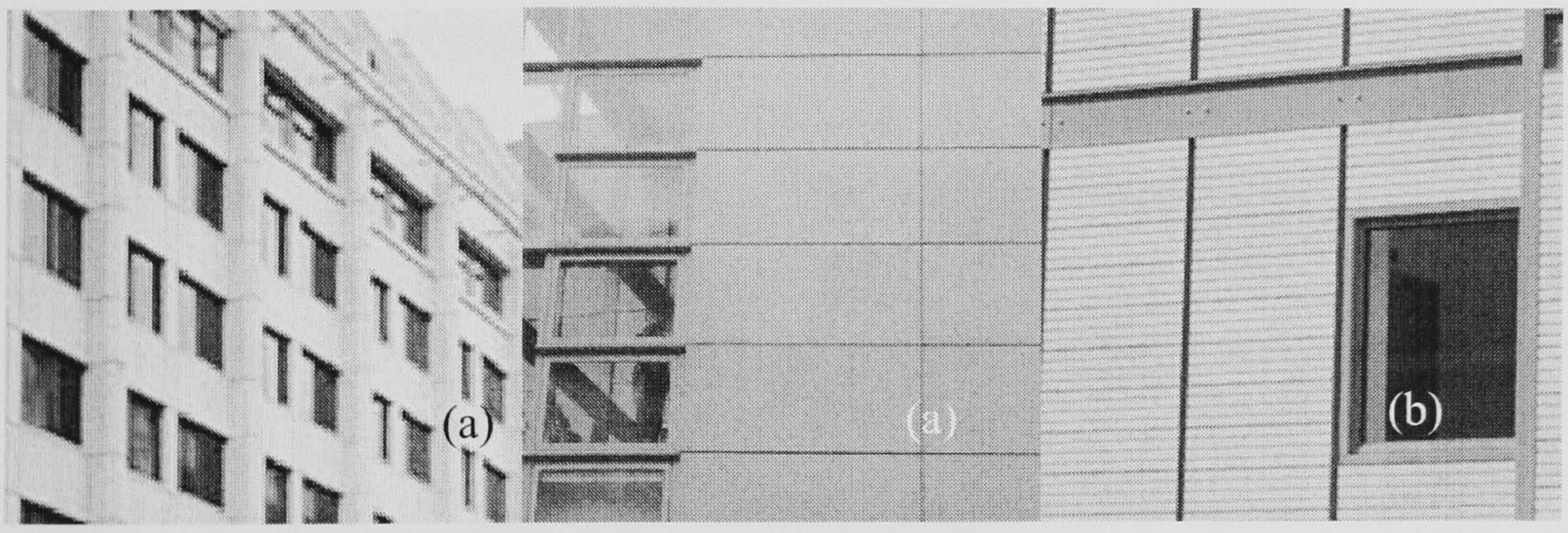

Figure C4 Lightweight cladding, (a) metal cladding (b) terracotta cladding.

A lightweight cladding facade with a 50% glazing ratio consists of a metal cladding panel (as described above) with a low response factor (below 6) and double- glazing. The construction details of the façade system used in this study are listed below:

Heavy Weight Cladding

Heavy weight cladding units tend to be of concrete construction. The concrete cladding can either consist of panels which are precast in a factory and transported to the building site or in-situ concrete which is poured on site into form work. Both methods of manufacturing concrete façade panels offer advantages. It is possible to face the concrete panes with various materials to give a variety of finished appearances including:

- Brick (Figure C5)
- Natural stone
- Aggregates to give a natural stone appearance
- Textured materials

The size and shape of precast panels is limited by the practicalities (concrete weighs approximately 2.4 tonnes per cubic metre) and the requirements of the building. Cladding panels are typically manufactured either to storey height or as spandrel panels. The panel widths are designed to coordinate with the structural grid of the building (CIRIA, 1992d). Concrete offers little thermal insulation (thermal conductivity of 1.2 W/m^2K) so panels are usually insulated. In this study a storey height concrete panel has been modelled which has internal insulation and thermally broken fixings. This is a heavy weight cladding system with a 50% glazing ratio which consists of a precast concrete sandwich panel with a response factor of 9.5 and double glazing. In this case both a standard (SS) and a high quality system (HQS) have be defined as below:

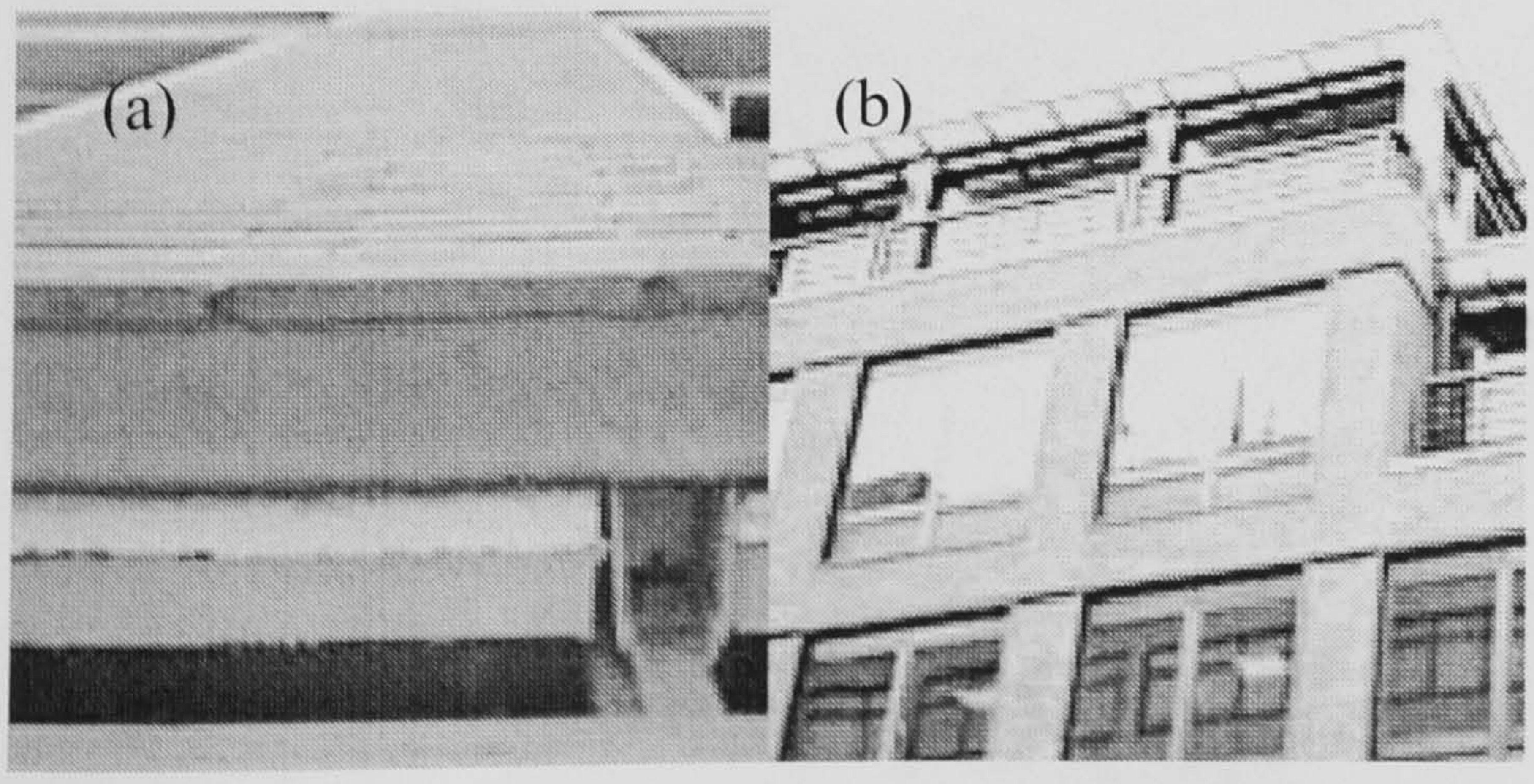

Figure C5: Brick faced concrete cladding, (a) in section (b) elevation.

Double-Skinned Facades

The term double-skinned façade simply refers to a pair of glass skins which are separated by an air corridor of varying width, which is made to work to the buildings advantage as insulation against external climatic extremes and external noise (Taylor, 2001). The double skinned façade offers advantages over a traditional singled-skinned façade, in particular the ability to alter the properties of the external walls (e.g. insulation values) according to the external conditions. The second skin of the building is often active and can act as a ventilation chamber, a heat sink, a thermal boundary and a sun space according to the time of year and the occupant requirements. By providing a second external barrier between the internal and external environment, a double-skinned façade allows natural ventilation to work in situations where either external noise or air quality would not otherwise permit its use. It is possible to use double-skinned facades in both air-conditioned and naturally ventilated buildings.

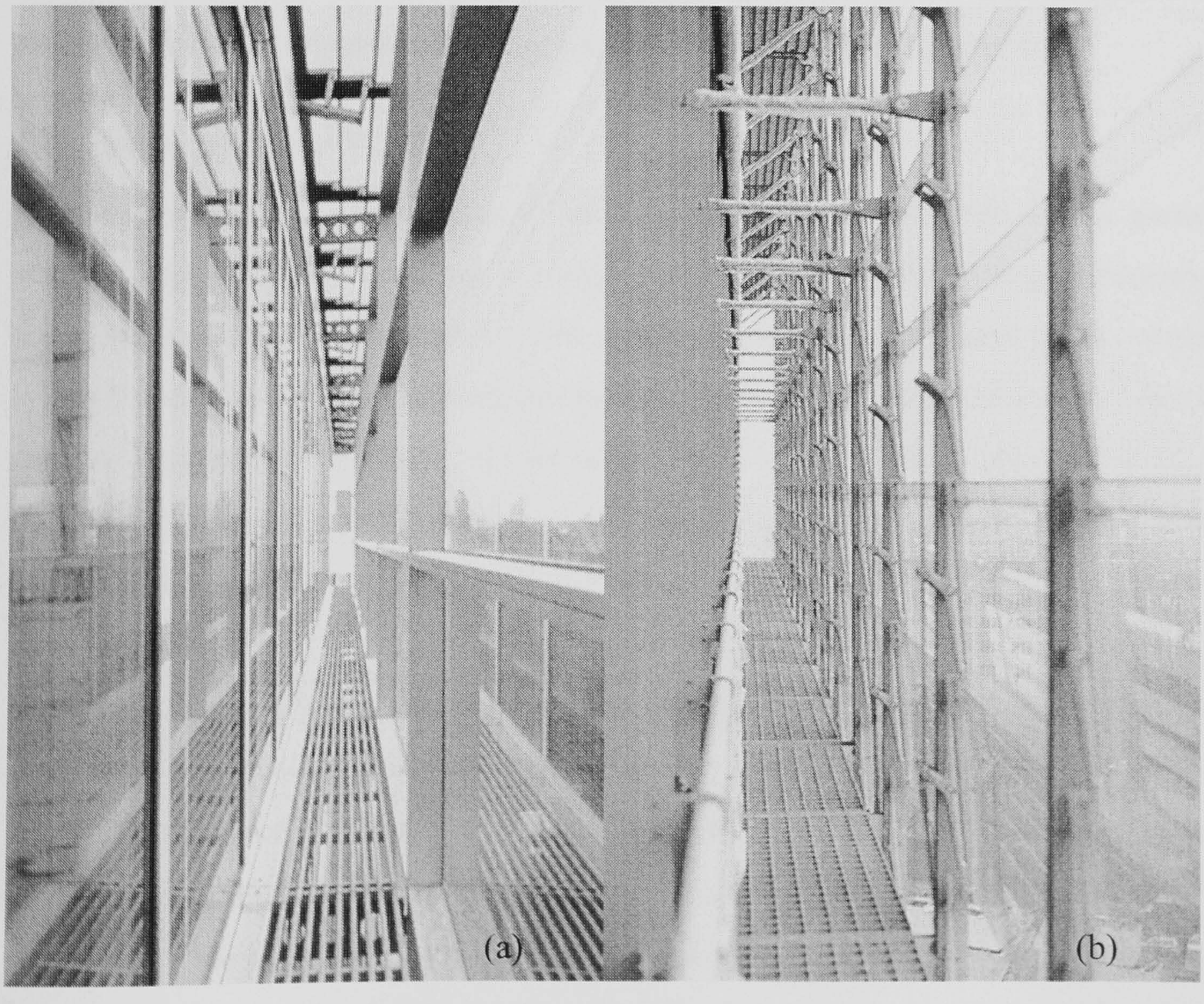

Figure C6 Double skinned façade, (a) external weather-seal, (b) internal weather-seal.

This study considered two types of double-skinned façade, one which has an internal weather seal with ventilation provided through a moveable external skin and the second has an eternal weather seal with a ventilated cavity.

Internal Weather-Seal Double-skinned façade

This façade shown in Figure C6a has two external skins, an openable outer skin of single glazing, which acts a weather shield and a buffer during the heating period, but offers ventilation to the inner skin of the façade during the cooling period. There is a double-glazed inner skin that forms the weather barrier. There is a continuous spandrel panel, which gives the façade a glazing ratio of 0.85.

External Weather-Seal Double-skinned façade

This system shown in Figure C6b has a sealed single-glazed outer skin, which acts as a weather barrier. There is a 0.8 m ventilated cavity and a double-glazed inner skin. As before a continuous spandrel panel gives the façade a glazing ratio of 85%.

Traditional Masonry Walls.

Masonry is the predominate form of wall in traditional construction and is particularly suitable for low rise housing, but is widely used in all types of buildings. Masonry walls are a composite of small ceramic units, either bricks or blocks, built up of overlapping layers bonded and sealed with mortar or soft sealants. The construction of a brick wall can be very labour intensive, so brick is either used in small areas of a façade in commercial buildings or the look is simulated using precast concrete panels faced with brick (CIRIA, 1992b).

This facade type in this study is based on a brick and block structure with an air gap and interstitial insulation. The facade is load-bearing masonry with the majority of the load carried by the internal block leaf and the outer brick leaf providing insulation and acting as a weather barrier. It is possible, however, to employ non-load bearing masonry where the masonry supports self weight and external environmental pressures. In this instance, the weight of the brickwork is transferred to the floor plates at each storey height, either by setting the first course of brick on top of the floor or by attaching the brickwork back to the floor with the use of angle brackets. This study models one type of brick cladding which is the typical type used in the UK and the construction details are presented in Table C3:

Curtain Walling

The term "curtain walling" usually refers to metal-framed glazing which can span from floor to ceiling, this type of cladding is typified by large amounts of glazing, see Figure C7, (CIRIA, 1992e). This is a prestigious type of cladding which is often used on high-quality commercial buildings. The curtain wall is not load bearing and only supports its own weight and the environmental forces which act upon it (CWCT, 2000). Curtain walls are often classified by the method of construction employed:

- Stick systems
- Unitised systems
- Panelised systems
- Structural sealant glazing
- Structural glazing.

Stick systems are assembled on site as a kit of parts; the members are cut to size in the factory and transported to site where they are assembled. Unitised systems comprise storey height units with the frame and infill panels already constructed, these are lifted into place and attached directly to the structure. This system is more expensive and has the advantage of reducing site installation time and increasing accuracy since all parts are assembled under factory conditions. Panelised curtain walling comprises two or more units which span from one structural member to the next. These panels will be fixed directly to structural columns with interstitial fixings along the length of the panel if required. These panels provide further savings in the building programme with a greater speed of erection, but the panel sizes are limited by the weight of the panels and the ability to move them from factory to site successfully.

Structural sealant glazing or structural silicone glazing uses a structural seal to attach the glazing unit to a frame, the framework is internal and there are no protrusions through the glazing line. This creates the effect that the glass is unsupported by framework. The glass may or may not be supported mechanically; the addition of mechanical support allows a reduction in the bead of silicone. Structural glazing is often bolted glass, sheets of toughened glass are assembled with special bolts and brackets and supported by a secondary structure. The space between the panes of structural glazing are sealed for weather resistance, this creates a flush, near transparent external surface.

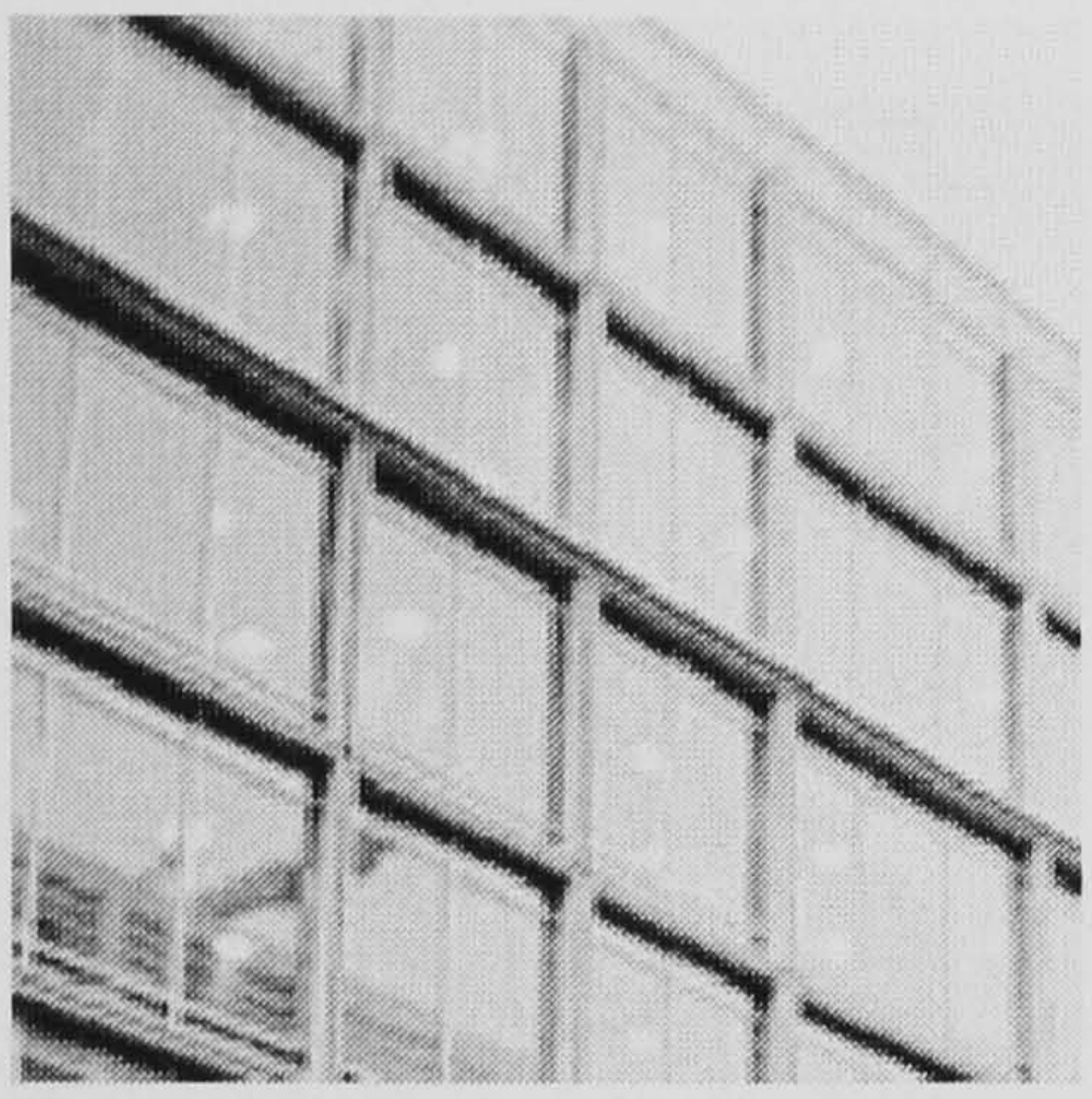

Figure C7 Curtainwall.

This study uses a traditional curtain wall, which is highly glazed (85% glazing ratio) and could be manufactured as either a stick, unitised or panelised system. The construction of the façade modelled is described in table C2.

C2.3 SOLAR SHADING

Solar shading is a very important consideration when specifying a façade and considering its environmental impact. The correct application of solar shading could aid the use of natural light in a building and reduce the solar gain, thus reducing the cooling load (Littlefair, 1999). Solar gains considerably increase heat gains and can be a source of glare. Four shading options were modelled for each façade type as follows :

- Type 1: Horizontal overhang 75cm deep with 0% transmittance
- Type 2: Louvers 40cm deep at 45° with 50% transmittance
- Type 3: Louvers 10cm deep at 45° with 0% transmittance

- Type 4: Vertical fins 75cm deep with 0% transmittance

These are types that are typically used for office buildings in the UK (Littlefair,1999).

Horizontal Overhang

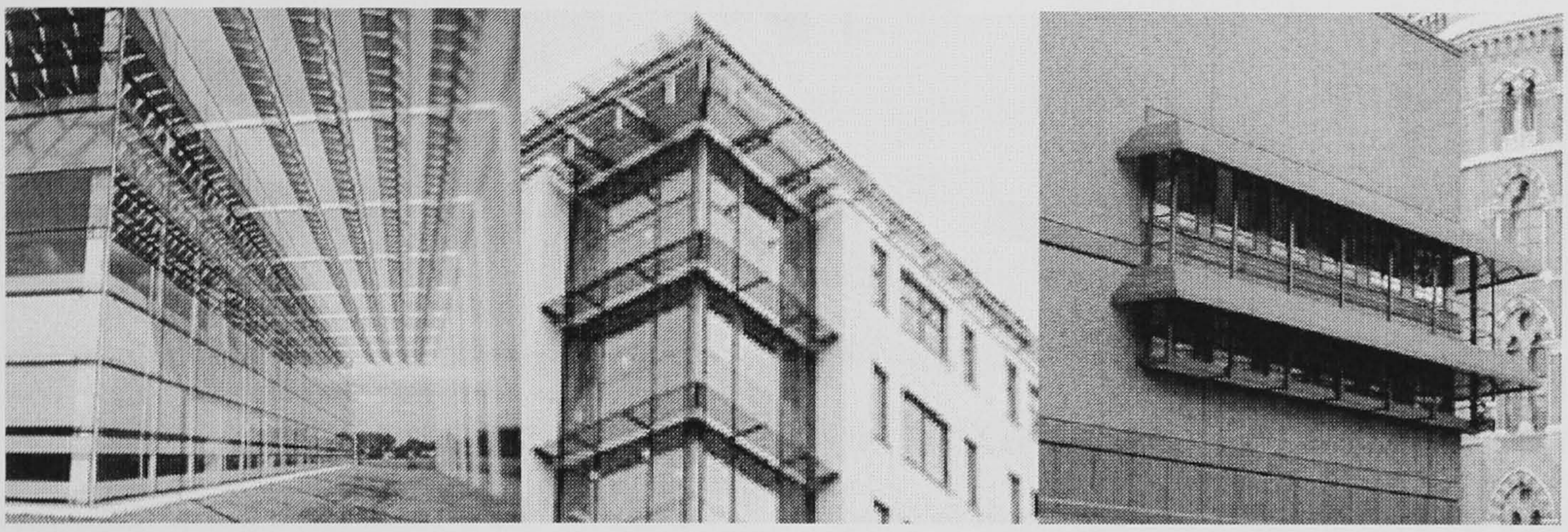

Figure C8 Horizontal overhang solar shading system.

Horizontal overhangs vary widely from fabric awnings to concrete fixed overhangs (see figure C8). The choice of an overhang is dependent on the aesthetics of the building and considerations such as the maintenance and durability of the shading choice. Overhangs are most effective when the sun is at a high angle, and hence are usually employed on south facing elevations.

Louvres

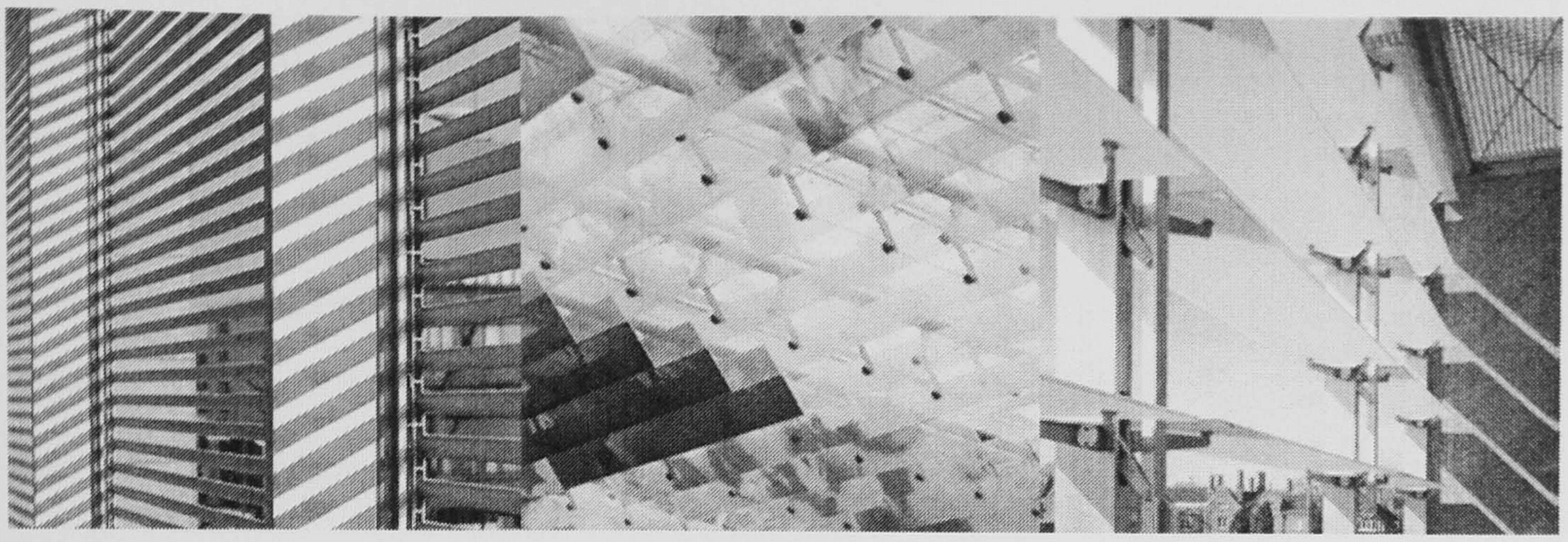

Figure C9 Horizontal louvre solar shading system.

Both fixed and moveable louvres are often employed as a shading device on buildings, see Figure C9. Moveable louvres provide flexibility, but require higher maintenance and management; they are often controlled by a Building Management System (BMS) which uses the incident radiation on a sensor to control the angle of the louvre blades. However, this can prove expensive and there are various examples of static louvres on existing buildings which are positioned in order to provide the most effective shading on a particular elevation.

The design of louvre blades is a compromise between light admission, and glare, the contrast between the louvre blades and the un-shaded area can provide a source of glare in a room. Traditional metallic louvre blades are still used in certain application, but in buildings the use of glass louvres which are either fritted or sandblasted have advantages as they reduce both the solar gain and the likelihood of glare.

Vertical Fins

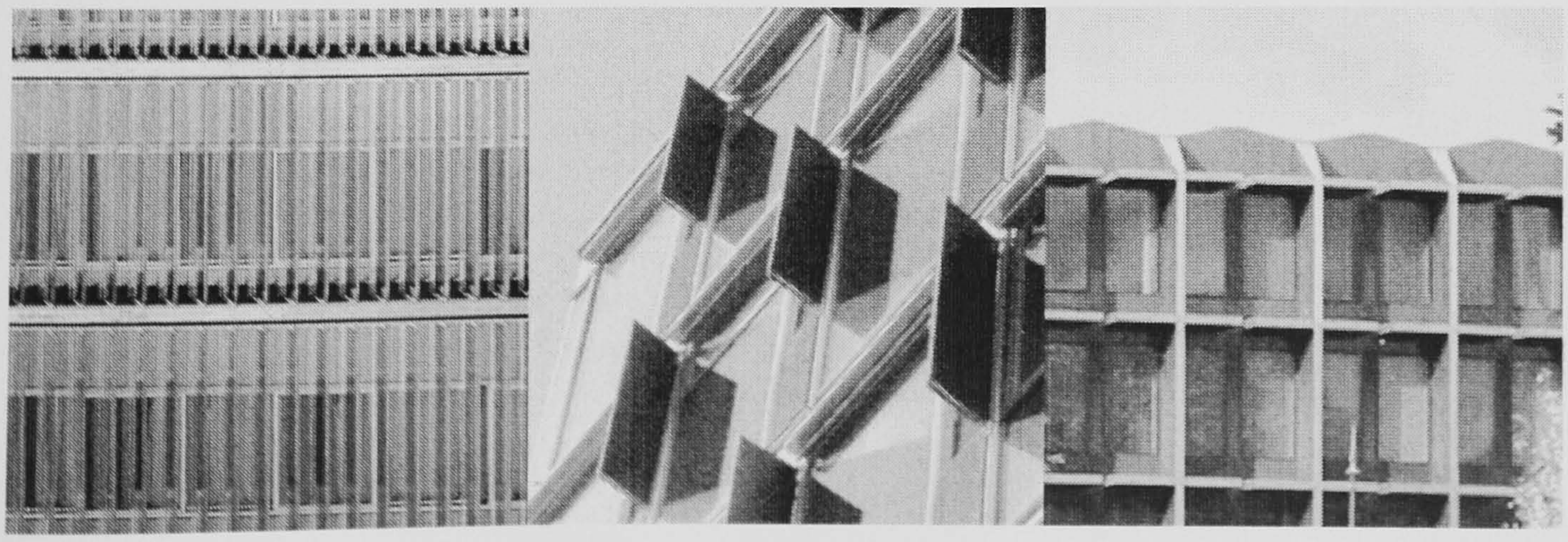

Figure C10 Vertical Louvre shading system.

Vertical fins are used to reduce the sunlight from a fixed angle and they are best used on east-west facing fenestration, see Figure C10. Vertical fins have a similar effect as that from a deep reveal to a window. As with the other shading types, there is a balance between the amount of shading provided and the view. The deeper a vertical fin is the more effective it will prove to be as a shading method. However, it must be noted that if the vertical fin is too deep it will restrict the view out.

C2.4 INTERNAL CONDITIONS AND ENERGY USE

The previous two sections presented the construction characteristics of the building model and façade systems and solar shading. This section presents the operational details of the model. The building occupancy, other internal heat gains, air exchange rate and temperature set points for each day are set as hourly values repeated for each day type. There are three-day types: Weekdays, Saturdays and Sundays. The occupied period is specified for each day type and this varies according to the building type; a type 2 office has longer occupation hours with some use at the weekends. The controls are linked to the occupation of the building, type 2 office (air conditioned) has both heating and cooling set points, while no cooling set point is specified for a type 1 office (naturally ventilated). For a type 1 office the openings are used to control the internal summer temperature; these are scheduled according to the external temperature, wind speed and wind direction.

Internal heat gains

The internal gains have been defined using the profiles in the ECON 19 Energy Survey (DETR 1998) separately for each building type and are presented as a total W/m^2 figure. There are two modes available for the level of internal gains, which reflect the energy practice of the building occupants; these represent good (energy-efficient) practice and typical practice, Table C3.

Ventilation rates

During the occupied period, it is assumed that the space has an occupancy rate of one person per 12m^2, who require 8 ls^{-1} (CIBSE, 1999c). The background air-infiltration rate depends on the air tightness of the façade and varies according to whether the building is air conditioned or naturally ventilated. Where mechanical ventilation is used the rates in ach^{-1} have been set to reflect the occupant requirements. However, in the naturally-ventilated building indoor air quality and summer temperatures are controlled by a combination of background ventilation, (i.e. through trickle vents) and comfort ventilation through opening windows.

Table C4 Building Internal gains and ventilation rates (DETR, 1998)

		TYPE ONE		TYPE TWO	
	Units	Typical practice	Good practice	Typical practice	Good practice
Lighting	W/m^2	15	12	20	12
Occupants	W/m^2	16	16	16	16
Equipment	W/m^2	12	10	18	15
Ventilation rate	Ach^{-1}	N/A	N/A	4	4

C2.5 WEATHER DATA AND EXTERNAL LOADS

The calculation of hourly heating and cooling load and internal temperatures requires a set of weather data with a year of hourly data (8,760 hours). The selection of this weather data is critical (Crawley, 1998) as it must be chosen to represent long-term statistical trends and patterns in weather data. However, the selection of a particular weather data set is dependent on the end requirement of the thermal load calculations. For example extreme weather data is required in order to estimate peak loads, whereas average weather data would be required in order to assess typical energy consumption.

Several methods are used in order to provide typical weather data for use in building energy simulation:

- The selection of an average year of actual weather, usually selected by statistical means
- The use of a synthesised weather year designed to represent the long term weather trends.

The Chartered Institute of Building Services Engineers (CIBSE) use a method which selects the least abnormal year from a selection of several years (Holmes and Hitchin 1978), this method preserves the interrelationship between climatic elements and permits retrospective inspection of secondary elements such as rainfall, if this is required. This type of data is considered adequate for predicting energy demands, but not for peak load estimation (Clarke 2001).

The weather data used in this study have been selected using the guidance in the CIBSE A Guide (CIBSE, 1999a). The example weather years (EWY) that have been used provide, temperature, global solar radiation, cloud cover, wind speed and relative humidity. The winter period (October – April) has been modelled using data from Kew 1964/5, while summer (May – September) has been modelled using Heathrow 1980 (Levermore, 1998). While this work has been in progress new guidance was published (CIBSE, 2002) on the selection of example weather years.

The CIBSE weather and solar data guidance (2002) replaced the summer weather data selection. The new selection was altered to take into account the increase in summer temperatures in London and the southeast (Levermore, 1998). The new recommendations suggest the use of Heathrow 1980 (example weather year) and Heathrow 1989 (summer weather) for the south of England. Although, it is realised that it would have been preferable to use this new guidance in the work presented here, the results would not have changed significantly as the weather sequences used for this work are comparable. In addition, the predictions of the tool are indicative and would be mainly used for comparing the various options offered within the tool during the concept design stage of a building.

C2.6 LIFE CYCLE ANALYSIS ASSUMPTIONS

A LCA requires a functional unit to represent the systems function rather than the quantities of materials used in the performance of a particular function. It is this requirement that differentiates LCA from other environmental analysis techniques (Consoli *et al.* 1993). The functional unit of this study is 1m^2 of façade. The facades under study are the external skin of a reference office space with a fixed dimension. This office is heated and cooled to a set of reference temperatures in order to provide an internal space of sufficient comfort according to the BS 7730 (1995) the advice given in the "Best practice for office specification" (BCO, 1997) and the standards set out in the CIBSE A guide (CIBSE 1999b). All systems under study are considered to be representative of the particular façade typology.

The results of LCA studies are highly dependent on the assumptions made when setting the system boundaries of a project. Product lifetime, transportation distances, product loses, maintenance intervals and end-of-life scenarios are the assumptions that define the product life cycle and have the largest impact on the results (Gebers *et al.* 1998).

Selecting a suitable life-cycle for the building elements is a difficult process due to the nature of buildings. Llewellyn and Edwards (1998) have summarised the main complications:

- Unlike other "products" buildings do not have an integrated manufacturing process. In many cases separate components are pre-manufactured and delivered to site for site assembly. In a few cases, (concrete floors for example) the raw materials are delivered to site and the manufacturing process is carried out in-situ.

- The life of a building is very long, typically 50 years (Aldaberth, 1997), but various components are either wholly or partially replaced during the life of the whole building. There is a relationship between the building components, which may not have reached the end of their service lives. An example of this would be wooden windows in a dwelling, if the window frame rots and requires replacement, the glass must also be removed. Although it is theoretically possible to replace the existing glass it is unlikely to occur in practice.

- The user demand and occupation patterns may change dramatically over the life of a building. Offices built in the 1900s and even the 1960s were not designed to cope with the high internal loads which result from the widespread use of the desktop computer. Any energy balance of a building product must take into account that this element is likely to change significantly during the building lifetime.

Due to the uncertainties involved in the setting of scope and system boundaries a sensitivity analysis was carried out to the impact of various system boundaries. The summary results of this analysis are presented in graph. The Y axis shows Eco-99 Pts and the X axis shows the various permutations which were investigated. . The results of the sensitivity analysis (see Figure C11) were used to define the final system boundaries and assumptions for this study and these are discussed in detail below.

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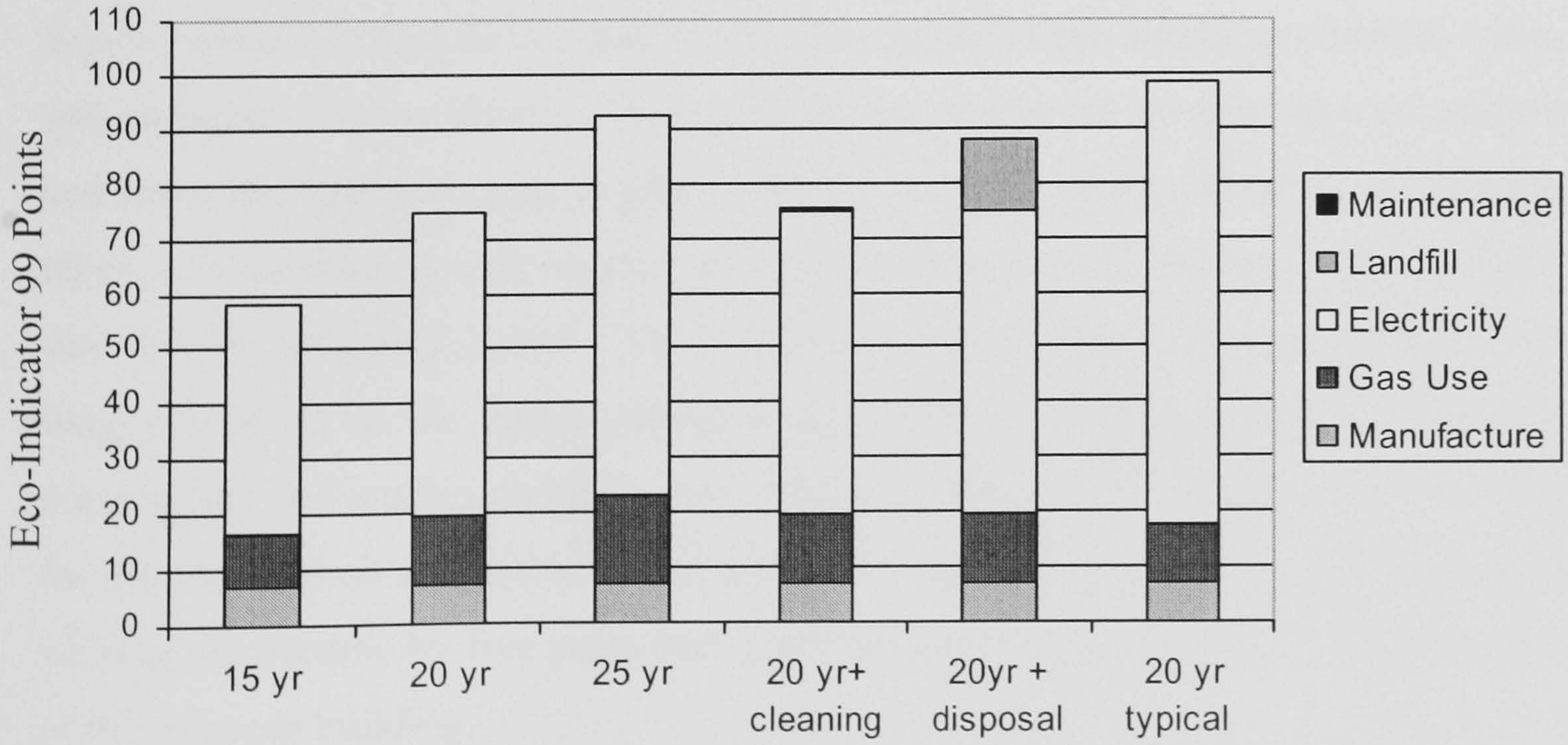


Figure C11 Result of sensitivity analysis into LCA boundaries.

Materials and Production

The materials and production phase of the lifecycle of a façade component are represented by the manufacture subsystem of the LCA. The energy used to produce the materials and the subsequent manufacturing process used to convert these materials into façade elements is included; however, the indirect inputs to the factory, i.e. energy used for factory buildings, lighting and heating of factory buildings, have been excluded. The material's quantities for the façade components are based on the façade component descriptions in Table C3 section C2.2, of the portfolio. A detailed description of the materials and processes involved in each component manufacture is included in Appendix C3.

Service life

Estimating the service life of cladding elements is imprecise. For reasons which have already been mentioned the theoretical service life of materials and components may differ widely from the actual service life. Hence, the approach taken in the study towards the service life of a façade must be clarified. This study has chosen to investigate a fixed life of the façade unit, with no further replacement or refurbishment. The length of this lifetime has been determined by the elements which will require replacement and refurbishment first. Thus, it has been assumed that (with the exception of the masonry façade) when one façade element needs to be replaced the whole structure is removed and replaced. For example it is very difficult to remove the glazing from a curtain wall and leave the spandrel panel in place. Hence, a façade element lifetime of 20 years is taken. It is assumed that the façade elements are disposed of at the end of this period, but this will be discussed further. The selection of this lifetime is a compromise of the longevity of all of the façade elements and is based on data from manufacturers of components and studies carried out by CIRIA (CIRIA, 1992a). The impact of varying the façade lifetime was tested in the sensitivity analysis, FigureC11. This showed that varying the lifetime by five years had a smaller impact than varying the energy practice of the example building.

Transport

Transport for construction elements is very variable and in order to show that the weight of the façade elements has an effect on the environmental impact of transport to site a nominal journey of 100km has been assumed. It has been assumed for the purpose of simplicity that once the façade elements have arrived on site they are immediately installed onto the main structure.

In Use Phase

The "in use phase" of a life cycle analysis study usually comprises of those flows which occur after the commissioning of a building and before the deconstruction and disposal. This would typically include energy consumption and maintenance of the building.

The values for the energy consumption used in this study have been gained from the literature review as shown in Table C4, section C2.4, and the results from the thermal analysis in the test rooms. The energy consumed during the lifetime of the product is presented per square metre of façade based on the test room over one typical year. It is important to note that different ventilation and heating systems would require different amounts of plant. Additional environmental loads for these plant have not been included in this LCA. This is because several types of plant are capable of satisfying the heating and cooling energy demand calculated during the dynamic thermal analysis. The impact of various types of plant on the overall energy analysis would be interesting data to accumulate in further work into this area.

The inclusion of a maintenance regime, which included by repair replacement and cleaning of façade elements, was investigated during the sensitivity analysis. Repair and replacement with regard to the façade is mainly driven by failure of façade elements. Hence, the most frequent maintenance activities carried out are cleaning of the façade and replacement of glazing elements due to breakage. Two levels of maintenance were investigated;

- Frequent maintenance was based on the replacement of 10% façade elements over the lifetime of the façade and cleaning once a month.

- Typical maintenance was based on the replacement of 5% of the façade elements over the lifetime of the façade and cleaning once every three months.

The environmental analysis model was relatively insensitive to inclusion of a maintenance phase, as shown in Figure C11.

Disposal and End of Life

"End of life" model for these façade elements make the assumption that the materials are separated and sent to landfill on removal from the structure. In construction industry certain materials have a history of being removed from the waste stream and recycled, (lead from roofs for example). However, this does not always occur and is not typical of all materials; the reduced recycling of construction materials is partially due to low prices for scrap and low demands from raw materials production industries and the low cost of landfill for construction waste. The low demand for construction scrap is often due to the quality of the materials being reduced by the contamination of the other materials during use. Materials which could be recycled from the construction process are combined with other materials for a long period of time and would require a large investment of time to accurately separate them, (aluminium spacer bars for example). The large elements involved in façade construction which could be recycled are contaminated other construction materials and hence are sent directly into the waste stream e.g. glazing is often contaminated by silicon from seals and gaskets and aluminium from spacer bars. There has been a push to facilitate recycling in construction and this has led to macro separation, i.e. separation of concrete elements from glass and steel. In the future the recycling of façade elements may become more profitable and hence more widely used. The effects of materials recycling on the environmental impact of construction is an interesting area for further research.

This chapter described the relevant parameters or the building models. The following chapter discusses the selection of the three simulation models used to derive the tool's database.

CHAPTER C3 SELECTION OF SIMULATION TOOLS

This chapter discusses the choice of a Dynamic Thermal Modelling software (DTM), a Lighting simulation software and an LCA software. The selection methods are described and any validations which have been carried out are discussed to give an indication of the accuracy of the results which were gained from these tools.

C3.1 TAS DEVELOPED BY EDSL

A-TAS is a dynamic simulation model based on the ASHRAE Response Factor Method. This software solves for conduction, convection, advection, long-wave radiation, short-wave radiation and casual gains to provide a zone heat balance, and calculate sensible loads. TAS solves the heat balance equation as described in Appendix C1. using the response factor method (Mitalas, 1971, Stephenson, 1967).

Response factor method models the transient conduction, this is complicated by the fact that the conduction series varies both time and space. The Laplace method is used to transform the problem into a different and imaginary time domain in imaginary space, where the equation can be solved using algebraic methods then the Laplace transform is inverted to obtain the solution in the original time domain. The Eigenvalue approach (Gough, 1982) is used to speed up this process by increasing the efficiency of the algorithm and reducing computing time

Both the response and the response factor are dependent on the thermo-physical properties and design parameters of the system. Hence, these only need to be calculated once for each system this reduces the computational memory and time required to complete the analysis. The thermo-physical behaviour is characterised using Unit Response Functions (URFs) which are dependent on external factors such as :

- External radiation.
- Dry bulb temperature.
- Sky long wave radiation.

And the response required

Cooling loads etc.

The response to a unit of excitation is the product of the response factors at that time and the unit excitation at that time.

. There are four steps involved (EDSL 1999):

1. Identify the thermal capacitance and resistance of each layer in of the external walls.
2. Represent the thermal characteristics of each layer of the wall as a transmission matrix in the Laplace Transform domain and obtain the transmission of the building component as a whole as the product of the layer transmission matrices.
3. Identify the eigenvalues of the system, these are the values of the Laplace Transform variable at which a particular matrix element becomes zero. The eigenvalues, S_n are always real and negative and form an infinite series. The series is truncated $n = N$, where N is chosen in accordance with the following criterion which ensures that the truncation of the eigenvalue series does not lead to errors greater than interpolation errors arising from the use of an infinite time-step:

   $$-S_{n+1}\Delta > 1.6 \qquad \text{(C- 1)}$$

   Where

   Δ is time step (1 hour)

   N is 0 for lightweight constructions and maybe as large as 12 for heavyweight constructions such as ground floors.
4. Using the eigenvalues and certain other constants derived from the transmission matrix, the constants for the use in the calculation procedure are calculated. The constants h_n have a simple relationship to the eigenvalues:

   $$\eta_n \exp(S_n\Delta) \quad (n = 1,2,....N) \qquad \text{(C- 2)}$$

where:

S_n are the eigenvalues

Δ is the time step

For massless components (a class in which TAS includes all transparent components including areas of glazing) the method is greatly simplified. N is zero and the response factors are given by:

$$X^0 = Y^0 = Z^0 = G \quad \text{(C- 3)}$$

$$X^1 = Y^1 = Z^1 = G \quad \text{(C- 4)}$$

where:

$G =$ Steady state conductance of the component (W/m^2/K)

$X, Y, Z =$ Response factors

G is the steady state conductance of the component (W/m^2/K), as measured between its surfaces (not to be confused with U-value, which incorporates radiative/convective surface resistances).

For lightweight but not completely massless elements, N may be zero but the response factors X^1, Y^1, Z^1 retain small values. The presence of these response factors ensures that thermal mass is not neglected in cases where a significant amount of mass is present in lightweight components of large volume.

The conduction heat flows into the surfaces of the component $q^{cond,int}$ and $q^{cond,ext}$, are calculated by multiplying the surface fluxes by the component area, which is the mean of the internal and external surface areas provided by 3D-TAS. Thus:

$$q^{cond,\text{int}} = AW^{cond,\text{int}} \quad \text{(C- 5)}$$

$$= A\left(X^0 T^{\text{int}} - X^1 \left\langle T^{\text{int}} \right\rangle - Y^0 T^{ext} - Y^1 \left\langle T^{ext} \right\rangle + \sum_{n=1}^{N} V_n^{\text{int}}\, v_n \right) \qquad \text{(C- 6)}$$

$$= AX^0\, T^{\text{int}} - AY^0 T^{ext} + q^{hst\_cond,\text{int}} \qquad \text{(C- 7)}$$

where:

$W^{cond,int}$ = Internal surface condition heat flux

T^{int} = Internal surface temperature

T^{ext} = External surface temperature

v = coordinate variables which describe he thermal state of the wall.

V = dimensionless constant which characterise the relationship between fluxes and normal c-ordinate variables

$q^{hst\_cond,\text{int}}$ is the sum of all the historical terms in equation C-7 ; these terms can all be evaluated from results from previous time-steps.

Similarly:

$$q^{cond,ext} = AW^{cond,ext} \qquad \text{(C- 8)}$$

$$= AZ^0 T^{ext} - \quad AY^0\, T^{\text{int}} + q^{hist\_cond,ext} \qquad \text{(C- 9)}$$

Model Validity

The ability of a model to predict accurately the energy consumption and internal conditions in a given building is very hard to measure. This is exacerbated by the fact that it is likely that a user error will have a greater impact on the accuracy of results than the inbuilt errors in the model's algorithms (Bloomfield 1986). Studies have shown that intra-model comparison, where more than one user is asked to perform the same task, can show a much wider variance than inter-model comparisons with a single user.

However, a validation exercise was carried out by an international research group on behalf of the International Energy Agency (IEA) as part of the Annex 21/Task group 12. These activities produced a set of Building Energy Simulation Tests (BESTEST) which could be applied to any model in order to validate the accuracy of the predictions. A set of controlled comparison and validation studies was carried out (Judkoff, 1985), which concentrated on DTMs which were widely used in the US. A similar study was carried out in the UK which compared the accuracy of predictions of 17 DTMs from Europe, America and Australia (Lomas et al, 1997) with measured results from a selection of test cells.

This study compared 17 different models, which were modelled using four different sets of modellers, the resulting 25 program/user combinations were compared against each other and results taken from a test cell. The test cells had either a single-glazed, double-glazed south facing window or, no window at all. The rooms were both heated and unheated. The use of several teams of expert modellers with standardised data was meant to reduce the differences in the predictions to those due to the inherent differences in the models rather than user variability.

The work carried out by Lomas (1997) showed that there was a large variation in the ability of a model to predict energy consumption with a variation of ± 20% of the mean of all 25 results, and a variance of up to 30% from the measured value. Similarly the prediction of the internal temperature in the test cells varied widely, in the glazed rooms the predicted peak air temperatures varied by 11°C, from 3°C to 14°C above the set point. Some models consistently under or over the predicted results, while results which lay further from the average result were not necessarily more or less accurate. A selection of results are shown, the results from TAS are highlighted. Table C-4 shows the summary results from five of the DTMs which were employed in the study. The energy consumption *E* was measured in MJ and all temperatures were measured in °C. The results from each tool are shown along with the average of all the tools included in the study and an indication of the spread of those results. The measured value is presented as is the lower and upper uncertainty bounds:

Table C5 Summary of predictions from five DTMs and their variability in the heated period.

Heated October Period										
	Double glazed			Single Glazed			Opaque			Sfvr
Program	E	T_{max}	T_{min}	E	T_{max}	T_{min}	E	T_{max}	T_{min}	
TAS v 7.54	**83.3**	**35.5**	**10.8**	**97.7**	**35.6**	**7.1**	**109.4**	**30.0**	**12.9**	**80.9**
APACHE v 6.5.2	86.1	36.3	12.6	102.1	35.4	10.3	118.6	30.1	14.8	76.0
TRNSYS v 13	66.6	36.1	11.6	78.2	36.6	8.7	93.4	30.0	12.9	82.4
SERI-RES v 1.2	82.2	36.8	11.1	95.7	36.1	8.9	103.8	30.0	13.2	73.5
ESP-R v 7.7	69.5	40.3	12.4	78.5	39.9	10.7	100.3	30.3	12.8	77.7
Average Prediction (of 25)	74.6	38.0	11.6	87.6	37.4	9.5	102.4	29.6	12.2	76.2
Range in Predictions	38.9	10.5	4.7	44.6	10.9	5.2	40.8	0.6	4.2	17.7
Measured value	89.3	37.8	11.9	-	-	-	117.1	29.8	14.6	81.1
Upper uncertainty bound	92.7	40.5	13.9	-	-	-	122.3	30.2	16.4	85.5
Lower uncertainty bound	78.1	36,5	11.5	-	-	-	105.3	29.4	14.0	76.7

Table C6 Summary of Predictions from five DTMs and their variability in the cooling period.

Free Floating May Period							
	Double Glazed		Single Glazed		Opaque		Sfvr
Program	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	
TAS v 7.54	**28.5**	**11.6**	**30.4**	**11.0**	**16.1**	**8.3**	**79.6**
APACHE v 6.5.2	26.9	12.1	27.5	11.0	15.8	8.9	79.1
TRNSYS v 13	29.1	12.3	30.2	10.8	16.8	9.7	78.5
SERI-RES v 1.2	28.9	11.8	29.5	10.6	16.7	9.2	77.6
ESP-R v 7.7	28.9	11.7	29.5	10.8	15.4	7.9	78.7
Average Prediction (of 25)	29.6	12.2	30.1	10.8	16.6	9.1	80.0
Range in Predictions	8.6	2.8	7.9	2.6	3.2	2.6	7.2
Measured value	31.0	12.2	32.6	12.1	16.8	9.2	82.8
Upper uncertainty bound	33.4	13.6	35.0	13.6	17.5	10.0	88.8
Lower uncertainty bound	29.6	11.6	31.2	11.6	15.7	8.6	76.8

The estimation of internal temperatures in a free floating box is one of the simplest tests for a DTM. This test is designed to show any anomalies in the dynamic thermal algorithm. The DTMs in this study predicted results consistently below the measured internal temperature in the physical model. All of the models predicted that the change from single to double glazing resulted in a reduction in the maximum temperature.

In this study none of the tools produced results within the error bands for all of the twelve measures. TAS is within the uncertainty bounds in five out of the twelve measures. The developers of TAS (EDSL) suggested that the consistently low estimation of internal temperatures was due to an under estimation of long wave radiation. The sky radiation model has been refined in the subsequent versions of TAS released. The release of the software used in the Lomas (1997) study was version 7.54. This study has utilised version 8.31 and 8.4.

C3.3 LIGHTING ANALYSIS TOOLS

This section describes the lighting model used for this study. theory used when modelling lighting and the selection of a lighting simulation tools, which have been used to provide a lighting assessment.

The development of lighting-analysis tools has lagged behind that of thermal analysis (Littlefair, 1992) in various respects. Littlefair (1992) sees the failure to place a high level of importance on reducing the use of electric lighting as a major omission when lighting can be responsible for 14.9% of energy usage in commercial office buildings (DTI, 1997). Littlefair (1992) argues that there will be greater focus on lighting as the other low-energy methods are implemented and eventually decrease the heating and cooling loads in non-domestic buildings. Artificial lighting use has a two-fold effect on the energy consumption of a building:

- As a consumer of electricity
- The additional internal heat loads generated from lighting, which in turn effects the thermal conditions inside the building and energy consumption.

In order to provide accurate daylighting information the sky illuminance, direct, diffuse and reflected radiation and the geometry of the office need to be considered. This data can be usefully calculated for a detailed design, but it is so case specific that it is of little use at the scheme design phase.

There is a difficulty when trying to combine dynamic thermal modelling (DTM) with lighting analysis; DTM is based on an hourly time step whereas due to the nature of daylight and weather conditions accurate calculations of lighting energy must be based on a much shorter time step (Littlefair,1992). This has led to the use of representative skies in order to provide a guide to daylight availability for use in lighting assessments.

Daylight availability is often regarded as an indication of the quality of light in a space. Daylight availability can be calculated in a number of ways, one of the most widely used methods is the average daylight factor. Lynes (1990) argues convincingly that average daylight factor is a good basic guide for the effectiveness of a façade in reducing the artificial lighting costs. However, a room with a high average daylight factor and a low uniformity will still result in an inadequate lighting solution. Hence, daylight distribution diagrams provide a daylight factor profile and this will allow the user of the façade tool to gauge the uniformity of the light provided.

Two different measures of daylight distribution have been used in the façade selection tool. The first is based on a standard sky and provides indicative daylight factors to describe the room. The second is based on a real sky distribution model at two different times of the year, to give a more accurate pattern of skylight distribution.

For the purpose of standard calculations the Commission Internationale de l'Eclairage (CIE) overcast sky daylight factor method has been used. The CIE sky is brightest at its zenith with approximately one third of the luminance at the horizon:

$$L_\beta = L_z(1 + 2\sin\beta)/3 \qquad \text{(C-10)}$$

where:

L_β is the luminance of the sky at an elevation of β above the horizontal in cd m^{-2}

L_z the luminance of the sky at the zenith.

In reality the luminance distribution is constantly changing due to cloud and sun movement (Tragenza, 1983). The use of this method, while it is not the most accurate for predicting real skies (Littlefair, 1992), provides a standard description of the daylight distribution within a particular space. This standard description can be compared objectively and used to make a quantative assessment of light availability. A combination of Average Daylight Factor (ADF) and distribution of daylight diagrams were used in this study to assess the lighting levels provided by the façade and the energy savings that can be made using a controlled lighting scheme.

The user interface should be easy to use, and should preferably be a Windows-based graphical interface. Lighting tools tend to require a conflation of several tools which combine a modelling element with a photometric rendering element. If possible these two parts of the tool should be integrated for ease of use. The ability to import a 3D model from previously used software, such as AutoCAD would be a useful feature.

The performance of a lighting rendering package can be considered in terms of its ability to render accurately spectral photometry. Photometric accuracy is important when the tool is being used to measure lighting levels. If the images are required the quality of visual output should be taken into consideration. Two models *ADELINE* and *Lightscape* were considered. These have similar capabilities although they are based on different global illumination algorithms. *ADELINE* requires a more complex geometry definition. *Lightscape* by Autodesk was eventually chosen as it has a model exchange capability with *Tas* which was the tool selected for the thermal simulation.

Lightscape was one of the first software tools to integrate both ray tracing and radiosity. The radiosity solution in Lightscape uses the "progressive" radiosity solution which provides an incremental solution at each step, which requires form factors from one surface to all others. This has the advantage of allowing the user to witness the test as it is carried out. Thus obvious errors can be rectified "in progress". Lightscape shows a high correlation with the Microstation and RadioRay models.

Model Validity

It is very difficult to validate models against natural conditions, because of the variability of the external weather conditions. The lack of research into lighting analysis tools has meant that there are several studies into the efficiency of lighting tools, but these have not been carried out with the rigour of the investigations of thermal analysis tools. Lighting analysis tools are sometimes used in architectural practices and universities, but the long established practice has been to use the BRE Daylight Protractor (BRE, 1989) or physical modelling in a heliodome or under an artificial sky.

Several validation exercises have been carried out to assess the accuracy of lighting simulation tools (Bennsasson 1978, Close 1996, Galasiu 1998). These studies aimed to correlate the lighting analysis of a scale model or physical measurements with the results gained from a computer simulation of the lighting environment. The Bensasson (1978) study was carried out before the widespread introduction of the Windows operating system and the majority of the models which were tested are no longer available. The study carried out by Close (1996) suffers in that it is both out of date and limited in scope, making only cursory remarks rather than measured comparisons between software types. The International Energy Agency (IEA) sponsored a research project to evaluate the use of daylighting in buildings (Annex 29), part of this research project (Subtask C) assessed the application of computer modelling to daylight in buildings. This study concluded that computer-based tools could provide accurate daylighting level assessments. However, the study focused on a single rendering package (Galasiu, 1998), ADELINE the Radiance based model.

One of the most comprehensive comparisons of lighting simulation software was carried out by the Martin school of Architecture at Cambridge University (Ashmore, 2001). The survey examined commercially available rendering packages which operate in a Windows environment. Lightscape, which utilises the radiosity method and ADELINE, based on Radiance, which uses a combination of deterministic and stochastic ray tracing techniques. The models were compared with the results from physical measurements from a fixed-scale model under both a mirror sky and an artificial sky.

All of the models were used to measure the light levels in a space with a single opening under the CIE overcast sky model for the UK. There was a high correlation between the mirror sky and the artificial sky (0.994). However, the computer-based daylighting models consistently under estimated the daylight levels in the test room. The percentage differences between the physical and computer models increased as the distance from the window wall increases. However, the computer simulations were found to correlate reasonably well with the results predicted by the physical model in the artificial sky at UCL, see Table C7. While the study concludes that the numerical results were useful enough to be used in daylighting design, the large experimental error in the study, approximately 20%, makes it difficult to say whether the difference between measured and simulated daylight factors is significant.

Table C7 Simple coefficients of determination (r^2) between different modelling techniques for daylight factors recorded across a working plane.

		Mirror Sky	ADELINE	Lightscape
X	UCL Sky	0.99	0.98	0.96
	Mirror Sky		0.99	0.97
	ADELINE			0.99
	Lightscape			

C3.4 LIFE CYCLE ANALYSIS MODEL

This section describes the selection of Life Cycle Analysis (LCA) tool to analyse the environmental impacts of the façade selections available in the Façade Selection Tool. The use of LCA in construction as a method of describing the environmental impact of construction methods and processes has been discussed in Part B1.1.

The LCA techniques employed in this study utilise a similar methodology and the application of an accounting based LCA tool. However, this study has used an additional tool Sima Pro (PRé). The tool (*Team*), whose use was described in Part B of the portfolio, was unavailable for use during this study. During the course of this work the software manufacturer Ecobilan was purchased by PriceWaterhouseCoopers, a consulting company, this company then proceeded to restrict access to the software for academic organisations.

The same LCA tool selection method was applied, as described in Part B of this portfolio, to the available software tools and SimaPro, developed by PRé Consultants was selected. Sima Pro V.5 has been developed to support the ISO standard 14040. Separate phases for goal, scope, inventory and impact assessment have been included for transparency. The inventory and impact assessment phases can be integrated for speed when the same calculations are applied repeatedly. Sima Pro has an integrated Data Quality Indicator (DQI) which allows the user to define an acceptable range of data quality to be applied to all of the data imported for use in an LCA. The software accepts data based on the SPOLD format which enables data to be imported from a variety of sources and exported to various other types of software. This version of Sima Pro has an extensive internal database, with data from BUWAL, the Swiss Agency for the environment, forests and landscape, ETH-ESU, the Swiss federal Institute of Technology, and IDEMAT developed by Delft University as well as other industry sources. The database covers a wide range of industries from glass making to Energy and Plastics Processing.

CHAPTER C4 DESCRIPTION OF THE FAÇADE DESIGN TOOL

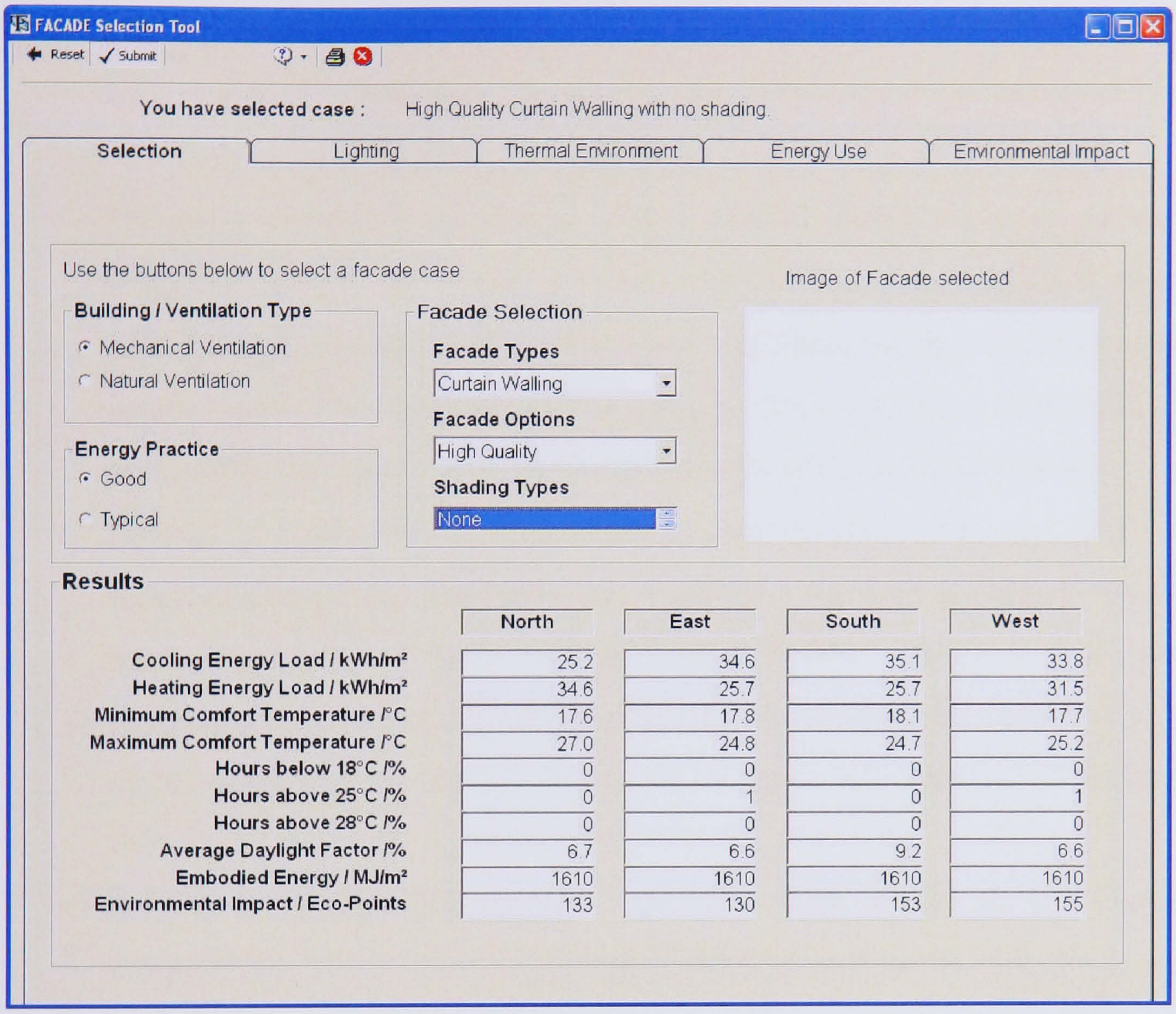
This chapter describes the façade selection tool in detail, listing the input and discussing the output parameters. The tool allows the user to access data collected about the environmental impacts and performance of the façade systems which have been under investigation.

The user interface of the tool was developed using Visual Basic 6.0 a programming language common to all Microsoft applications. Visual Basic allows the user to write, test and edit windows applications in a visual environment. Visual Basic has the advantages of a visual programming space and being an object-orientated programming language; which allows the user to write small programming modules which can be recalled with ease (Lomax, 1998).

As previously discussed the tool requires a small number of input parameters in order to provide access to the data from the parametric study. The input parameters were chosen to allow the user to select all of the cases with the minimum number of selection inputs, so that the data in the database would be easily accessible. The user is required to alter a set of default settings in order to access the first level of output:

- Building type / ventilation strategy
- Façade type
- Shading type
- Energy consumption of occupants.

The building type and ventilation strategy are linked and there is a selection of a low mass air-conditioned structure or a high mass, naturally-ventilated structure. The user has a choice of six façade types and there are four shading strategies which can be applied to the facades, although this is dependent on the compatibility of the façade type and the shading option. For example it is not possible to select an externally-ventilated, double-skinned façade and external horizontally-louvered shading as the façade system and ventilation method would clash. The final option to be selected is the energy strategy of the building users. A discussion of the selection of user input options and a more detailed description of the choices available is provided in Chapter C2.



You have selected case : High Quality Curtain Walling with no shading

Use the buttons below to select a facade case

Building / Ventilation Type
● Mechanical Ventilation
○ Natural Ventilation

Energy Practice
● Good
○ Typical

Facade Selection

Facade Types: Curtain Walling
Facade Options: High Quality
Shading Types: None

Results

	North	East	South	West
Cooling Energy Load / kWh/m^2	25.2	34.6	35.1	33.8
Heating Energy Load / kWh/m^2	34.6	25.7	25.7	31.5
Minimum Comfort Temperature /°C	17.6	17.8	18.1	17.7
Maximum Comfort Temperature /°C	27.0	24.8	24.7	25.2
Hours below 18°C /%	0	0	0	0
Hours above 25°C /%	0	1	0	1
Hours above 28°C /%	0	0	0	0
Average Daylight Factor /%	6.7	6.6	9.2	6.6
Embodied Energy / MJ/m^2	1610	1610	1610	1610
Environmental Impact / Eco-Points	133	130	153	155

Figure C12 Image of the initial screen of the Façade Selection Tool.

Two levels of information are contained within the output parameters. Key performance criteria have been chosen for the first level (Summary Results) while more detailed information is provided at a second level (Detailed Results). The following parameters can be assessed very quickly and they describe the performance of a specific façade type throughout a whole year. These appear in the first screen of the tool (see Figure C12).

C4.1 SUMMARY OUTPUT

- *Heating Energy Load.* This is the annual energy (normalised per m^2 floor area) required to maintain the set internal minimum air temperature during operation hours throughout the year.
- *Cooling Energy Load.* This is the annual energy (normalised per m^2 floor area) required to maintain the set internal maximum air temperature during operation hours throughout the year. It applies to a Type 2 office only.
- *Maximum comfort temperature.* This comfort index (average of surface weighted radiant and room air temperature) has been selected over air temperature because radiant temperature could play an important role in some façade types. For example, curtain wall facades can create a large cold or hot area within the space, which will significantly affect internal comfort.
- *Number of hours that maximum temperature exceeds 25°C and 28°C.* This index is particularly important for naturally-ventilated buildings for which recent research (CIBSE 1999b, Brager 2000) indicates that internal temperatures could be allowed to increase above 25°C for more than 5% of the working year and should not be greater than a maximum of 28°C for more than 1% of the year.
- *Minimum comfort temperature.* For a similar reason as for maximum temperatures, the comfort temperature index is used to describe the provision of minimum comfort conditions.
- *Daylight Levels.* An average daylight factor is provided which is calculated using algorithms set out in (CIBSE 1999d).
- *Embodied Energy.* The overall energy use of a building is likely to be a guide to its efficiency, but this must be traded off against the embodied energy (ee) in the building. The embodied energy of a building is a function of the materials used in its construction, and it gives some indication of a building's impact on the environment but it does not take into account the lifetime effects of the choices used (Amato *et al.* 1996). This is considered in the calculation of Eco-points.
- *Eco-points.* These are derived from the Eco Indicator method (Goedkoop *et al.* 2000) of environmental impact assessment and were developed using a attitude questionnaire, which attempted to assess the public attitude to

environmental harm. The advantages of this method are that it has been widely tested and it is respected internationally. The data collected has Europe-wide applicability, i.e. the data is normalised according to the environmental harm caused by one European citizen.

C4.3 DETAILED OUTPUT

More detailed information about the examined façade is provided as follows:

Thermal comfort. Average hourly comfort temperature and relative humidity can be assessed in a graphical form. There are two ways of investigating the internal temperatures in the tool ether by month and direction, or by season. If the *month* option is selected: a graph can be displayed which shows a week of data to represent the month of the year selected (see Figure C13); the average hourly values have been calculated by averaging the predicted temperature and humidity values for each hour of the day of the week over of the examined month. However, if investigation by *season* is selected, the values shown correspond to all four orientations for the extreme week selected to represent the season.

You have selected case : High Quality Curtain Walling with no shading

● View by Month
○ View by Season

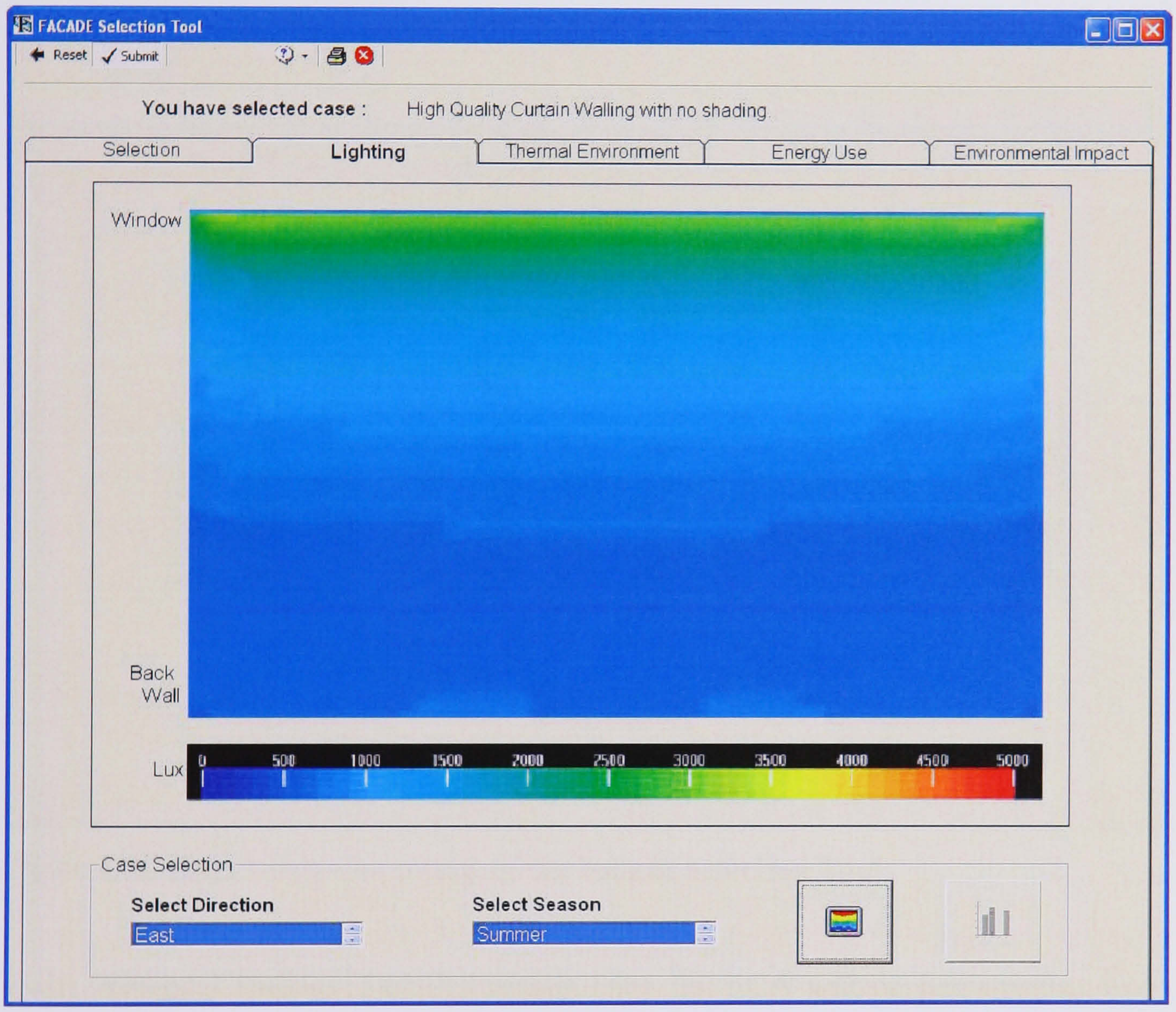
Select Direction: South

Select Month: March

Select Season: Summer

Figure C13 The thermal environment screen in the Façade Selection Tool.

Lighting. Daylight distribution diagrams are provided, see Figure C14, which represent average conditions using the CIE overcast sky (CIBSE 1999d). In addition, minimum and maximum availability daylight distribution diagrams are provided. These are calculated for overcast sky conditions on March 21st (azimuth of 40 with an average sky luminance of 20 klx) and clear sky conditions on June 22nd (azimuth of 60 with an average sky luminance of 35 klx) as suggested by the BRE (1986).



You have selected case : High Quality Curtain Walling with no shading

Select Direction East

Select Season Summer

Figure C14 The *Lighting* screen within the Façade Selection Tool.

Energy demand: The annual energy demand is displayed for each building orientation, see Figure C15. The totals are provided for each month of the year and energy demand is presented by category (showing heating, cooling, humidification, dehumidification and internal equipment and lighting).

You have selected case : High Quality Curtain Walling with no shading.

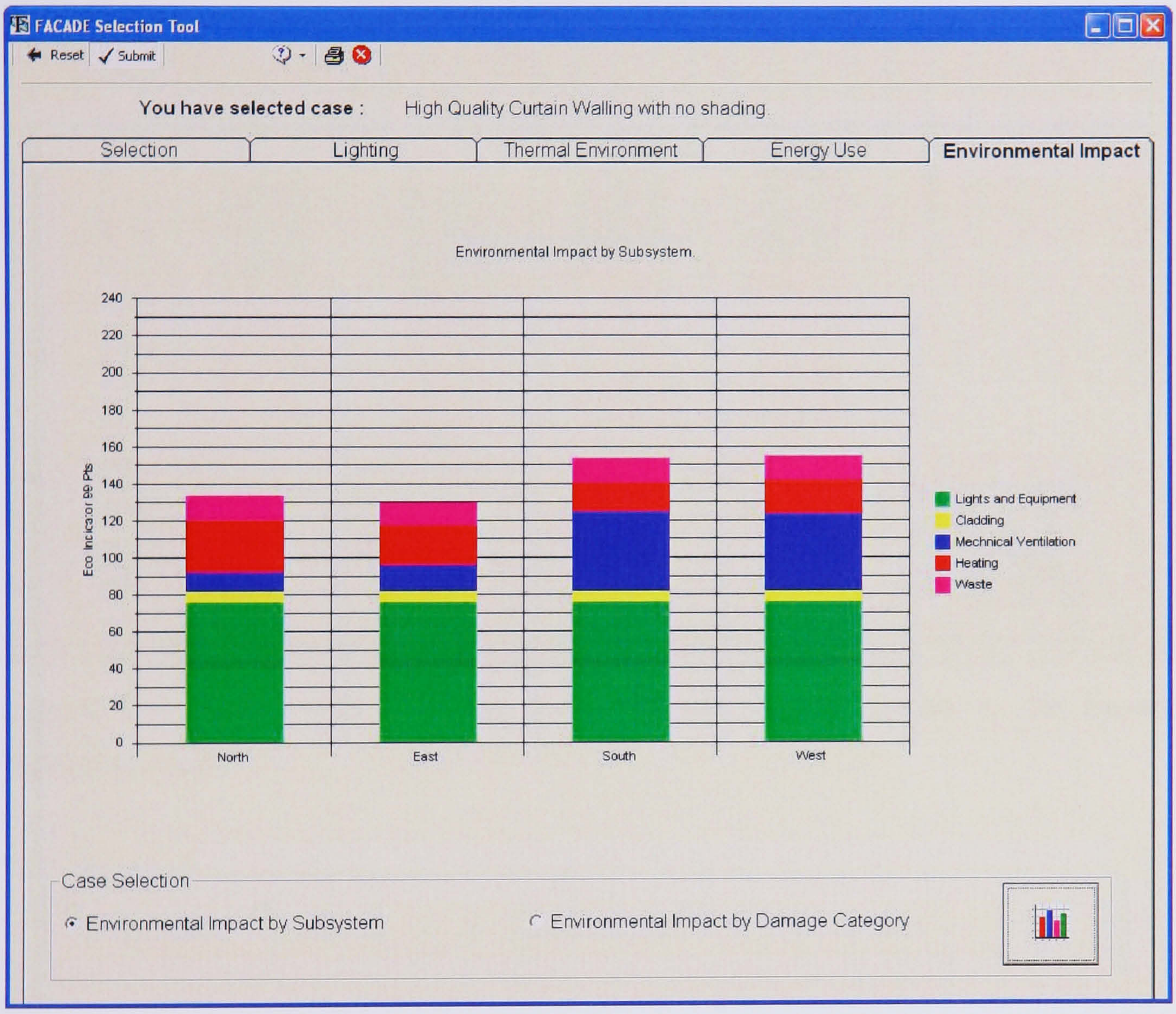
Select Direction: South

Figure C15 The *Energy Use* screen of the Façade Selection Tool.

Environmental Impact. Detailed results from the LCA will be presented as Eco-Indicator Points, see Figure C16. The environmental impact is displayed for each orientation of the building. There are two options, one in which the Eco-indicator Points illustrate the contribution of the sub-systems to the environmental impact of the whole LCA. These results are split up into the following three components

- Manufacture: which encompasses raw material production, façade element construction and pre-assembly phases.

- In use phase: which includes energy consumption during the lifetime of the façade element. This is shown as heating energy, cooling energy and energy used for equipment and lighting.
- Disposal : this shows the environmental impact associated with the disposal of the materials to landfill.



You have selected case : High Quality Curtain Walling with no shading

● Environmental Impact by Subsystem

○ Environmental Impact by Damage Category

Figure C16 Screen shot 1 of the *Environmental Impact* screen in the Façade Selection Tool.

The second option displays the same data as previously, but in this instance the environmental impacts are categorised by the sphere in which those impacts occur, see Figure C17. As previously discussed in section B2.3 the Eco-Indicator 99 method uses three categories to describe environmental impacts: Human health, Eco System Damage and Resource Depletion.

You have selected case:

High Quality Curtain Walling with no shading.

Case Selection

○ Environmental Impact by Subsystem ● Environmental Impact by Damage Category

Figure C17 Screen shot 2 of the *Environmental Impact* screen in the Façade Selection Tool.

C4.4 CASE STUDY 1

A case study is described in this section as a way to demonstrate the type of summary and detailed results that the tool can provide. The user is required to select initially two input parameters; building type and façade type. For this case study a type 2 office is selected with a highly-glazed curtain wall façade (0.85 glazing ratio) and an insulated spandrel panel. As mentioned before for each façade type, there are two options; a high quality system (HQS) and a standard system (SS). The HQS is selected for this case-study. A 'good practice' energy operation is also selected. Orientation is assumed south and no shading is provided.

Summary Output

After completing the input parameters, a summary output in the form of a table will appear. For the inputs specified above the summary output results are shown in Table C8.

Table C8 Summary output results for the examined case-study.

Cooling Energy Load / kWh/m^2	35.10
Heating Energy Load / kWh/m^2	25.70
Minimum Comfort Temperature / °C	18.10
Maximum Comfort Temperature / °C	24.70
Hours below 18 °C / % of year	0
Hours above 25 °C / % of year	0
Hours above 28 °C / % of year	0
Average Daylight Factor / %	7.3
Embodied Energy / MJ/m^2	1610
Environmental Impact/ Eco points	153

For the façade type, shading type, orientation and energy practice selected for the office building examined the annual cooling energy load is 35 kWh/m^2 while the annual heating load is approximately 26 kWh/m^2. This can be easily converted to energy consumption by making reasonable assumptions about the type of fuel and mechanical ventilation system used. For example if the heating system is assumed to have an efficiency of 75%, from delivered gas to supplied heat then the annual energy consumption for heating would be approximately 35 kWh/m^2 while for a cooling system with a coefficient of performance (COP) of 3, the annual energy consumption for cooling would be 11.5 kWh/m^2. This does not take into account the energy required by the distribution system and in the case of cooling the refrigeration plant itself. It is merely a direct conversion of demand to energy consumption to which an additional amount must be added depending on the building services systems employed in a building. The delivered fuel energy consumption can be then converted to carbon dioxide production on the basis of 0.2 kg CO_2/kWh for the use of gas, and 0.52 kg CO_2/kWh for the use of electricity (BRECSU, 1999). Therefore, for the case study examined here the CO_2 burden due to heating and cooling would be 6 kg CO_2/m^2/year. The overall environmental impact would be an embodied energy of 1610 MJ/m^2 and 153 eco-points per m^2.

For the case study discussed the summary output also indicates that the minimum comfort temperature is 18°C and the maximum comfort temperature is 24.7°C. The annual average daylight factor in the office is 7.3%.

Detailed output and further analysis of detailed results for the case study.

Data available in the detailed output can be interrogated by the user for specific information. As mentioned in the previous section, standard tabular and graphical data are available. An example is shown in Figures C18 to C23 which are discussed below.

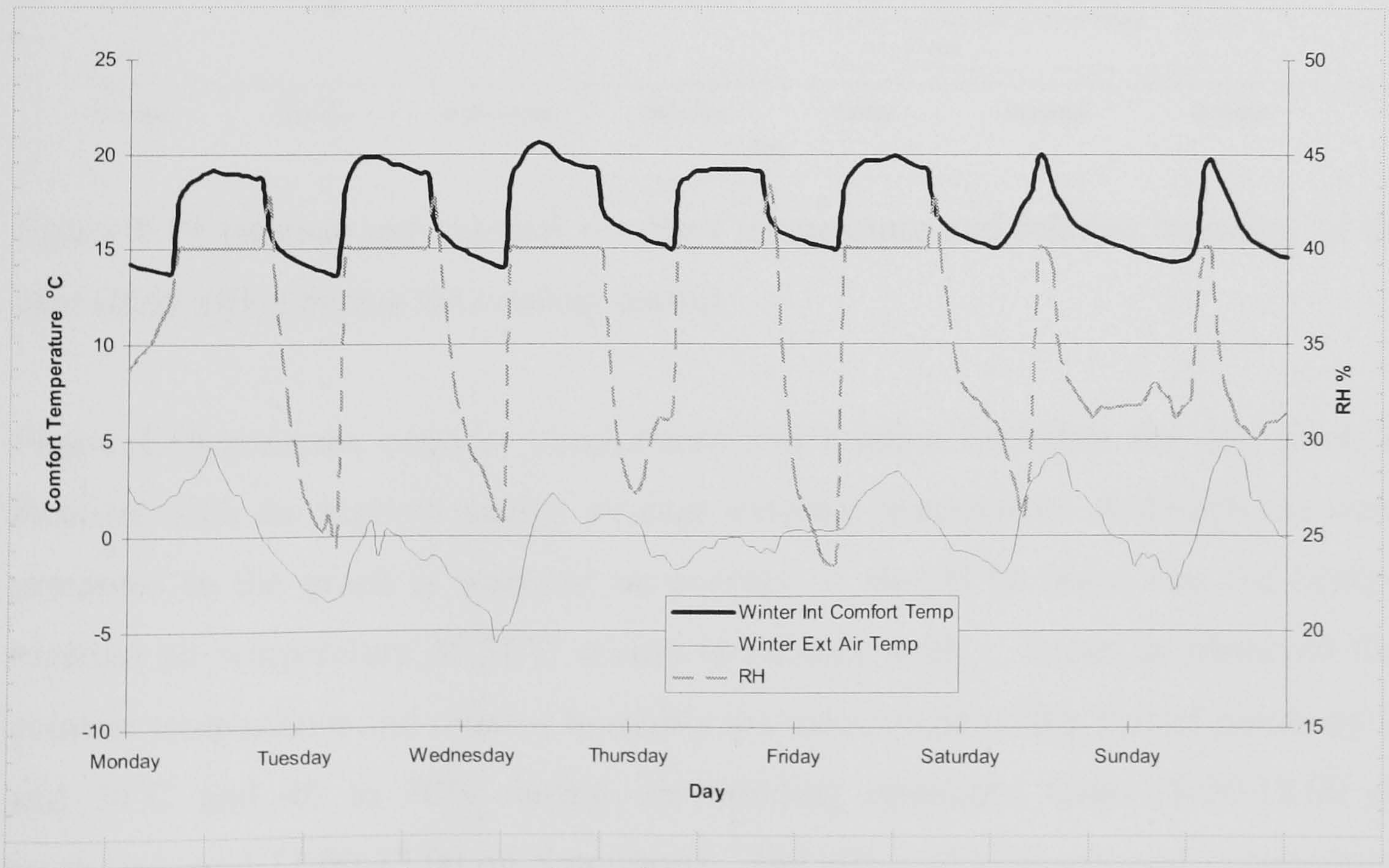


Figure C18 Internal and external resultant temperature and relative humidity of the case study office during the heating season.

Figure C18 presents comfort temperature and relative humidity for one week in winter with the lowest weekly average external temperature. It should be noted that similar weekly profiles are included in the tool for representative weeks for the 12 months of the year, in addition to the coldest and warmest week. It can be observed that comfort temperature and relative humidity are maintained within the set points of 18 and 24°C and 40 to 70% during the building operation times (8.00-18.00 on weekdays, and 11.00-13.00 on Saturdays). The effect of the solar gains can be also observed on Sunday for this south-orientated office. The effect of low external humidity can also be observed in the resulting relative humidity values during the night.

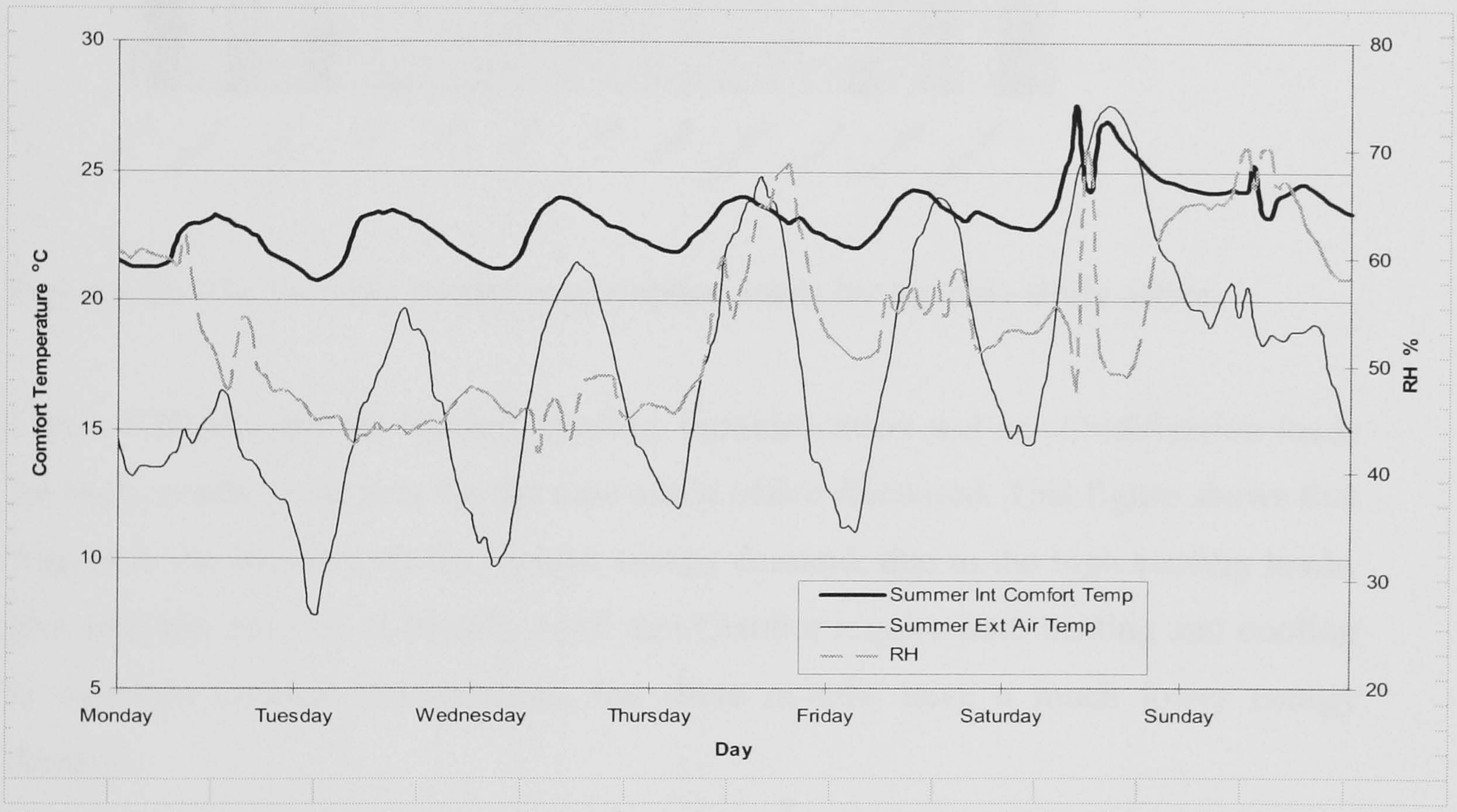


Figure C19 Internal and external resultant temperature and relative humidity of the case study office during the cooling season.

Figure C19 presents comfort temperature and relative humidity for one week in summer, with the highest weekly average external temperature. Although the week presented in the graph is warmest on average, it should be noted that the highest external air temperature of 31°C occurs in another week. It can be observed that comfort temperature and relative humidity are maintained within the set points of 18 and 24°C and 40 to 70% during the building operation times (8.00-18.00 on weekdays, and 11.00-13.00 on Saturdays). The effect of high external temperatures and solar gains on the internal comfort temperatures can be also observed on Saturday and Sunday for this south-orientated office.

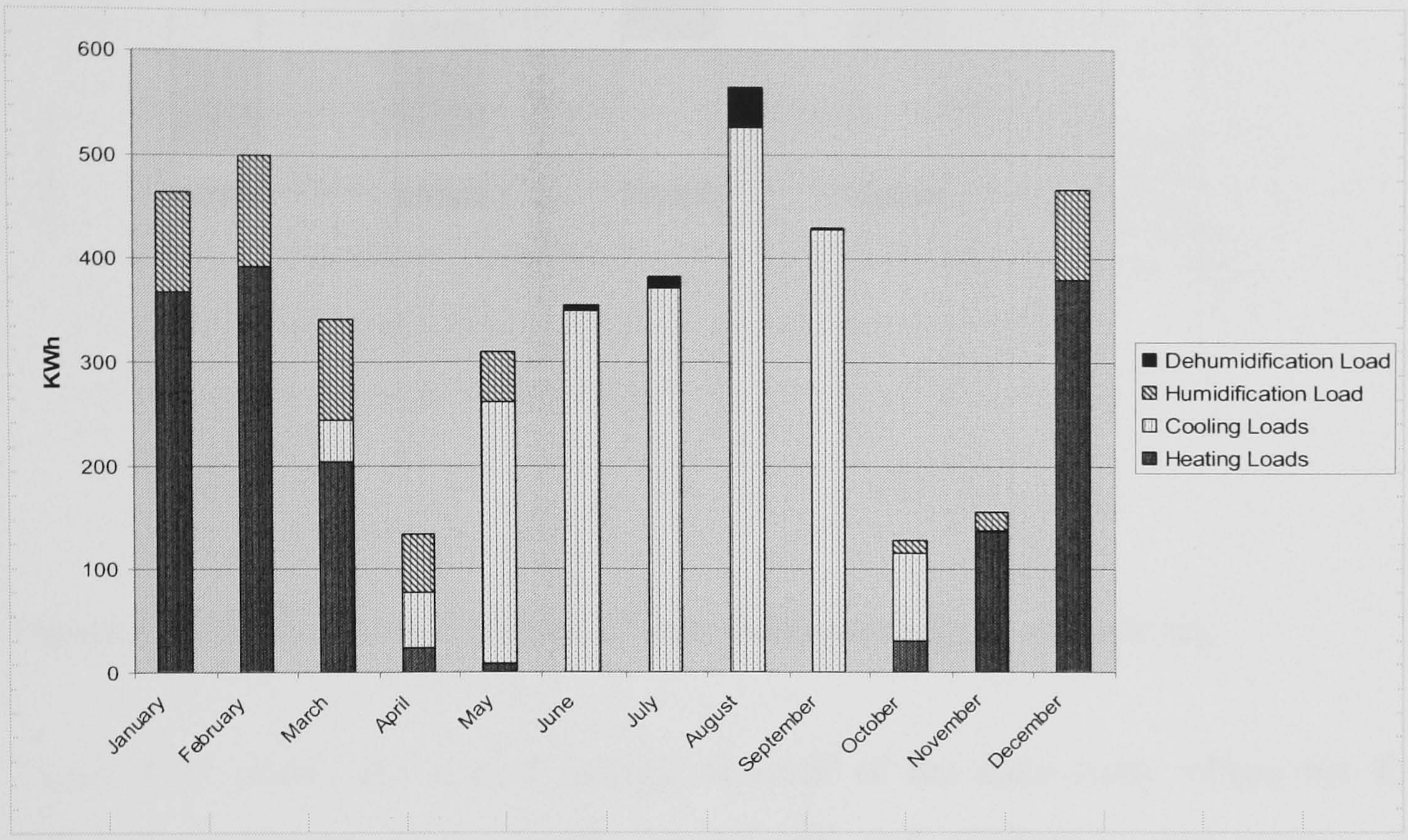


Figure C20 The monthly energy consumption loads for the case study office.

Figure C20 presents the heating, cooling, humidification and dehumidification loads for each month of the year for the case-study office discussed. This figure shows that August is the month with the highest energy demand, due to the high cooling loads. The shoulder months of March, April and October require both heating and cooling to maintain comfort temperatures, but these months have a much lower energy demand.

Daylighting levels are provided within the tool in the form of daylight factors and lighting contours for the two months under study. This case study has a daylight factor of between 6.2% and 9.2% depending on the orientation of the façade and season.

The environmental impact score of this case is 142.8 points ± 9% .There is a large variation with orientation, as shown in Figure C21. This shows that the higher energy consumption of the south and west facades, 7% and 8.5% above the average respectively, results in a higher environmental impact for this façade type in those orientations.

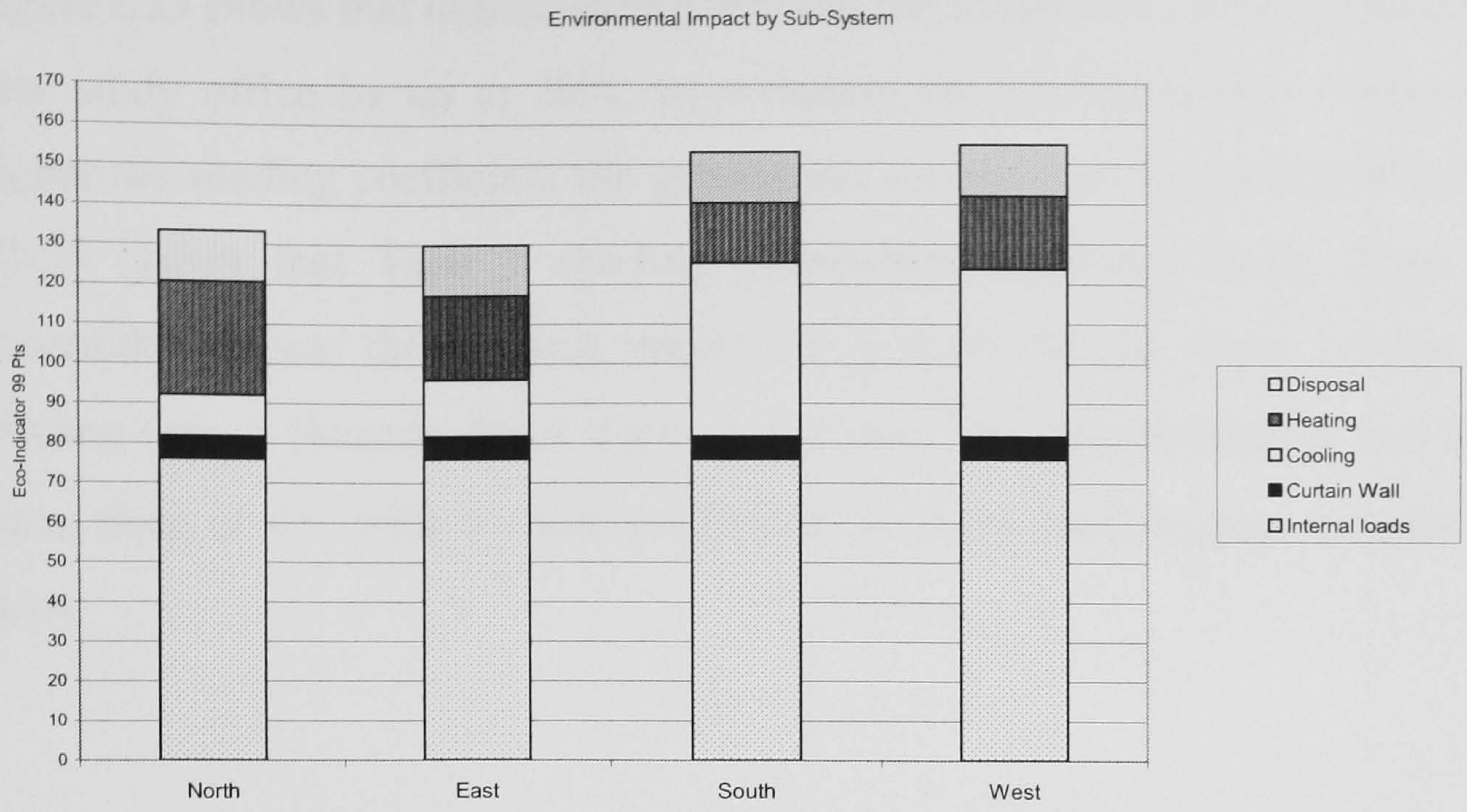


Figure C21 Environmental Impact of case study building by sub system.

Figure C22 shows the annual energy demand of the case study office for four different orientations of the façade for the high and standard quality systems and changes in the energy practice of the occupants, from typical to good. This graph shows that while changes in the façade have the largest impact, the energy practice is particularly important with regard to a south-facing façade rather than any other orientation.

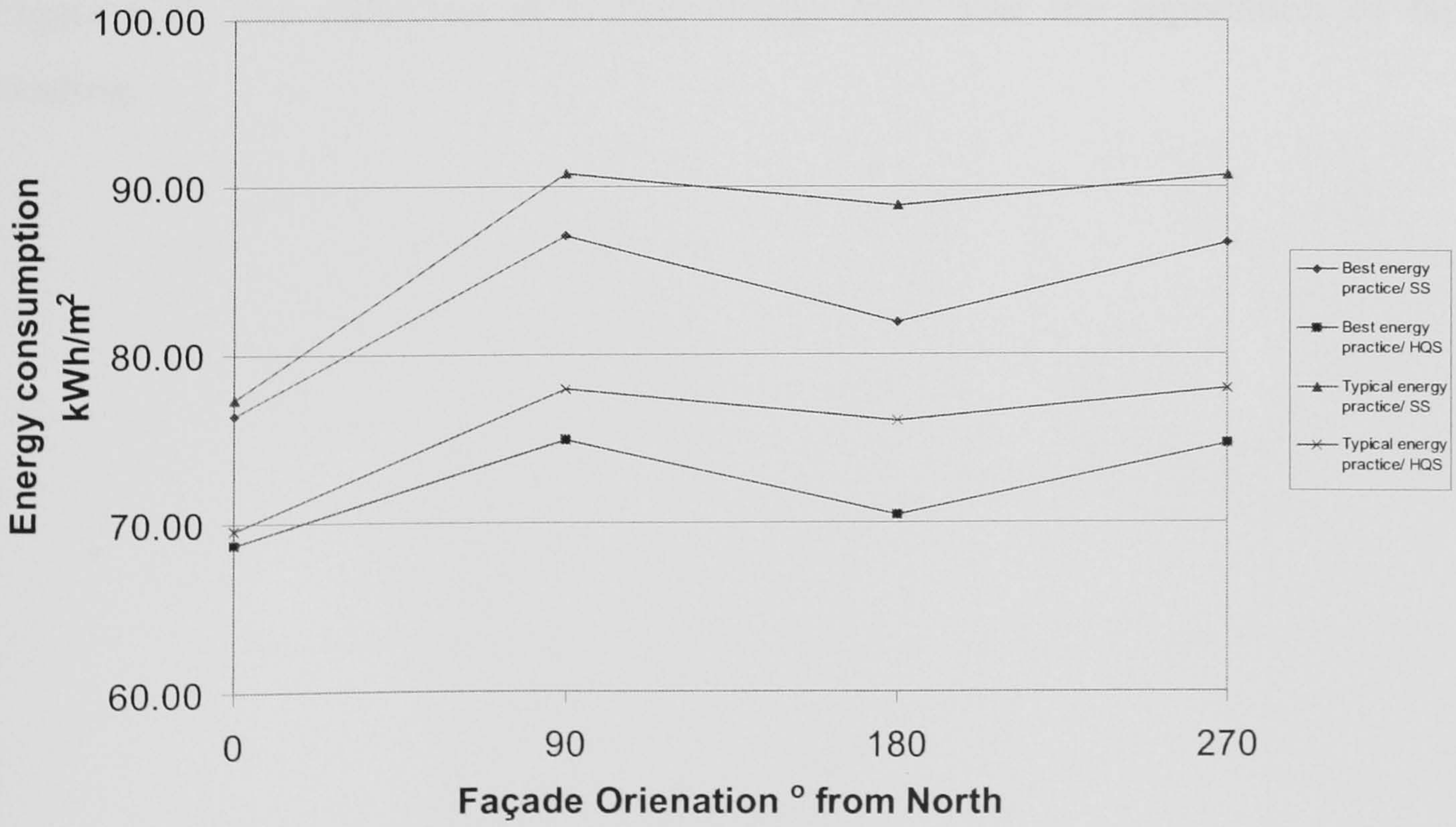


Figure C22 The annual energy demand for the case study office.

Figure C23 shows that implementing shading can reduce the energy consumed by the case study office by up to 20%, by reducing the cooling energy consumed. The higher the shading coefficient the greater the savings which can be realised. Figure P3-24 shows that Type 1 shading (horizontal overhang 75cm deep with 0% transmittance) has the greatest impact on a south façade while louvers, such as shading type 2 (louvres 40cm deep at 45° with 50% transmittance) and 3 (louvres 10cm deep at 45° with 0% transmittance), have the most impact on east and west faces.

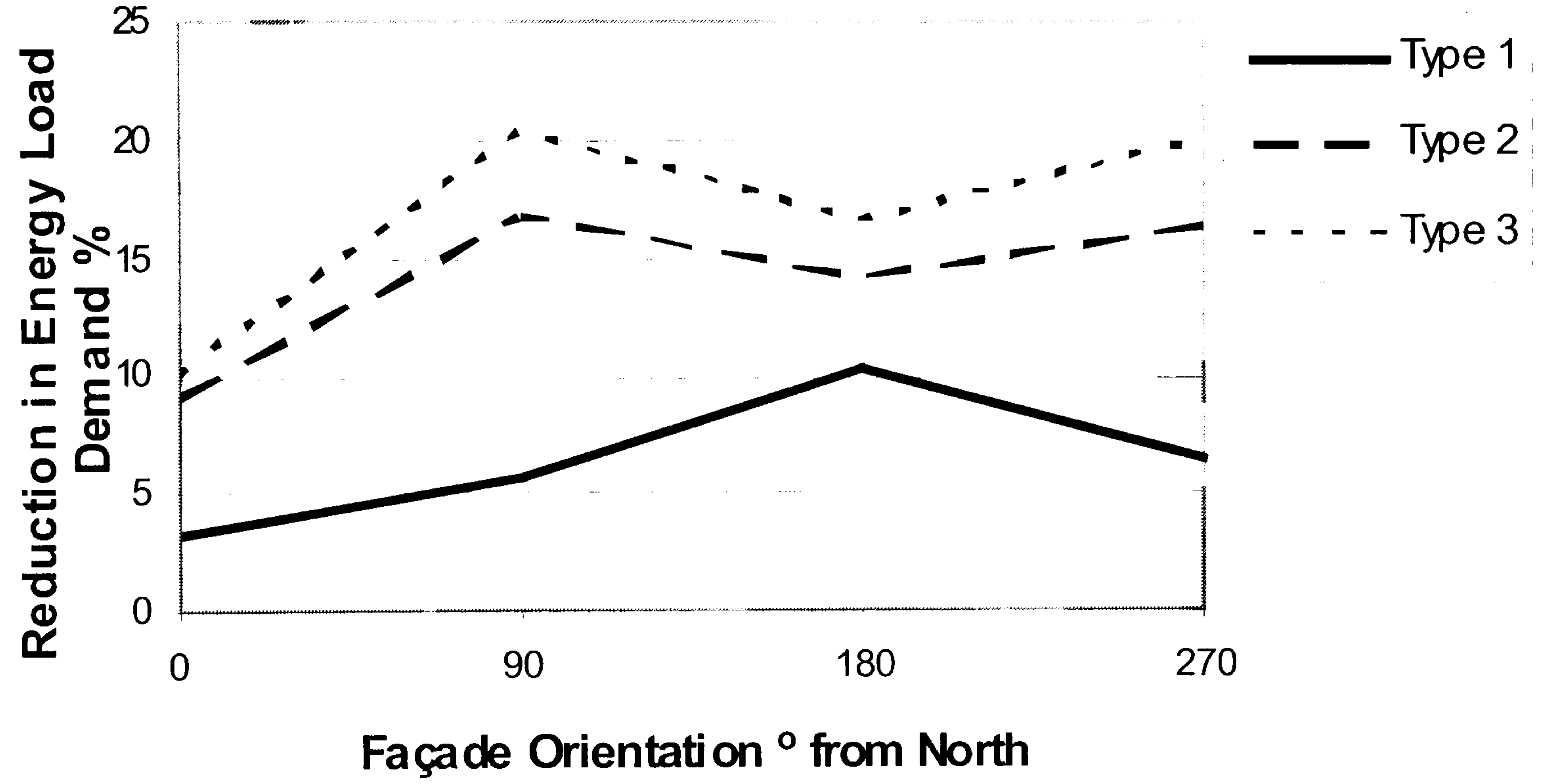


Figure C23 The reduction in annual energy load with the application of façade shading.

C4.5 CASE STUDY 2

This case study shows how the Façade concept design tool can be used during the design process. The tool is a concept design tool designed to be used at the earliest stages of design, when many of the factors, which will affect the environmental performance of a building will be determined. Choices made at this stage will not have been studied in detail, but the choices will become locked into the design of the building as a whole at this point (Hauglustaine 2000).

The case study building is part of a mixed-use development comprising one office building, a residential tower, retail block and a car park, see Figure C24. These buildings together are intended to define a new public square. The building measures 37.5m x 37.5m and its main entrance faces North onto an existing public square. The building has office accommodation set over seven floors with a typical floor area of

Figure C24 A plan of the site showing the location and relative size of the case study building.

1440 m^2 and approximately 2,500m^2 of façade. The building has a structural grid of 7.5m with an intermediate façade grid of 2.5m. The building's superstructure will be either pre-cast concrete or structural steel.

In a precedent study carried out by the architect an interest was expressed in the façade of the Barbirolli Centre in Manchester, see Figure C25. This building has a 50% glazing to solid ratio and uses a tinted glass and a granite solid panel. This type of visual effect can be achieved either with a pre-cast concrete panel or a light-weight wall with stone facing. The architect would like to pass part L2 of the Building Regulations using the elemental method, which requires that, the building has the same average U-values as the case study (i.e., 40% glazed area with a U-value of 2.2 W/m^{2}K and 60% solid area with a U-value of 0.35 W/m^{2}K). The building internal load levels will not have been determined yet, but, the design team is committed to sustainability and it is envisaged that a good BREEAM rating will be a major selling point for the building. The building is likely to include low energy measures and so the good energy option i.e. energy conscious building occupants will be selected. The design team has assumed that the offices will be open plan with 20% of the façade as modular prestige office and meeting space. The design team is interested in using a low energy cooling system hence they are particularly interested in reducing the cooling loads in the building.

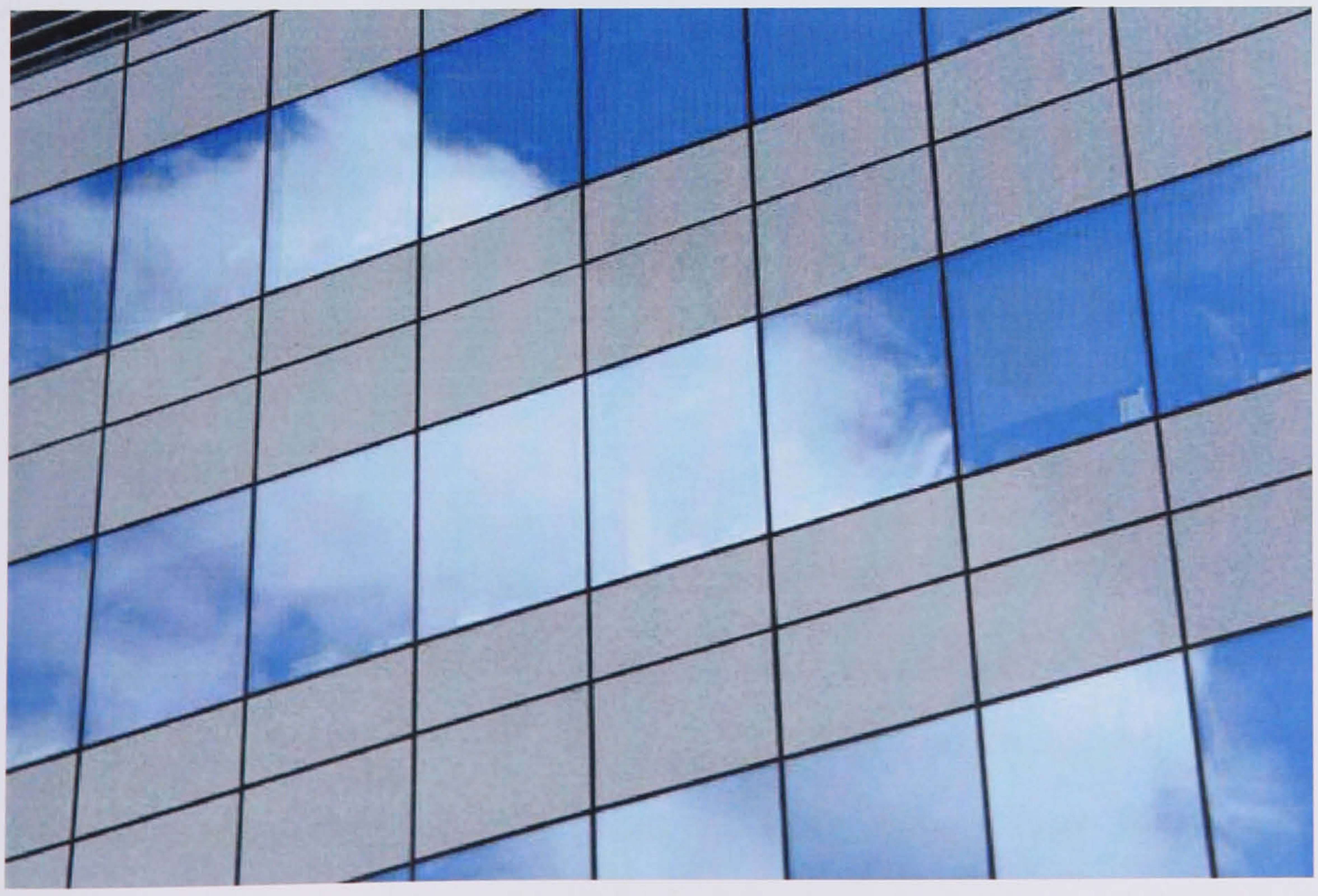


Figure C25 The north elevation of the Barbirolli Centre, Manchester.

With this background information the tool user can open the Façade Design Tool and use the initial screen to make some choices about the type of façade that would be suitable. The user would begin by determining the structure of the façade by comparing the two structural options, i.e. a lightweight panel and a heavyweight panel.

Table C9 Introductory screen for high quality lightweight façade panel with good energy practice.

	North	East	South	West
Cooling Energy Consumption / kWh/m^2	24.5	32.9	33.1	32.2
Heating Energy Consumption / kWh/m^2	26.1	19.8	19.8	24.0
Minimum Temperature °C	18.0	18.2	18.5	18.1
Maximum Temperature °C	23.6	24.4	24.2	24.6
Below 18°C %	1	1	1	1
Above 25°C %	0	0	0	0
Above 28°C %	0	0	0	0
Average Daylight Factor / %	6.8	6.6	9.2	6.6
Embodied Energy MJ/m^2	769	769	769	769
Environmental Impact	117	117	117	119

Table C10 Introductory screen for high quality heavyweight façade panel with good energy practice.

	North	East	South	West
Cooling Energy Consumption / kWh/m^2	25.1	32.4	32.5	31.7
Heating Energy Consumption / kWh/m^2	26.4	20.0	20.0	24.2
Minimum Temperature °C	18.0	18.2	18.5	18.1
Maximum Temperature °C	23.5	24.3	24.2	24.5
Below 18°C %	1	0	0	0
Above 25°C %	0	0	0	0
Above 28°C %	0	0	0	0
Average Daylight Factor / %	6.8	6.6	9.2	6.6
Embodied Energy MJ/m^2	1041	1041	1041	1041
Environmental Impact	130	128	128	131

Table C9 and C10 show the initial screen that the tool user is presented with when the two options are selected. It can be seen that the resulting temperatures from the two facades are very similar with less than 0.5°C between any pair of maximum and minimum temperatures. The space with the heavyweight façade has slightly lower cooling energy requirements and slightly higher heating requirements. This would be explained by the increased response factor of the heavyweight façade. The higher thermal mass requires a slightly higher (0.2 kWh/m^2) energy input into the space.

The total comfort performance of the two façade options is similar, as is the average daylight factor. This is because the average daylight factor indicator is attributable to the size and position of windows and openings rather than the constituents of the solid material in the façade. When confronted with very similar thermo-lighting performance the design team is likely to rely on the environmental impact associated with each façade. Despite the similar energy performance of the two facades there is a large difference in the number of eco-points associated with each façade. In both cases the west façade has the highest energy consumption, 119 eco-points for the lightweight façade and 131 eco-points for the heavyweight façade, a difference of 10%. If the heavyweight façade was used as standard over all four elevations, this would result in an increase of 296,100 eco-points and an increased embodied energy of the façade of 1 GJ. This would result in the selection of the lightweight façade.

If the lightweight façade was chosen on this basis there would be a feedback loop into the design team to investigate the influence of the outside actors on this choice, such as contractor availability, site conditions, storage space on site, lead times for construction etc.

Solar Shading

Once the façade type has been decided, the solar shading of the façade may be considered. This is generally considered at an early phase because it has an influence on the external appearance of the building, the external appearance must be settled as early as possible in order to guarantee consent from both the client and the planning authorities. A consideration of the solar shading is also required because the 50% glazing ratio is too high for the building to use the standard procedure to pass the solar overheating requirements in Part L2 of the Building Regulations in any façade elevation other than the north (DTLR 2002).

Table C11 The indicators for the east elevation

	No Shading	Horizontal Overhang	Glass Louvers	Metal Louvers	Vertical Louvers
Cooling Energy Consumption / kWh/m^2	32.9	29.2	22.0	18.1	28.2
Heating Energy Consumption / kWh/m^2	19.8	24.7	27.6	29.3	22.0
Minimum Temperature °C	18.2	18.1	18.0	17.9	18.0
Maximum Temperature °C	24.4	24.0	23.2	22.7	23.9
Below 18°C %	0	0	1	1.4	2
Above 25°C %	0	0	0	0	0
Above 28°C %	0	0	0	0	0
Average Daylight Factor / %	6.6	4.5	4.3	3.9	4.7
Embodied Energy MJ/m^2	769	975	1090	1170	912
Environmental Impact	117	119	119	118	126

Solar shading for the east elevation must deal with the early morning sun. The metal louvres are most effective in reducing the direct solar gain and reducing the cooling energy consumption. Their use also has a direct impact on the heating energy increasing the heating requirement by 10.5 kWh/m^2, the hours below 18°C has increased to 1.4% which suggest that the façade is being over cooled. The metal louvres produce the largest reduction in the average daylight factor. The façade with the metal louvres have the largest embodied energy, however, due to reduction in cooling energy this is not reflected in the overall environmental impact. The combination of reduced daylight factor and the number of hours below 18.0°C would cause the rejection of the metal louvres as a satisfactory shading option.

The next most effective shading type are the glass louvres, which reduce the cooling energy consumption from 32.9 kWh/m^2 to 22.0 kWh/m^2 a decrease of 10.9 kWh/m^2. The use of the glass louvres will result in an increase in the heating load of 7.8 kWh/m^2 while the average daylight factor will remain suitable for an office building.

Table C12 The indicators for the South elevation

	No Shading	Horizontal Overhang	Glass Louvers	Metal Louvers	Vertical Louvers
Cooling Energy Consumption / kWh/m^2	33.1	28.0	22.0	18.3	27.0
Heating Energy Consumption / kWh/m^2	19.8	21.2	25.2	29.3	22.0
Minimum Temperature °C	18.5	18.4	17.9	17.9	18.3
Maximum Temperature °C	24.2	23.8	23.3	22.8	23.8
Below 18°C %	0	0	1	1.4	0
Above 25°C %	0	0	0	0	0
Above 28°C %	0	0	0	0	0
Average Daylight Factor / %	9.2	6.4	6.9	6.2	7.4
Embodied Energy MJ/m^2	769	975	1090	1170	912
Environmental Impact	117	116	118	118	126

Table C12 shows that the use of an external horizontal overhang increases the embodied energy of the façade from 769 MJ/m^2 to 975 MJ/m^2, but the environmental impact is slightly reduced. Although, both the heating load and the embodied energy are increased, the reduction in cooling energy reduces the overall environmental impact of the façade as well as reducing the cooling energy consumption by 3.1 kWh/m^2. The use of the horizontal overhang reduces the average daylight factor, but the resulting factor of 6.4 is still within the guidelines for an office building. In this instance the horizontal louvres would be selected.

Table C13 The indicators for the West elevation

	No Shading	Horizontal Overhang	Glass Louvers	Metal Louvers	Vertical Louvers
Cooling Energy Consumption / kWh/m^2	32.2	28.6	21.6	18.0	27.5
Heating Energy Consumption / kWh/m^2	24.0	25.0	27.8	29.6	25.9
Minimum Temperature °C	18.1	18.0	17.9	17.9	18.0
Maximum Temperature °C	24.6	24.3	23.5	22.8	24.2
Below 18°C %	0	1	1	1.4	1
Above 25°C %	0	0	0	0	0
Above 28°C %	0	0	0	0	0
Average Daylight Factor / %	6.6	4	4.3	3.9	4.7
Embodied Energy MJ/m^2	769	975	1090	1170	912
Environmental Impact	119	119	119	118	130

Table C13 shows the indicators for the west elevation of the case study building. In this instance the metal louvres have the lowest environmental impact in eco-points. The metal louvre façade has the lowest cooling energy consumption 18.0 kWh/m^2, and the highest heating energy consumption 29.6 kWh/m^2. The higher percentage of hours below 18°C (1.4%) means that this façade is probably over shaded. While the horizontal overhang and the glass louvres and un-shaded elevation have the same environmental impact, the elevation must be shaded to comply with the Building Regulations, therefore the horizontal overhang and the glass louvers should both must be considered next.

Although these two options have the same environmental impact, the internal conditions, including the daylight factor should be taken into consideration. The glass louvers cause a slightly larger reduction in the cooling load 10.6 kWh/m^2 in comparison to 3.6 kWh/m^2 for the horizontal overhang. There is also a slight difference in the resulting daylight factor of the two shading types. In this case glass louvers would be the most suitable option.

Table C14 Energy consumption of shaded and un-shaded elevations.

	Un-shaded Elevations		Shaded Elevations	
	Cooling Load kWh/m^2	Heating Load kWh/m^2	Cooling Load kWh/m^2	Heating Load kWh/m^2
North elevation	24.5	26.1	24.5	26.1
East elevation	32.9	19.8	22.0	27.6
West elevation	33.1	19.8	28.0	21.2
South elevation	32.2	24.0	21.6	27.8

If the energy consumption before and after the shading solutions are applied is considered there is change in the energy demand, Table C14. Figure C26 shows the cooling energy consumption of the façade zone by elevation both with shading and without. The shading provides the largest reduction on the east elevation this is a reduction of 13,734 kWh per annum, or 33%. Over the whole building the implementation of these shading types results in a reduction of 33,500 kWh/ annum.

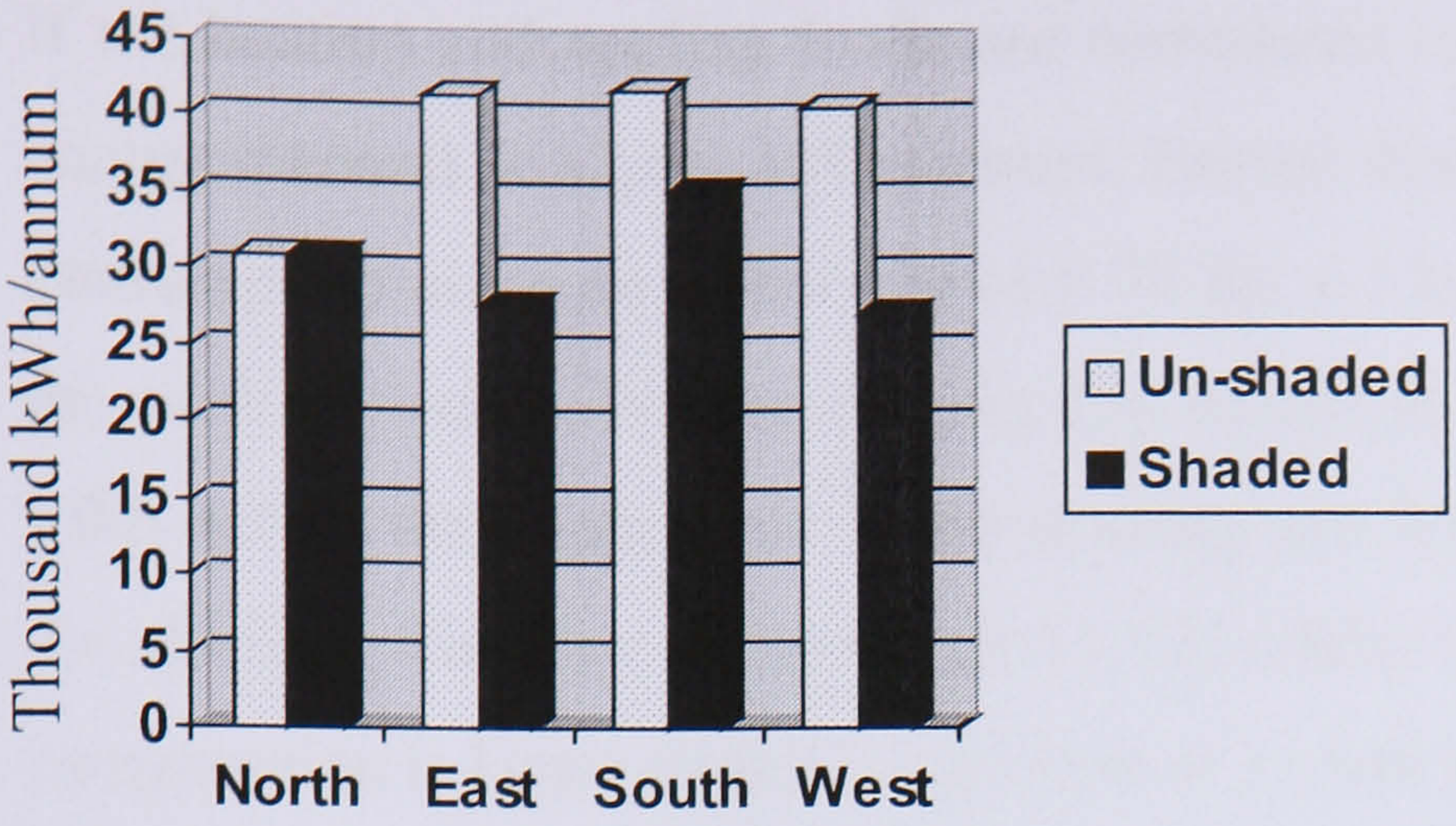


Figure C26 Cooling energy demand by elevation.

There is an increase in the heating energy requirements of the building, which corresponds, to the reduction in solar gain during the winter months. Figure C27 shows the heating energy consumption in the façade zone by elevation, both with shading and without. The largest increases are in the east and west elevations, an increase is an increase of 28% and 16% respectively. This is due to the reduction of beneficial solar gain admitted into the space during the heating season and corresponds with the decrease of the cooling energy demand during the cooling season. Over the whole building the increase in heating energy required is 15% or 16,400 kWh per annum.

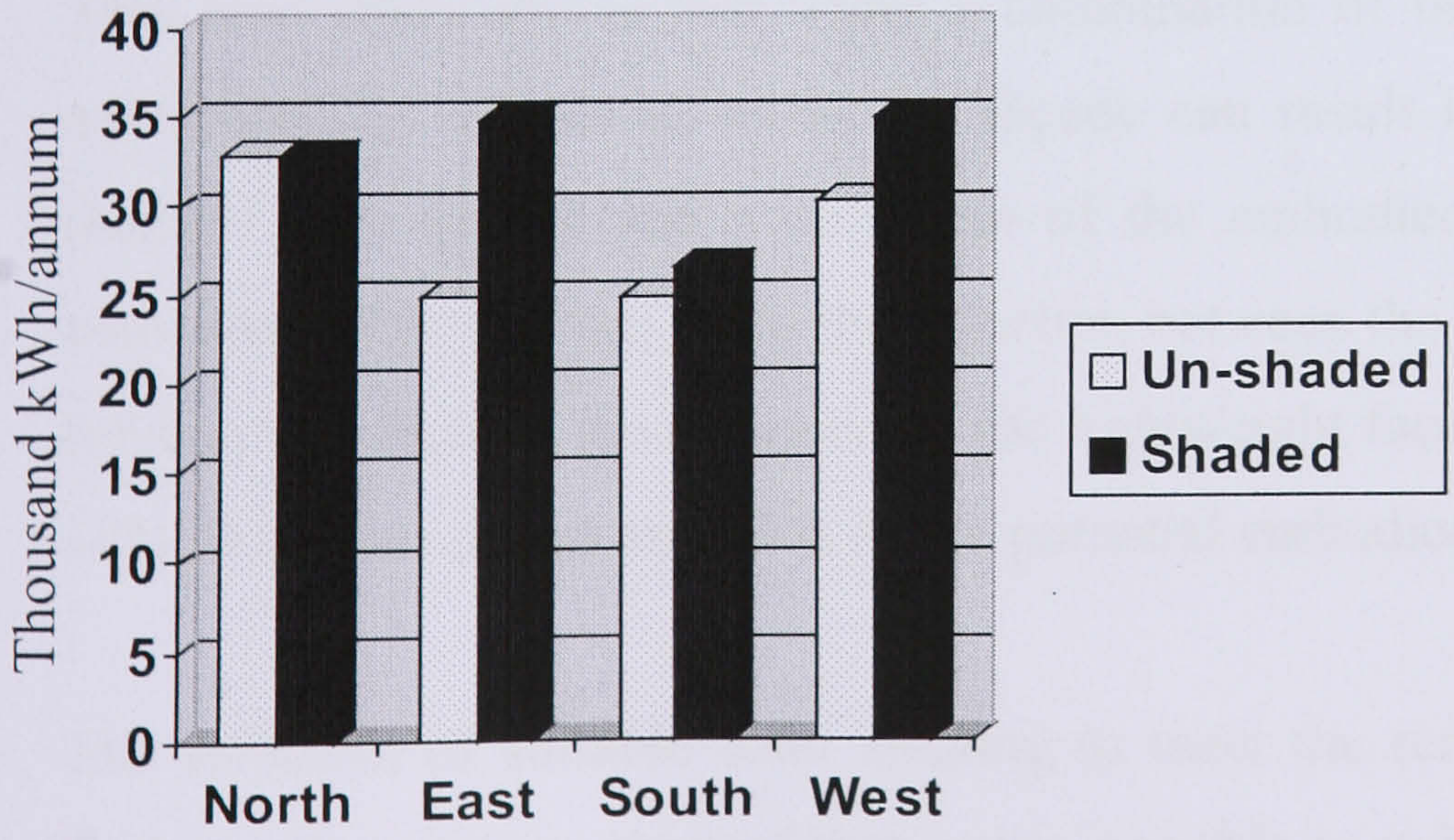


Figure C27 Heating energy demand by elevation.

If the heating and cooling loads are considered together there is a reduction in the energy demand of 17,136 kWh/annum. Energy demand can be converted into energy consumption using an efficiency of 0.75 for the heating system and a COP of 3 for the cooling system. For the cooling this results in an energy consumption of 51,534 kWh before the application of the shading and 40,362 kWh after the application of the shading. This is a decrease of 11,172 kWh, the increase in the heating energy consumption is larger than this decrease at 21,840 kWh (from 150,696 to 172,536). The energy loads can be further translated from energy consumption to kg of CO_2 using a conversation factor of 0.52 kg CO_2 for electricity and 0.2 kg CO_2 for gas. After the application of this conversion factor there is a decrease in the CO_2 emitted from the cooling of 5.8 tonnes per annum and an increase in the amount of CO_2 emitted from heating of 4.3 tonnes per annum. This is an overall decrease of 1.44 tonnes of CO_2 per annum, a reduction of 3% of the total CO_2 for the façade zone per year. This does not take into account any increases in lighting use that might occur as a result of the reduced daylighting factor.

It should be noted that although the use of shading results in a reduction in the total CO_2 emissions for the building, it increases the environmental impact in eco-points by 1,890 (6%) and increases the embodied energy of the façade by 534 GJ (27%).

Summary of Results

This case study shows that using a combination of the building performance and environmental impact to select the façade can result in a reduction in the energy demand of a façade and a reduction of the embodied energy and the eco-points associated with the façade. In the selection between the heavy weight façade and the light weight façade, the selection of the lightweight façade resulted in a reduction of 10% in the eco-points and 25% of the potential embodied energy of the façade.

The selection of suitable solar shading to meet the requirements in part L2 of the Building Regulations showed that is was possible to reduce the energy demand from heating and cooling resulting in a reduction in the CO_2 emissions associated with the cooling and heating. This is the stated aim of the Building Regulations, but the implementation of the recommendations do not reduce the overall environmental impact and result in an increase (27%) in the embodied energy of the façade.

The use of the tool can help to choose the options with the least environmental impact. Use of the tool during the concept design process gives the design team access to detailed building performance data, which would not otherwise be available at this point in the design process. This data can be used a guide and can be investigated in detail for the particular job at a later point in the design process.

CHAPTER C5 RESULTS OF PARAMETRIC ANALYSIS

The analysis detailed in Chapter C2 to C3 has been used to provide a database. This database can be interrogated using the methods described in chapter C4 to give an indication of the performance of a particular façade. In this chapter a selection of results are presented so that the impact of façade selection on internal conditions and environmental performance can be discussed.

The summary performance indicators described in section C4 are presented for two of the building options in each of the cases. These results are presented in Figures C29 to C45. In each of the graphs the high standard façade with low internal gains is presented on the left and the results for the standard façade system with high internal gains is presented on the right. There are two graphs for each summary output indicators, one which represents the results from the type 1 naturally ventilated building, and the other which represents the type 2 air-conditioned building. In the case of cooling load only the type 2 building is shown as the type 1 building does not utilise any form of mechanical cooling.

A building case code is used to refer to each façade/building option case. Each case code is made up of five parts, as shown in figure C28, these represent the outcomes of the facade option choices described in section C2. A key to the code used in the graphs is presented in Table C15.

$$\underbrace{\text{ac}}_{\substack{\text{building}\\ \text{code}}} \quad \underbrace{\text{g}}_{\substack{\text{energy}\\ \text{code}}} \quad \underbrace{\text{cw}}_{\substack{\text{façade}\\ \text{code}}} \quad \underbrace{1}_{\substack{\text{façade}\\ \text{standard}}} \quad \underbrace{0}_{\substack{\text{shading}\\ \text{code}}} \qquad = \text{acgcw10}$$

Figure C28 Description of the building case code.

Table C15 Key to the building case reference codes.

Part of Reference	Code	Description
Building Type	nv	Type 1 building with natural ventilation
	ac	Type 2 building with mechanical ventilation
Energy Conservation	g	Good energy use
	t	Typical energy use
Façade Code	cw	Curtain Wall
	br	Masonry Cladding
	cl	Lightweight Metal Cladding
	rs	Heavyweight Concrete Cladding
	ds	Double-Skinned Facade
Façade Standard	1	Standard system
	2	High Quality System
Shading Code	0	No Shading
	1	Horizontal Overhang
	2	Horizontal Glass Louvres
	3	Horizontal Metal Louvres
	4	Vertical Metal Louvres

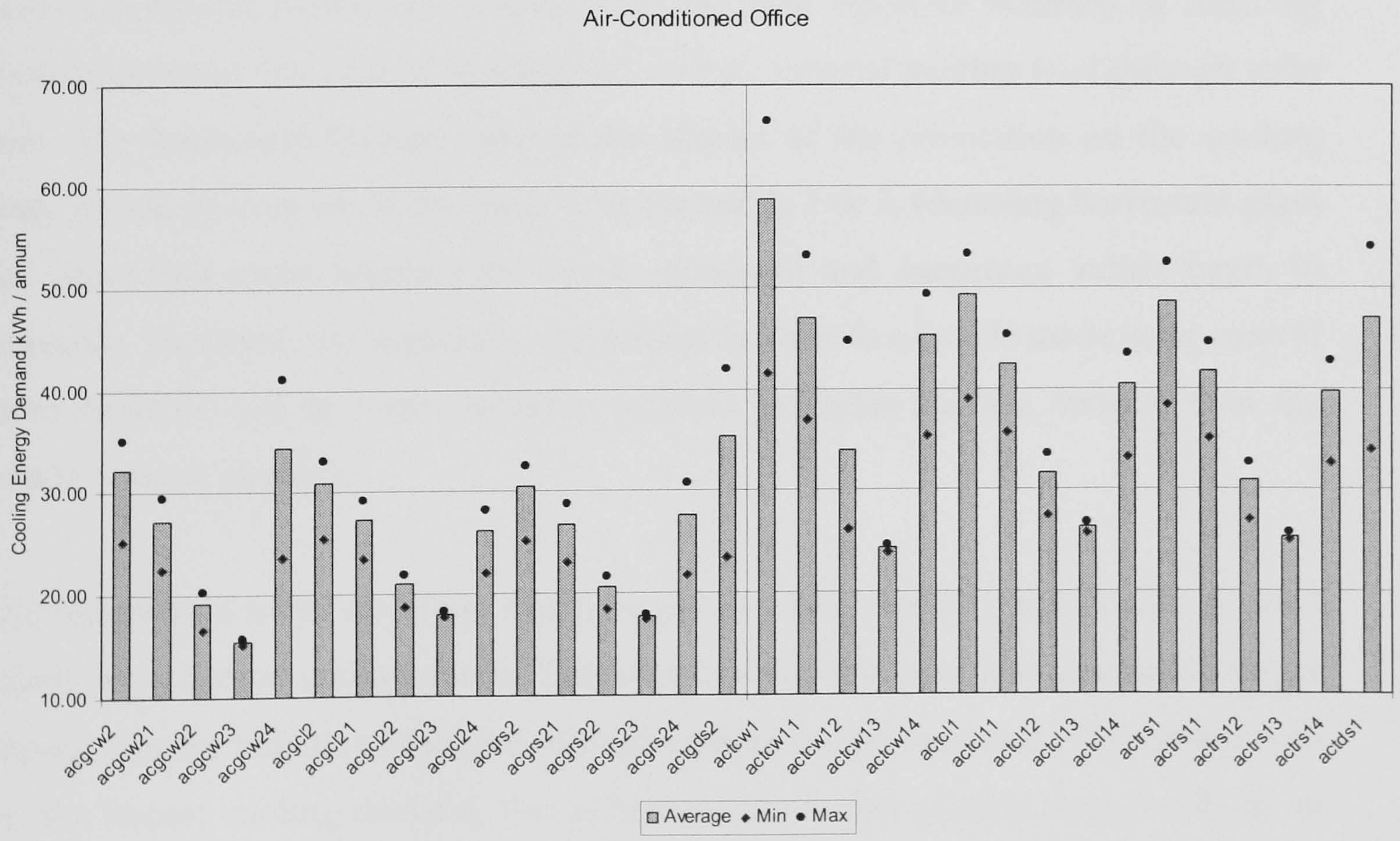


Figure C29 Cooling Energy Demand for air-conditioned building.

C5.1 COOLING LOAD

The cooling energy load for the air-conditioned building types is shown in Figure C29. The cooling loads have been calculated by the dynamic thermal analysis of the air-conditioned building, as discussed in Appendix C1. The cooling energy demand for the high quality façade with low internal gains, left hand side of the graph, has an average value of 25.65 kW/m^2 with a variation of ± 63%, which differs from the average value for the standard quality façade with high internal gains, shown on the right hand side of the graph, of 39.50 kW/m^2 with a variation of ± 68%. The variation between the two types of façade and energy options is larger than the variation within the two sets of cases. These results show that improving the performance of the façade and reducing the internal heat loads from equipment and lighting sources can dramatically reduce, in the case of an un-shaded curtain wall by 48%, the cooling load in an office building.

The application of shading to the façades had an impact on the cooling demand in all cases. Horizontal louvres are indicated as the most effective methods of reducing cooling demand; this type of shading reduced the internal heating load through solar gain. The horizontal louvres reduced the impact of the orientation on the cooling load. As can be seen all of the cases with the suffix 2 or 3, (denoting horizontal glass and horizontal metal louvres) the mean, minimum and maximum values begin to converge. However, the application of vertical louvres to a facade made solar control more complex and in some instances resulted in higher cooling demand than the facade without shading.

The lightweight metal cladding, heavyweight concrete cladding and double skinned façade have similar cooling loads. This suggests that the solar heat gain has a larger impact than the radiative heat gain through opaque façade materials. The curtain wall has the largest cooling demand, this is because the higher glazing ratio results in an increased solar gain and higher internal heat gains. However, when the façade is heavily shaded by the horizontal metal louvres the cooling demand of the curtain wall falls below that required by other façade types. This is because the shading is only applied to the glazing area and some of the heat load in the other offices occurs as radiation through the non-glazing elements.

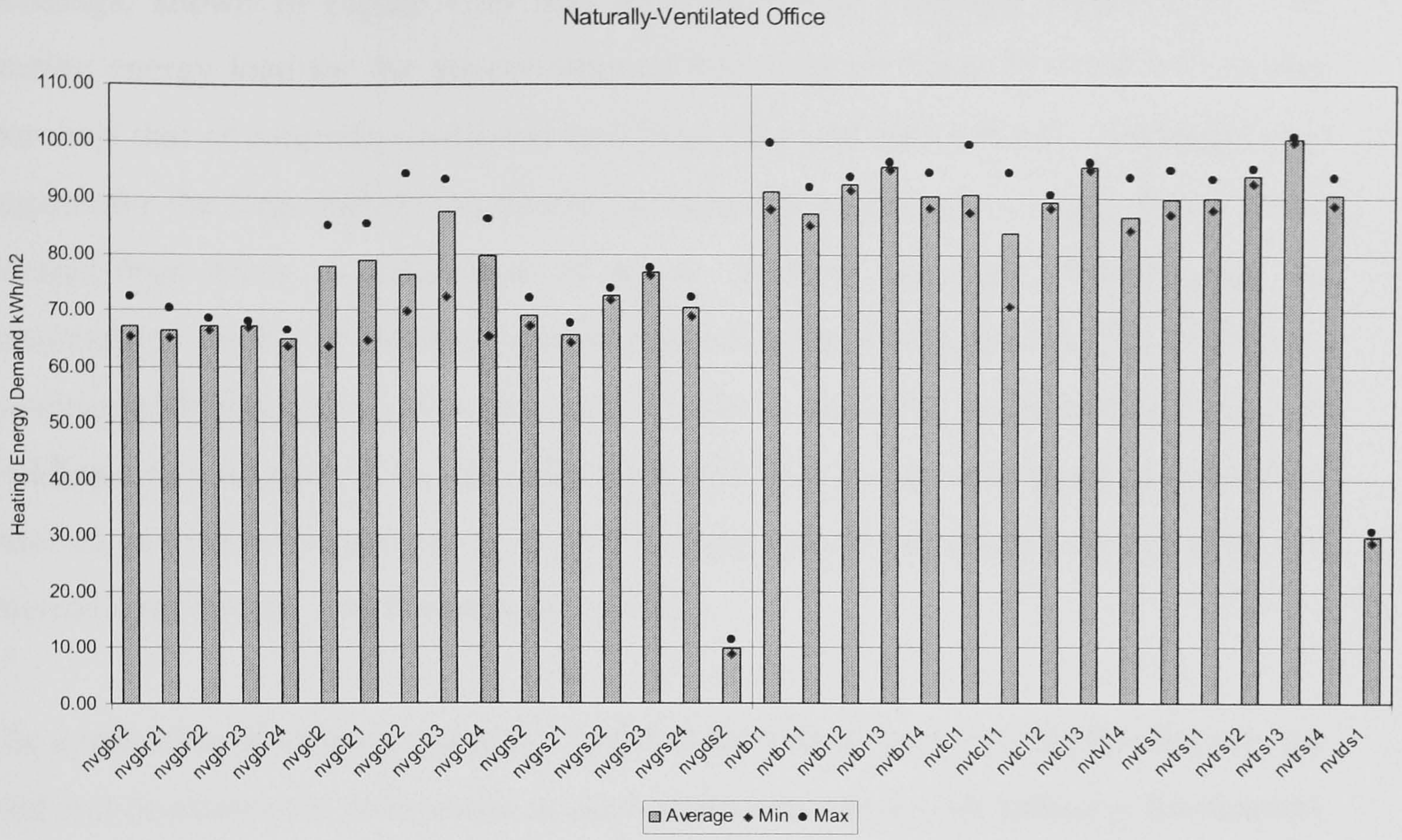


Figure C30 Heating energy load in naturally-ventilated office.

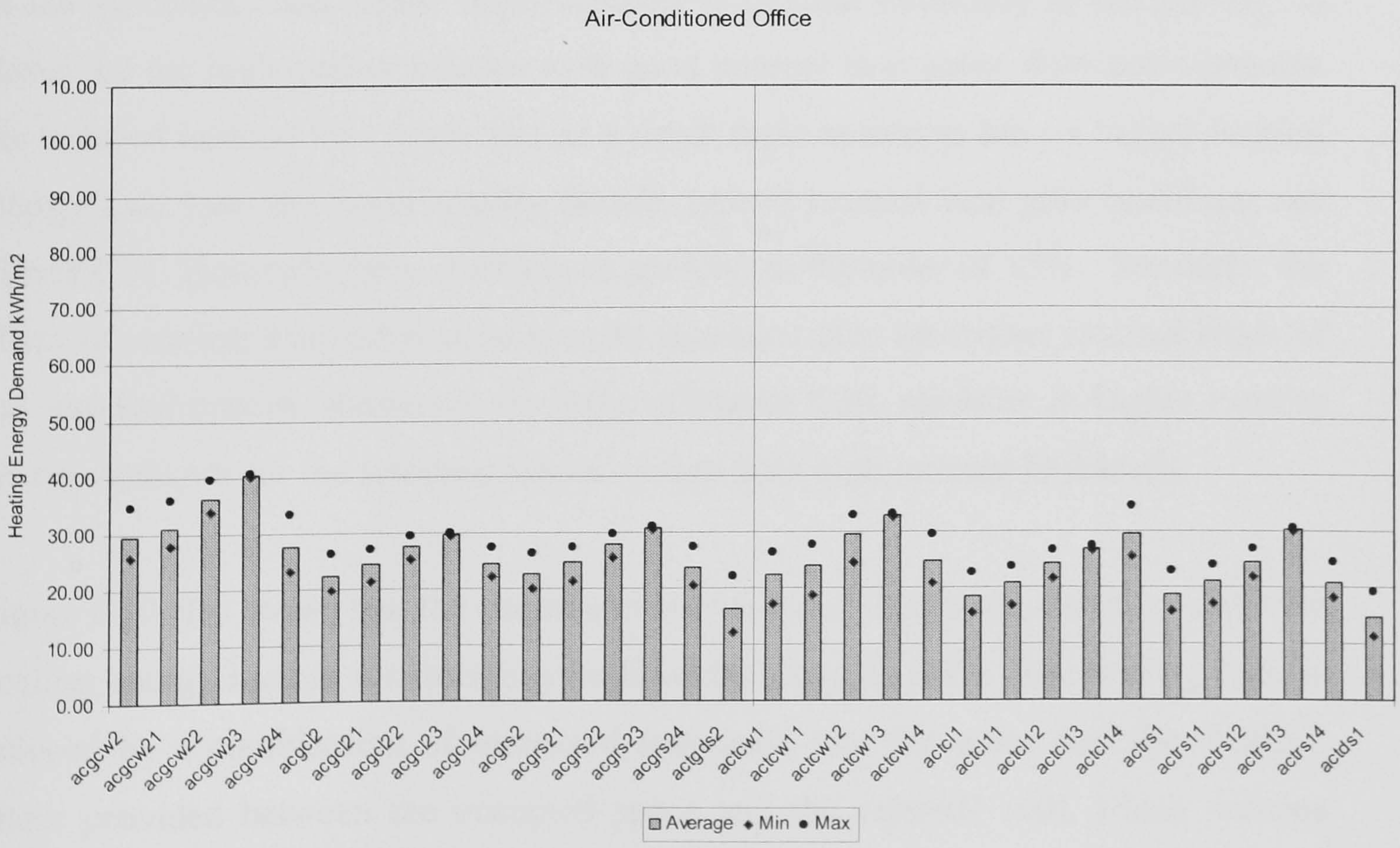


Figure C31 Heating energy load in air-conditioned office.

C5.2 HEATING LOAD

There is a marked difference between the results for the naturally-ventilated buildings, shown in Figure C30 and air-conditioned buildings Figure C31. The heating energy load for the air-conditioned buildings (average 25.4 kW/m^2) is less than half that of naturally-ventilated buildings (average 78.1 kW/m^2). There are two reasons for the large difference; firstly the naturally-ventilated buildings have lower internal heat loads, a difference of up to $20W/m^2$ per hour, which must be compensated for by the heating system. Secondly, the air infiltration rate in the air-conditioned buildings is lower due to the high air tightness associated with sealed buildings. A reduction of the air infiltration rate reduces the amount of uncontrolled external air whose temperature, in the heating season, is usually lower than the internal temperature, which enters the space.

The application of shading types 1, 2 and 3 to the façade increases the heating energy load and decreases the differences in loads due to orientation by reducing the amount of beneficial solar heat gain available during the heating season; the higher the solar shading factor the higher the energy demand.

In the air-conditioned façade improvements in thermal efficiency of the glazing, as shown by the high quality facades with good internal heat gains, does not overcome the reduced internal heat loads and as a result these buildings have a higher heating energy load than the lower quality facade, typical internal heat gain buildings, see Figure C31. However, these differences are low, in the order of 15%. Similarly, the effect of unwanted air infiltration is more dominant than the higher internal loads of the standard system, shown on the right of Figure C30, resulting in higher heating energy demands for the standard façade system with high internal heat loads.

Figure C30 also shows that the use of a double-skinned façade system can reduce the heating energy load in a naturally ventilated building, by 44%. The heating load is reduced by a combination of increased solar gain into the space and the "buffer" effect provided between the occupied space and the external wall, which reduces internal heat losses due to transmission through the façade.

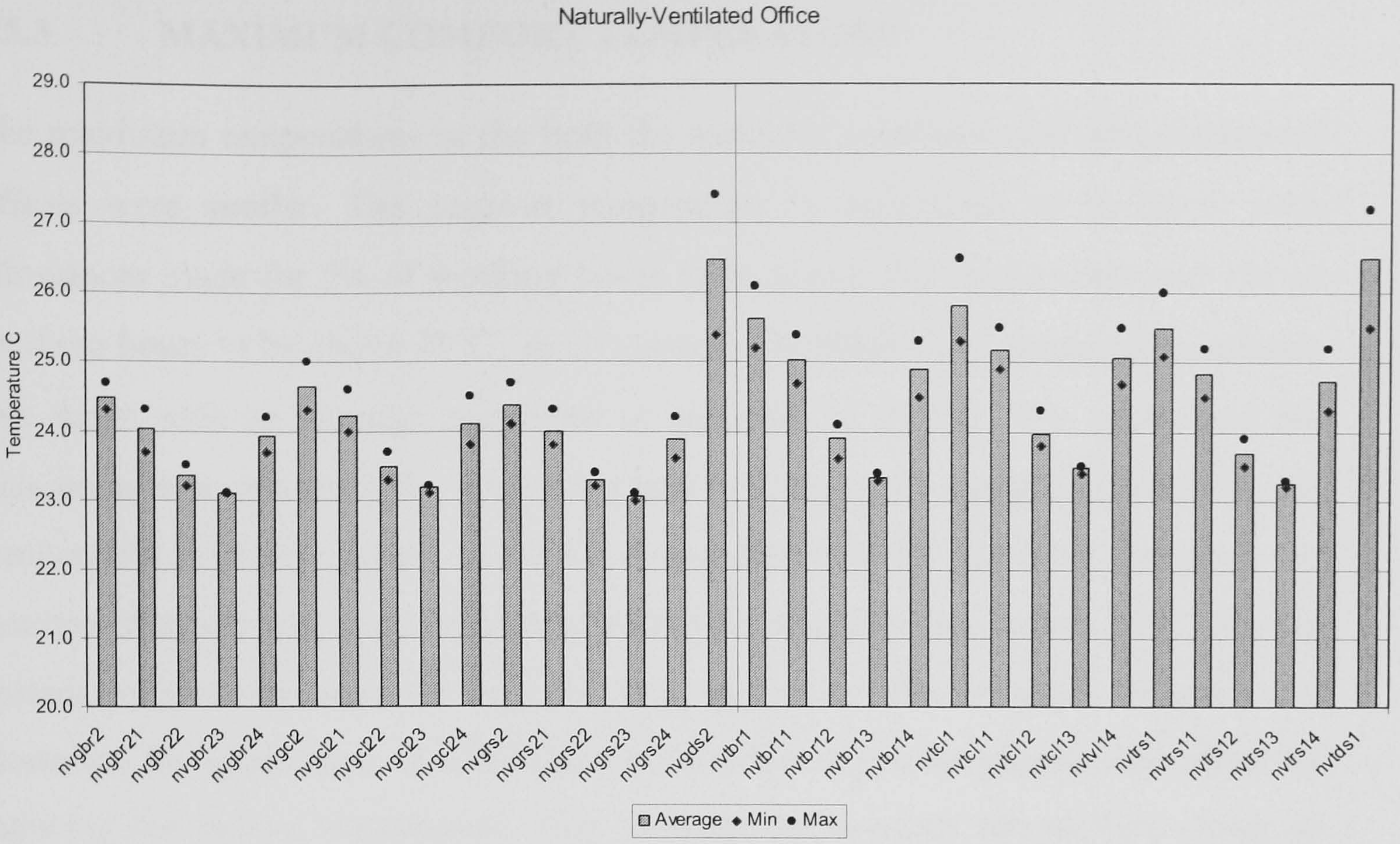


Figure C32 Maximum comfort temperature in naturally-ventilated office.

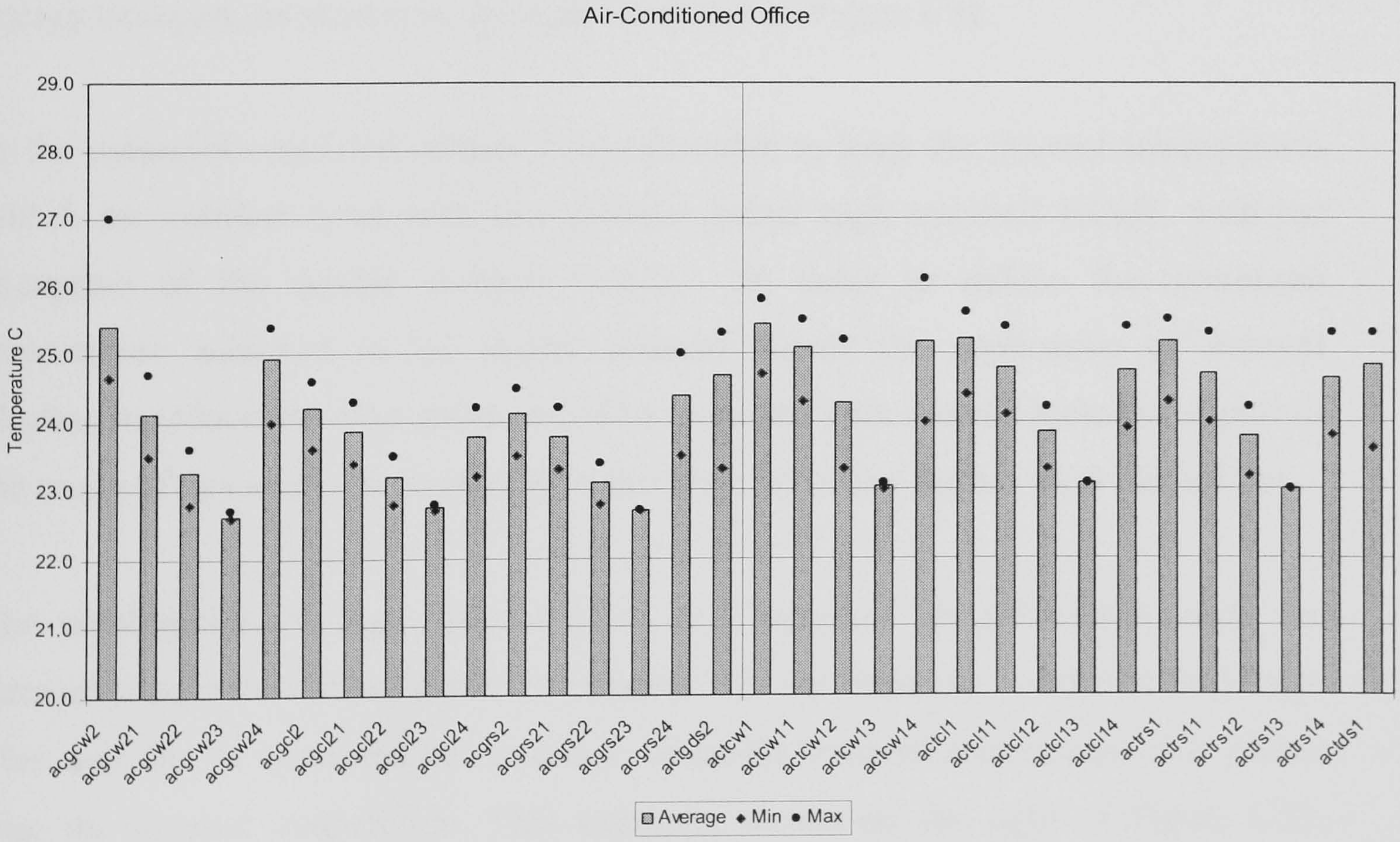


Figure C33 Maximum comfort temperature in air-conditioned office.

C5.3 MAXIMUM COMFORT TEMPERATURE

The maximum temperatures in the both the naturally ventilated and air-conditioned offices were similar. The comfort temperature is considered to be 25°C with allowances made for 5% of working hours to be above this temperature and 1% of working hours to be above 28°C in all cases the building have managed to achieve this target with an average maximum temperature of 24.2°C. The control of the maximum temperatures in the air-conditioned buildings was complicated because the temperature controls operate on the air temperature and the indicator measures the resultant temperature. In all cases the internal air temperature is below 25°C, but the radiant temperature may be higher, thus increasing the resultant temperature. However, the application of solar shading to reduce the solar gain has the effect of reducing the radiant temperature, thus bringing the resultant temperature closer to that of the air temperature. The higher internal gains and increased air infiltration, shown on the right hand side of Figure C33, resulted in a slight increase in the maximum temperature; however this was controlled and resulted in higher cooling energy demands, as shown on the right-hand side of Figure C31.

In the naturally-ventilated offices it was possible to keep the internal temperatures within the comfort band with low internal gains/ high standard façade, with the exception of the double skinned façade. In order to reduce the maximum temperature achieved in the double-skinned façade the application of internal shading to reduce the solar gains would be required. This was not included as part of the scope of this study, but it should be investigated in any further work carried out.

The combination of high internal gains and increased air infiltration made the internal temperature more difficult to control in the naturally ventilated buildings. This was due to unwanted air exchange when the external temperature was higher than the internal temperature. This example, shown on the right of Figure C33, highlights the limitations of cross-ventilation to remove high internal gains. In these instances the reduction of the solar gain by the application of solar shading enabled all of the façades to achieve the comfortable temperatures.

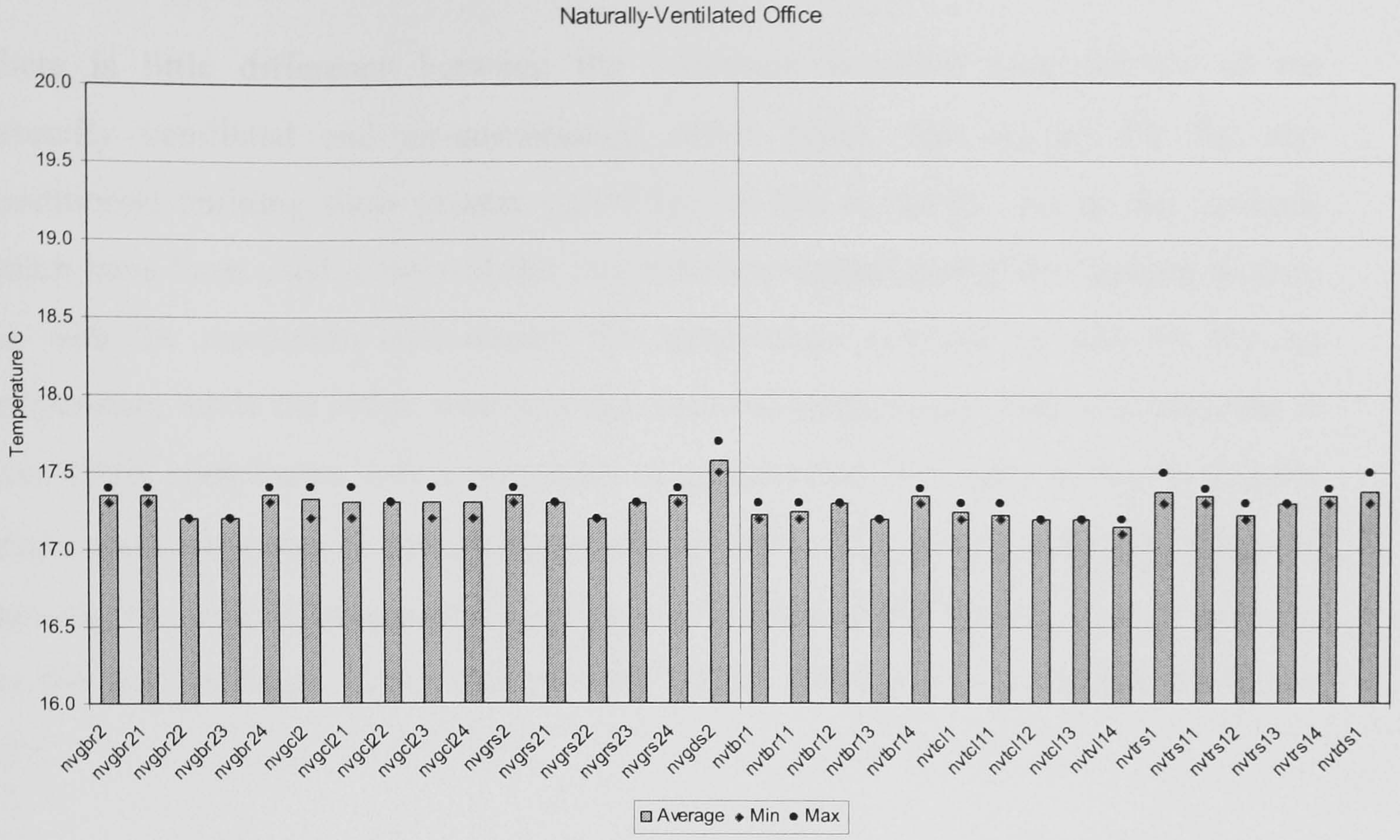


Figure C34 Minimum comfort temperature in naturally-ventilated office type.

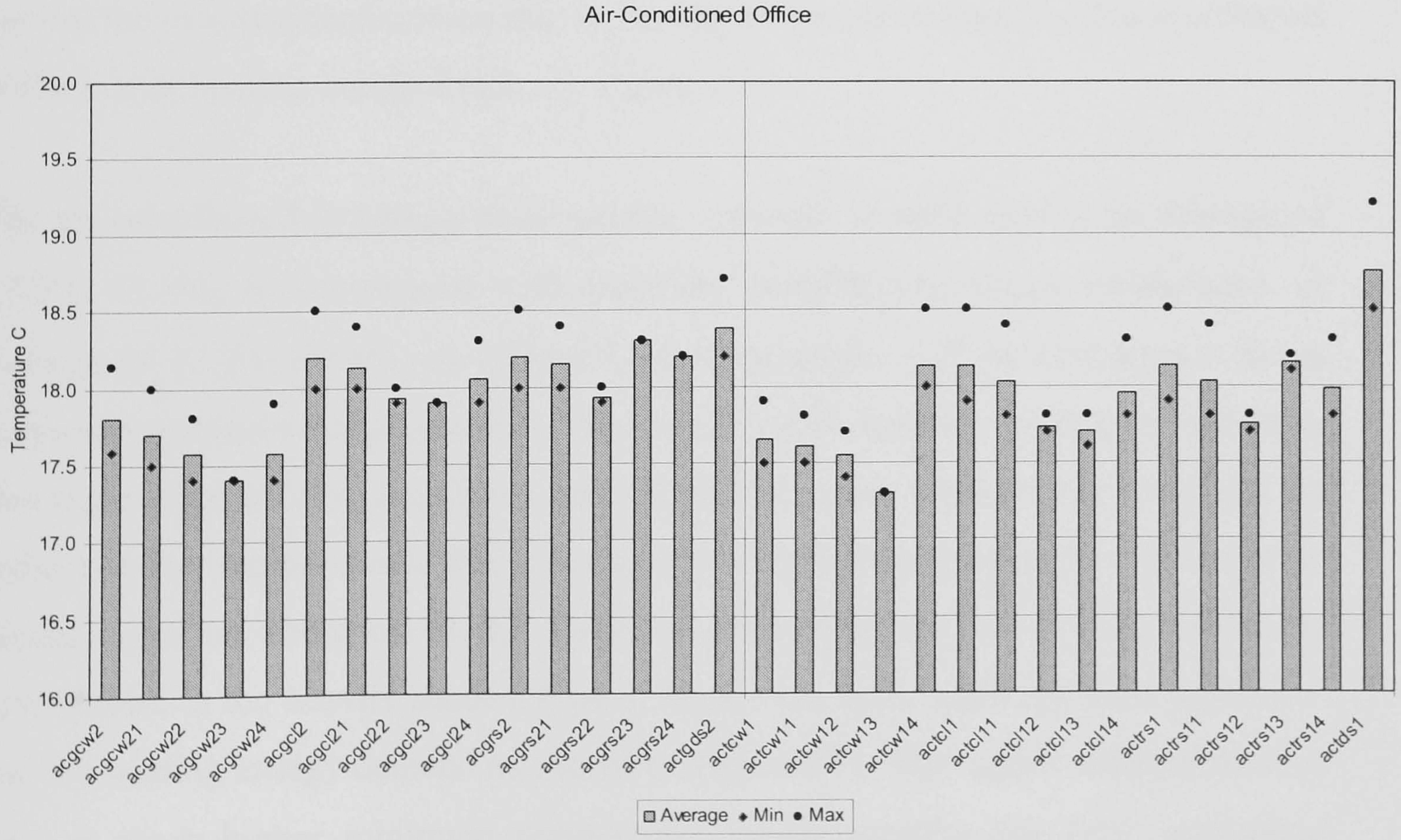


Figure C35 Minimum comfort temperature in air-conditioned offices.

C5.4 MINIMUM COMFORT TEMPERATURE

There is little difference between the minimum resultant temperatures of the naturally ventilated and air-conditioned office types. The results for the air-conditioned building show greater volatility, but this is mainly due to the methods which have been used to control the internal temperature during the heating season. As with the maximum temperature the temperature controls operate on the air temperature while the index measures the resultant temperature. Thus it is possible to have 100% compliance with a minimum temperature of 18°C only by increasing the temperature set point to temperatures above 22°C. This would have the effect of skewing the internal temperature profile and distorting the heating energy demand for the test buildings. Hence the majority of the temperatures measured are below 18°C.

In the naturally ventilated buildings, Figure C34, the minimum resultant temperature is consistently just below 17.5°C which presents a compromise between the guideline of 18°C and overheating the building. It was slightly more difficult to control the resultant temperature due to the higher air infiltration and this is reflected in the higher heating energy loads, see Figure C31.

The air-conditioned buildings show greater volatility in their results, an average of 17.9°C ±1.9%, in comparison with naturally ventilated buildings which have an average of 17.3°C ±0.6%, see Figure C34. The curtain wall facades have a lower minimum comfort temperature than other façade types. This was more pronounced in this façade type because the higher glazing ratio increases the difference between the radiant and air temperatures, thus creating a lower resultant temperature. In the other façade types an alteration of the set point temperature to increase the minimum temperature in the heavily shaded, type 3, façade has both increased the temperature and the heating energy demand as shown in Figure C31. The double skinned facades have a much higher minimum temperature, easily meeting the 18°C minimum, despite having lower heating energy demand.

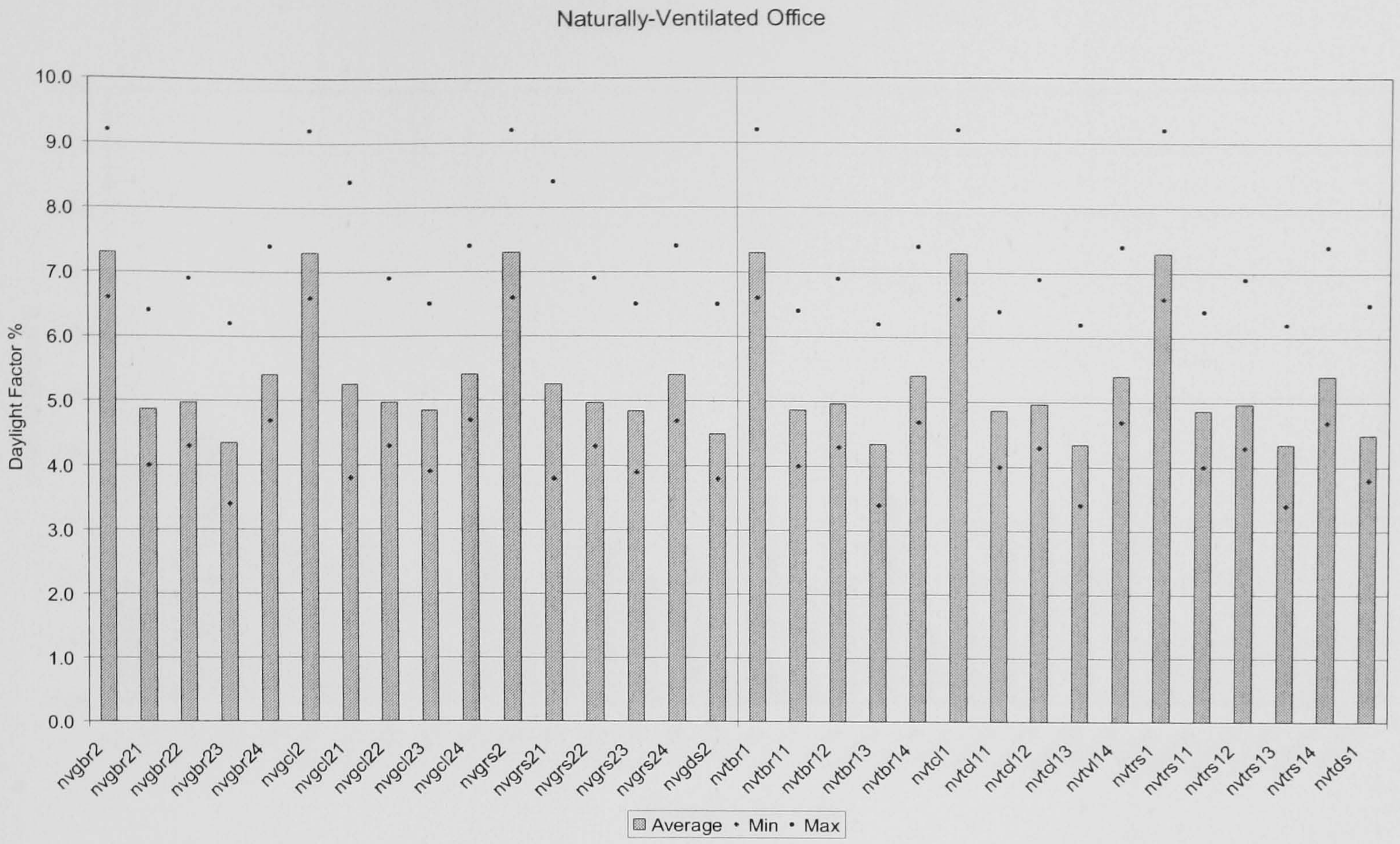


Figure C36 Daylight factors for naturally-ventilated offices.

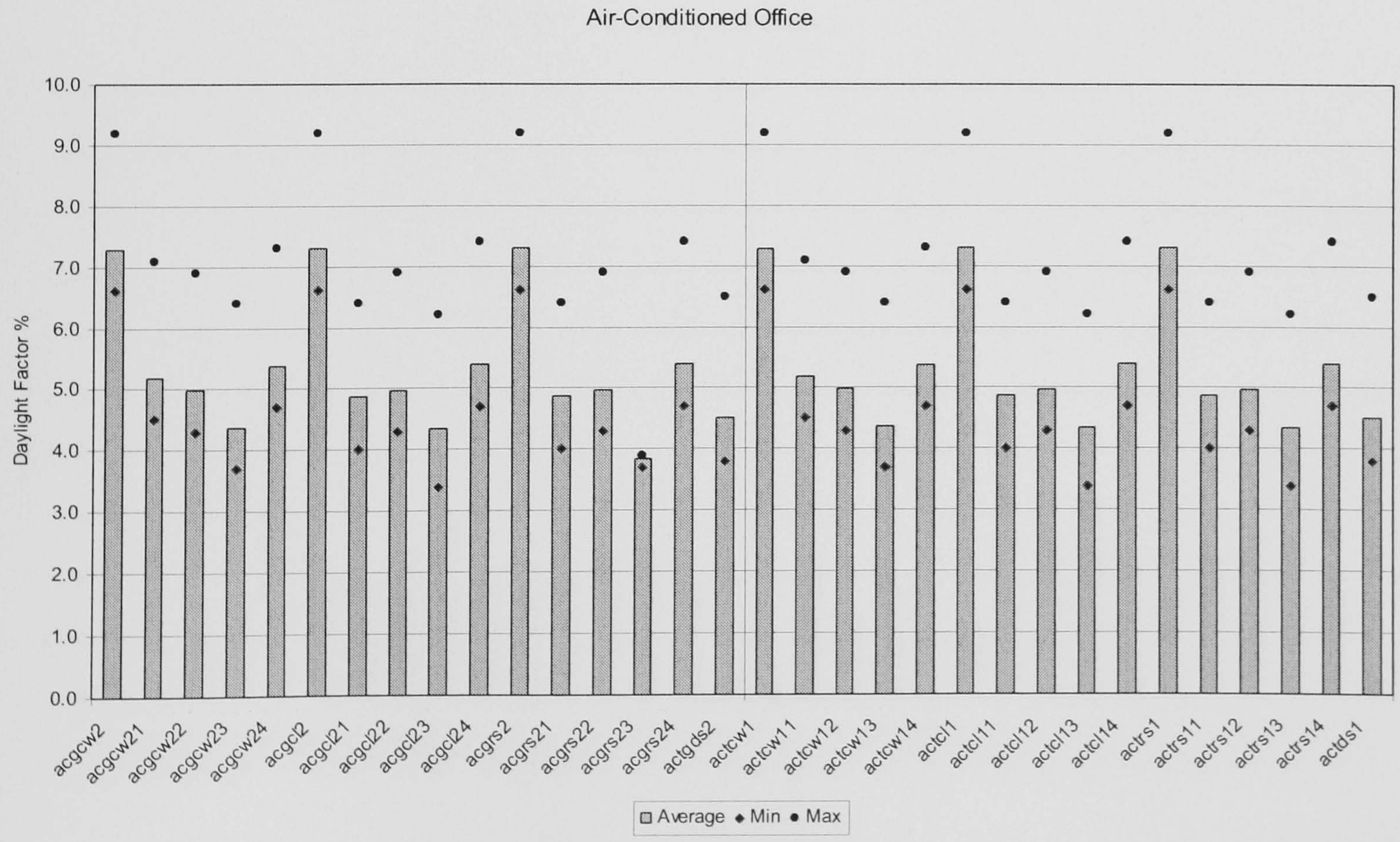


Figure C37 Daylight factors for air-conditioned offices.

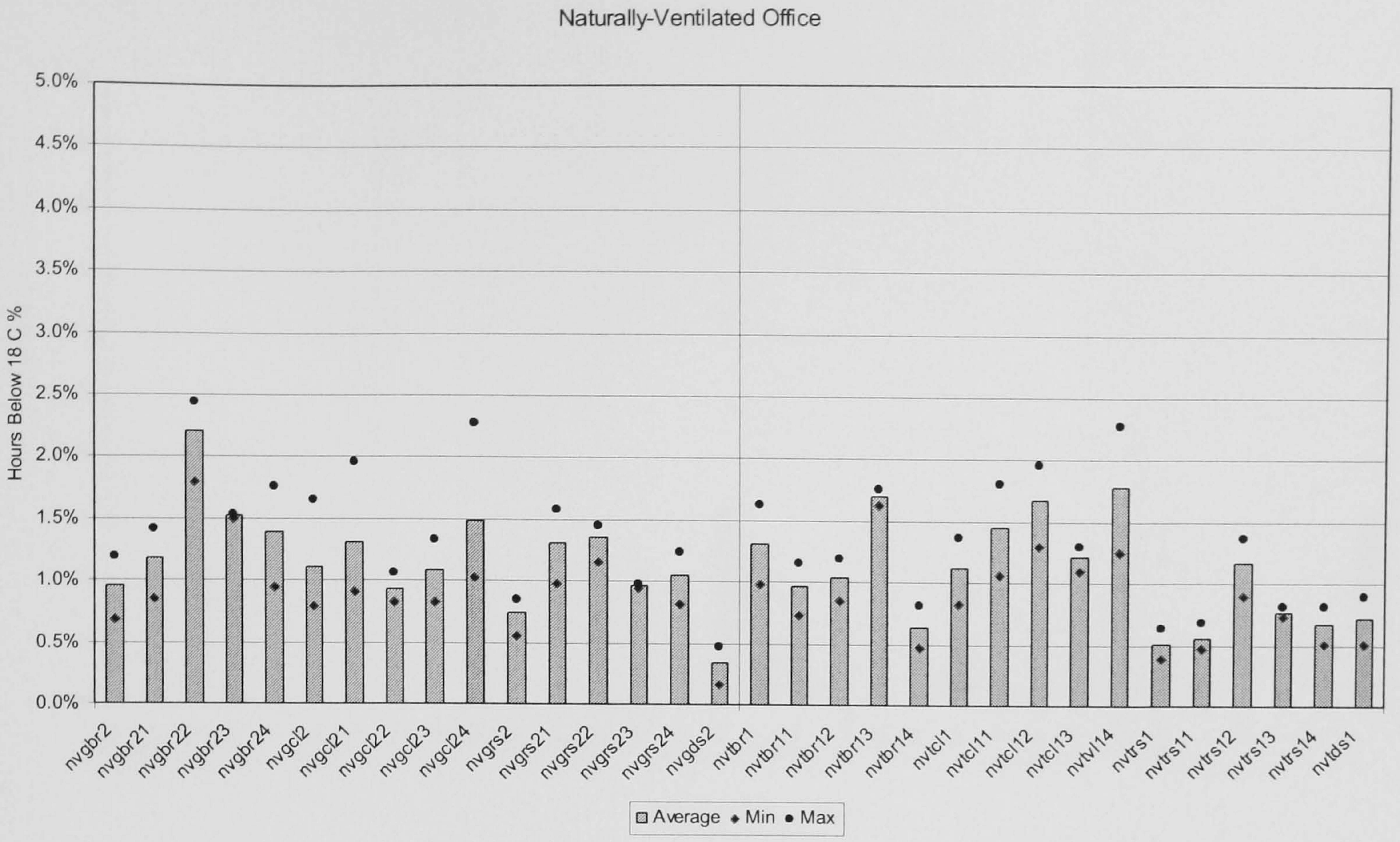


Figure C38 Percentage of working hours with a comfort temperature below 18°C in the naturally-ventilated offices.

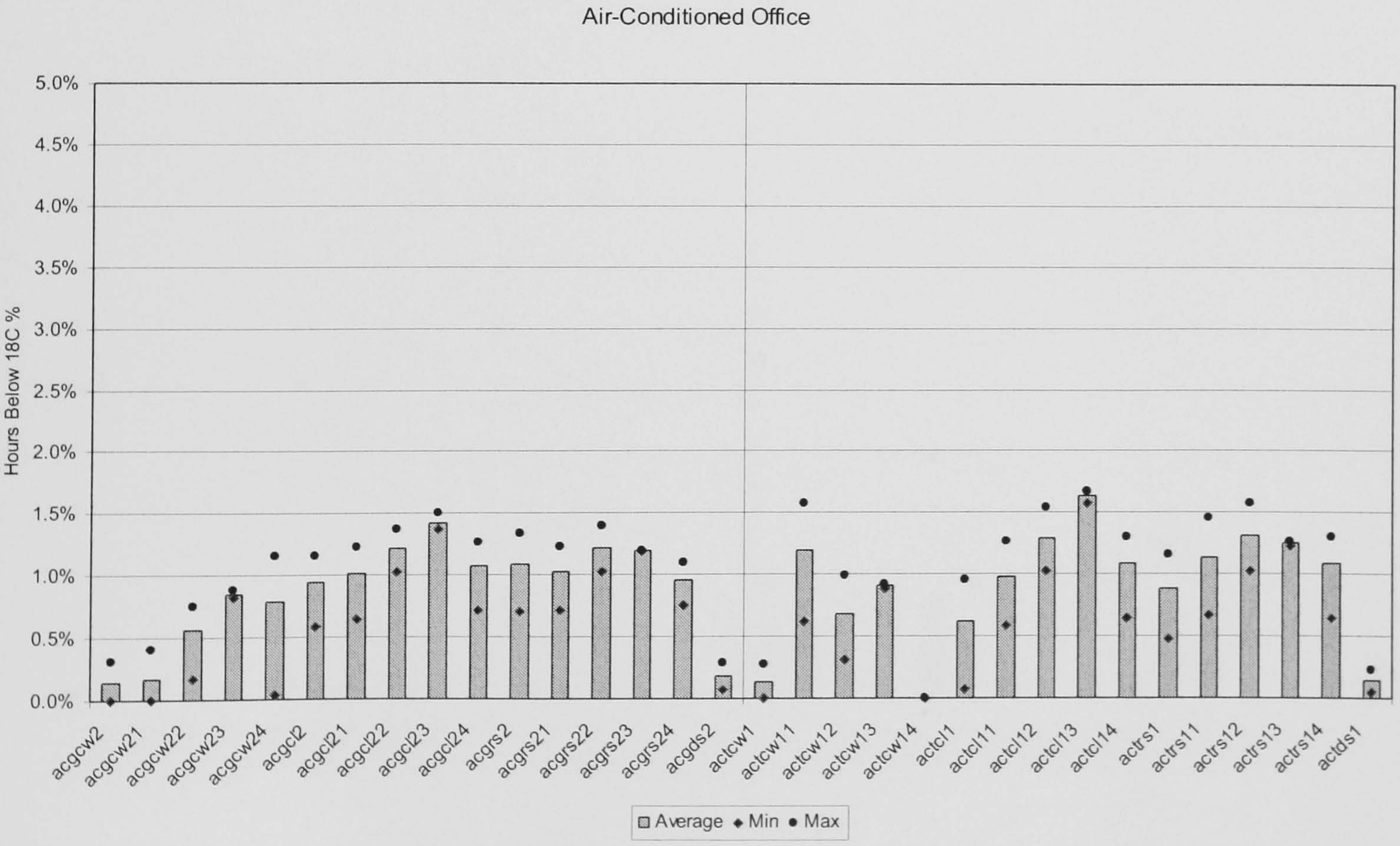


Figure C39 Percentage of working hours with a comfort temperature below 18°C in the air-conditioned offices.

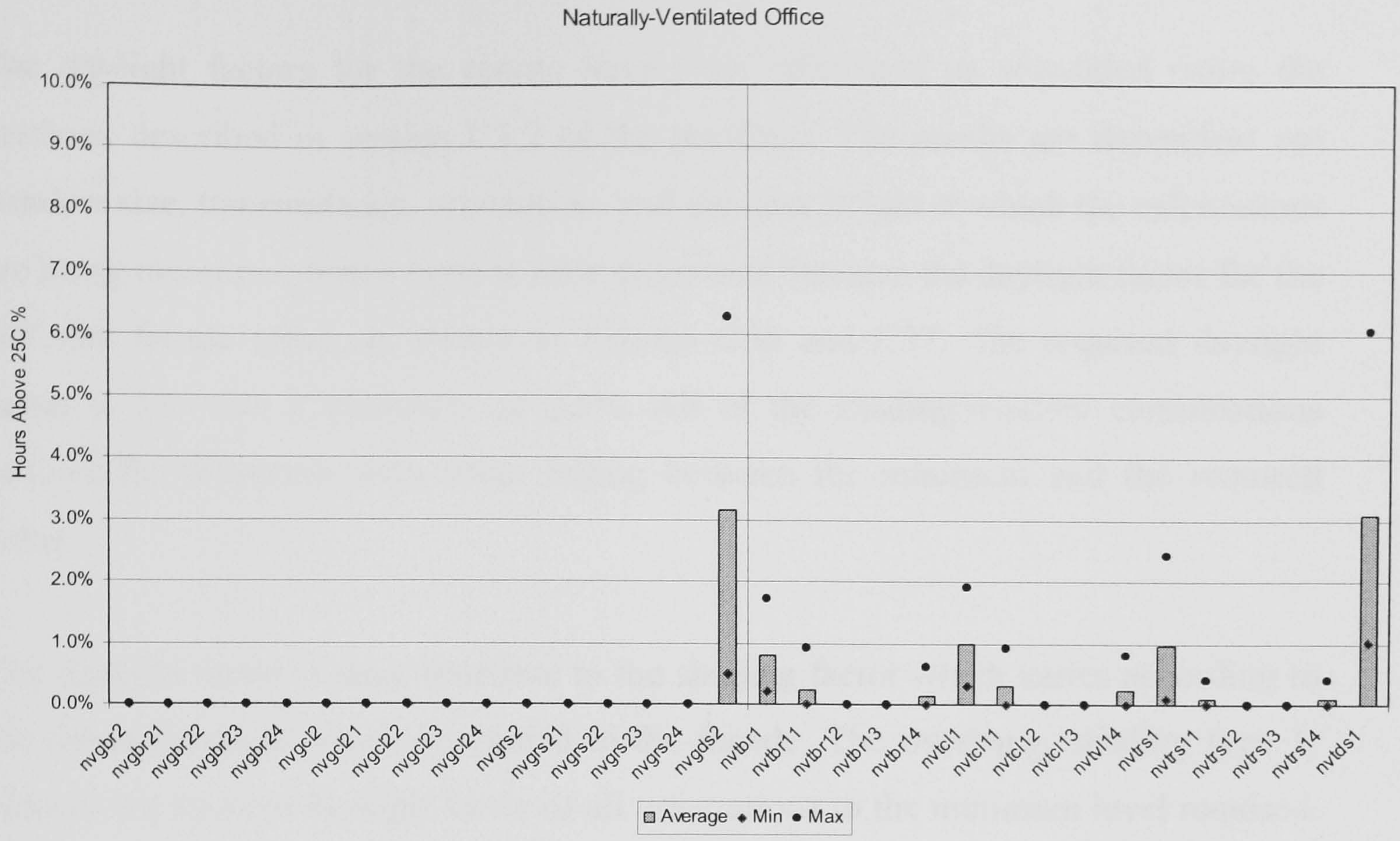


Figure C40 Percentage of working hours with a comfort temperature above 25°C in the naturally-ventilated office.

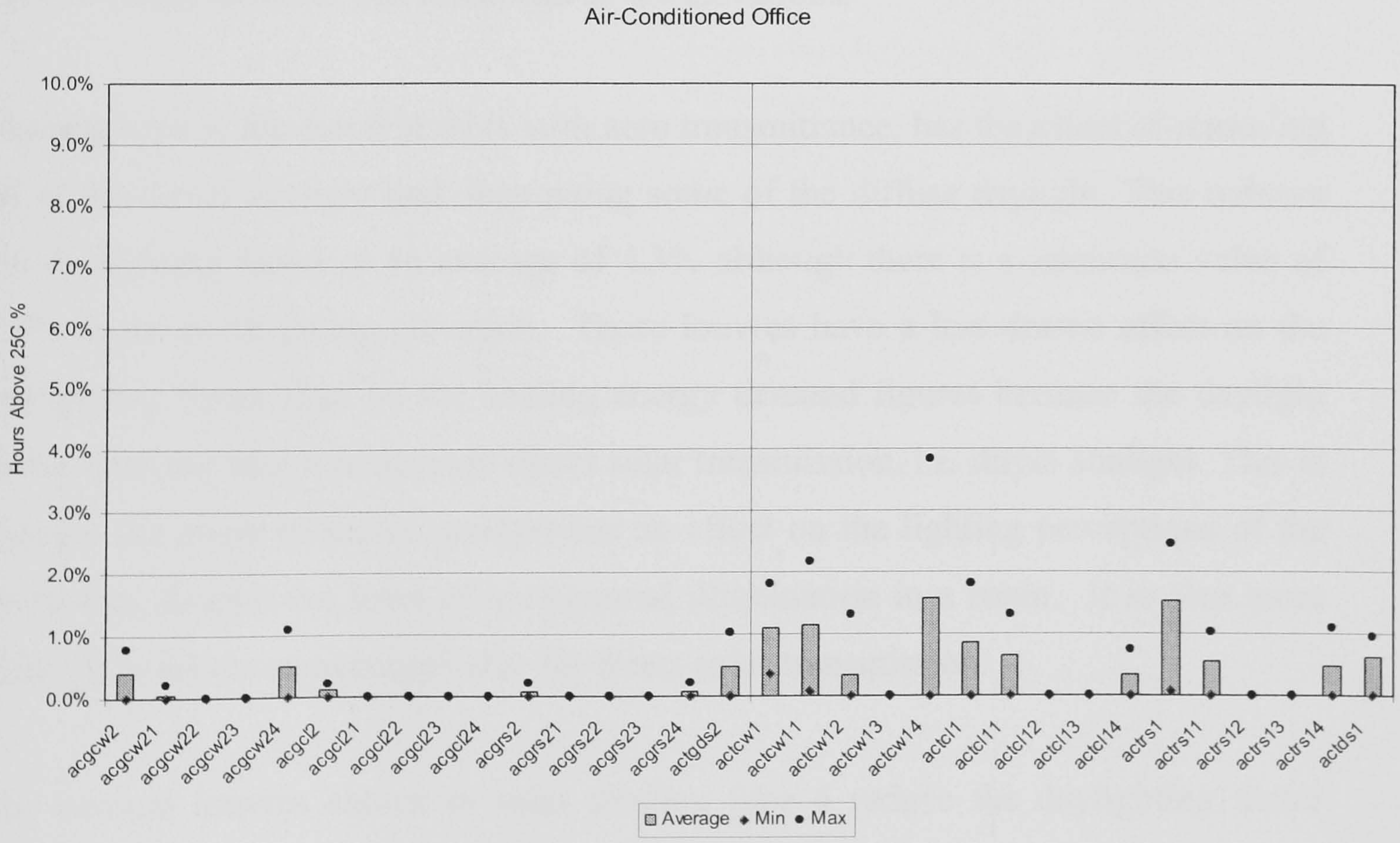


Figure C41 Percentage of working hours with a comfort temperature above 25°C in the air-conditioned office.

C5.5 DAYLIGHT FACTOR

The daylight factors for the rooms have been calculated as stipulated using the methods described in section C3.2 of the portfolio. The results are dependent on: window size, transmittance, orientation, and the desk height at which the calculations are being measured; hence there is little difference between the daylight factor for the different façade types, as shown in Figures C36 and C37. The required daylight factor is 5% with a minimum of 2.5%. All of the shading/window combinations achieve the minimum with some falling between the minimum and the required value.

The daylight factor is most sensitive to the shading factor which varies according to the shading system which is applied to the façade. The overhang, shading type 1, reduces the average daylight factor of all orientations to the minimum level required. However, it has very little impact on the east and west facing elevations, but has the largest impact on the south facing elevation. Shading type 2, the glass louvres with 50% transmittance, has the effect of reducing the daylight factor to a similar level as the overhang; however this affects all of the elevations.

Shading type 3, the metal louvres with zero transmittance, has the effect of removing all of the direct daylight and obstructing some of the diffuse daylight. This reduces the daylighting factor to an average of 4.3% although there is a minimum value of 3.5% in the north facing elevation. These louvres have a less drastic effect on the daylighting figure than on the heating energy demand figures because the daylight factor does not take into account direct solar transmission, i.e. direct sunlight. This is because the angle of direct sunlight has an effect on the lighting perceptions of the occupants, despite the level of background illumination in a room. It is also more difficult to derive an average value for direct solar transmission.

The vertical louvres shown in solar shading type 4 reduce the daylighting factor slightly by obstructing the glazing. They have a small impact on the average daylight factor because they are designed to reduce direct sunlight from a low angle, i.e. sunlight from the east or west at the beginning or end of the day.

C5.6 HOURS BELOW 18°C

The aim of this index is to compliment the minimum temperature index shown in Figures C34 and C35. There are no specific standards about the amount of hours for which the minimum comfort temperature of 18°C should be achieved. However this study has aimed to keep the hours below 18°C to a maximum of 2% of working hours.

The hours below 18°C in the naturally-ventilated offices, shown in C34, are variable by façade type and shading system. However, this is due to the methods used to control the temperature internally which were discussed in the maximum and minimum temperature section of this chapter. Of note is the fact that the double-skinned façade has a very low incidence of hours below 18°C. This shows that this building type is probably overheating during the heating season.

The hours below 18°C in the air-conditioned buildings, shown in Figure C39, are all below 1.6% of working hours, however, on inspection of the records the hours with temperatures below 18°C tend to occur in the weekend where the building has less opportunity to build up internal heat loads. As with the naturally-ventilated facades the double-skinned façade office has a much lower incidence of under heating which would suggest that this building is overheated.

C5.7 HOURS ABOVE 25°C

The indicator which shows the hours above 25°C is intended to compliment the Figures C32 and C33 which show the maximum resultant temperature. This indicator shows how many hours are above the comfort temperature of 25°C. In the tool there is another indicator which shows the hours above the maximum temperature of 28°C, however there were no instances of buildings with comfort temperatures above 28°C and this indicator was not included.

In the naturally-ventilated offices, shown in Figure C40, the offices with the high standard façade and the low internal gains had the lowest incidence of hours above

25°C, with the exception of the double-skinned façade which has an average of 3% of hours over the index. On the right hand-side of Figure C40 the offices with the high internal gains and standard façade system show a greater number of hours above 25°C. This is controlled by the application of façade shading systems as it can be seen that only the unshaded office, the office with an overhang and the vertical fins have any hours above 25°C.

In the air-conditioned offices, shown in Figure C41, the case is similar to that of the naturally-ventilated offices. The high standard façade system, with low gains has very few cases with hours above the comfort temperature. The offices with the high internal gains and the standard façade system have a greater incidence of hours above 25°C, particularly where the façade is unshaded. The double-skinned façade is within an acceptable range in the air-conditioned offices.

C5.8 ENVIRONMENTAL IMPACT

This embodied energy indicator, shown in Figures C42 and C43 is a measure of the primary energy embodied in the construction of the facade. The indicator varies by façade type rather than building type. The masonry facade, heavyweight cladding and lightweight cladding have a similar embodied energy, 1028 MJ/m^2, 1041 MJ/m^2 and 769 MJ/m^2 respectively. In each case the energy embodied in the façade is increased by the application of shading systems, particularly the metal louvres which in the case of the lightweight cladding increases the embodied energy by 52% to 1170 MJ/m^2, this is because the shading systems are constructed from materials with a high embodied energy such as aluminium and glass. When the shading devices are applied to the curtain wall façade, with the exception of the horizontal overhang, they result in a larger increase than with the other façade types. This is due to the larger glazing area and hence, larger area of the shading devices.

The curtain wall façade and the double-skinned façade, which are similar in construction, have the highest embodied energy at 1610 MJ/m^2 and 2120 MJ/m^2. However, this does not translate directly into the highest environmental impact when the Eco-Indicator 99 points, shown in Figures C44 and C45, are considered. The reduced energy consumption in the double skinned façade results in a lower environmental impact than the standard curtain wall in both cases. This is important, because the air-conditioned, double-skinned façade performs well in the internal performance indicators.

The environmental impact, in eco points, of the naturally ventilated facades is lower 122.6 pts ± 25% than that of the air-conditioned facades 146.7 pts ± 45%. The largest contributor to the eco-points scores are the points associated with the internal lighting and equipment, up to 48.2 pts in the naturally-ventilated offices and 105 pts in the air conditioned offices.

In the naturally-ventilated offices improving the façade standard and reducing the internal heat load results in a reduction 17% in the environmental impact. The double-skinned façade has the lowest environmental impact at 67 pts and 93pts. This reflects the low heating energy consumption of this façade type. The masonry façade displays a low environmental impact with an average of 98.5 pts for the high quality façade/low internal heat loads and 122.0 pts for the standard façade/high internal heat loads. This is despite a similar embodied energy to both the heavyweight cladding and lightweight cladding. The environmental impact of the lightweight cladding and heavyweight cladding is similar, although the lightweight cladding shows greater volatility by orientation.

Improving the standard of the façade and reducing the internal heat loads can reduce the environmental impact by 22% in air-conditioned offices. The curtain wall façade has the largest environmental impact of the air-conditioned offices, an average of 159.8 pts when compared to overall average of the air conditioned façades of 146.7 pts.

The application of shading systems increased the embodied energy of the facades. In the naturally-ventilated offices the reduced energy consumption resulting from the shading has resulted in very little difference between the eco-points of the various shading types. However, in the air-conditioned facades the application of shading has different effect on the different façade types. In the cooling dominated façade, the curtain wall, the application of shading systems results in a reduction of the environmental impact. The same is true to a lesser extent for the and the lightweight cladding façade. Whereas in the heating dominated heavyweight façade system the application of shading types 2, 3 and 4 results in a higher environmental impact.

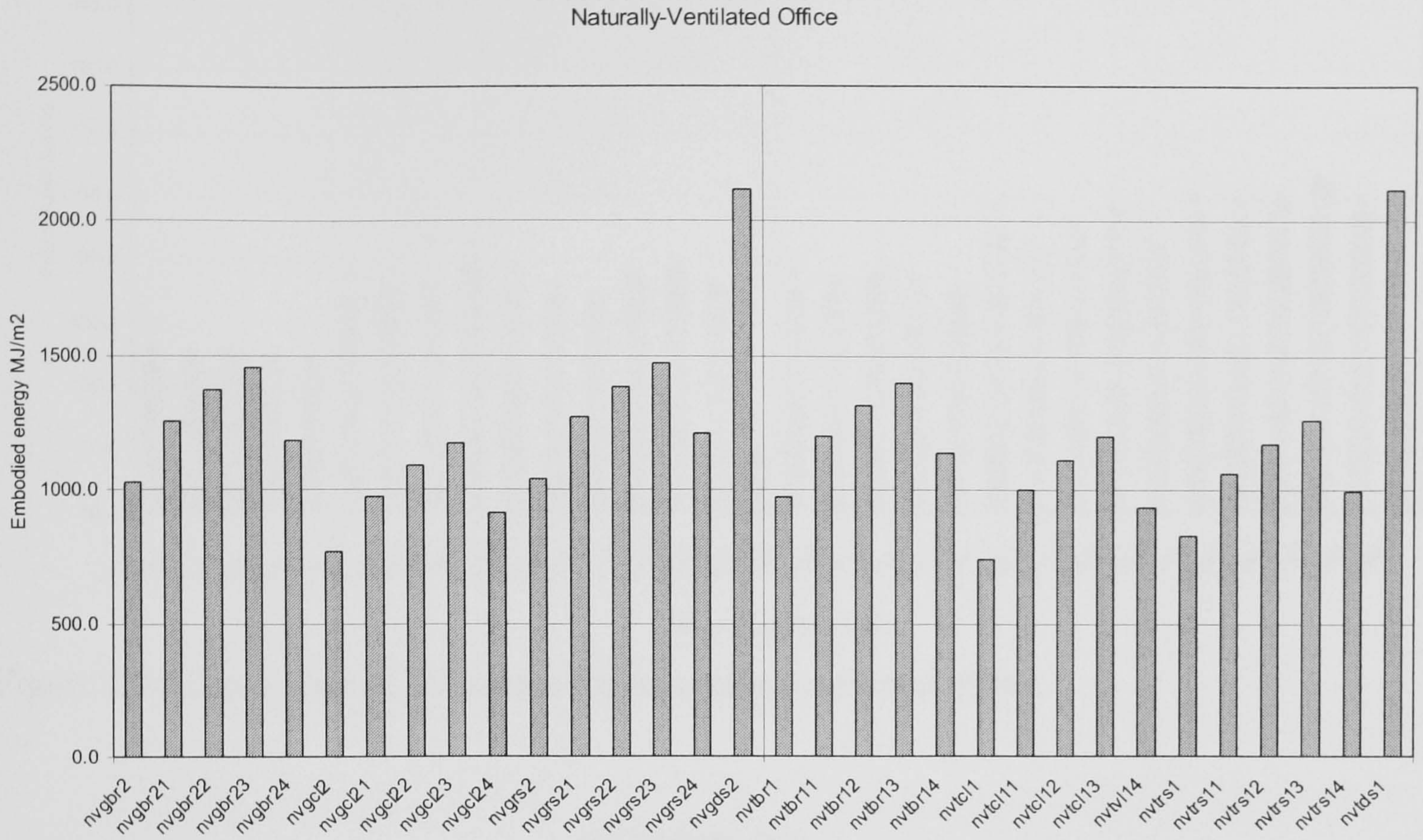


Figure C42 Embodied Energy of the facades in the naturally-ventilated office.

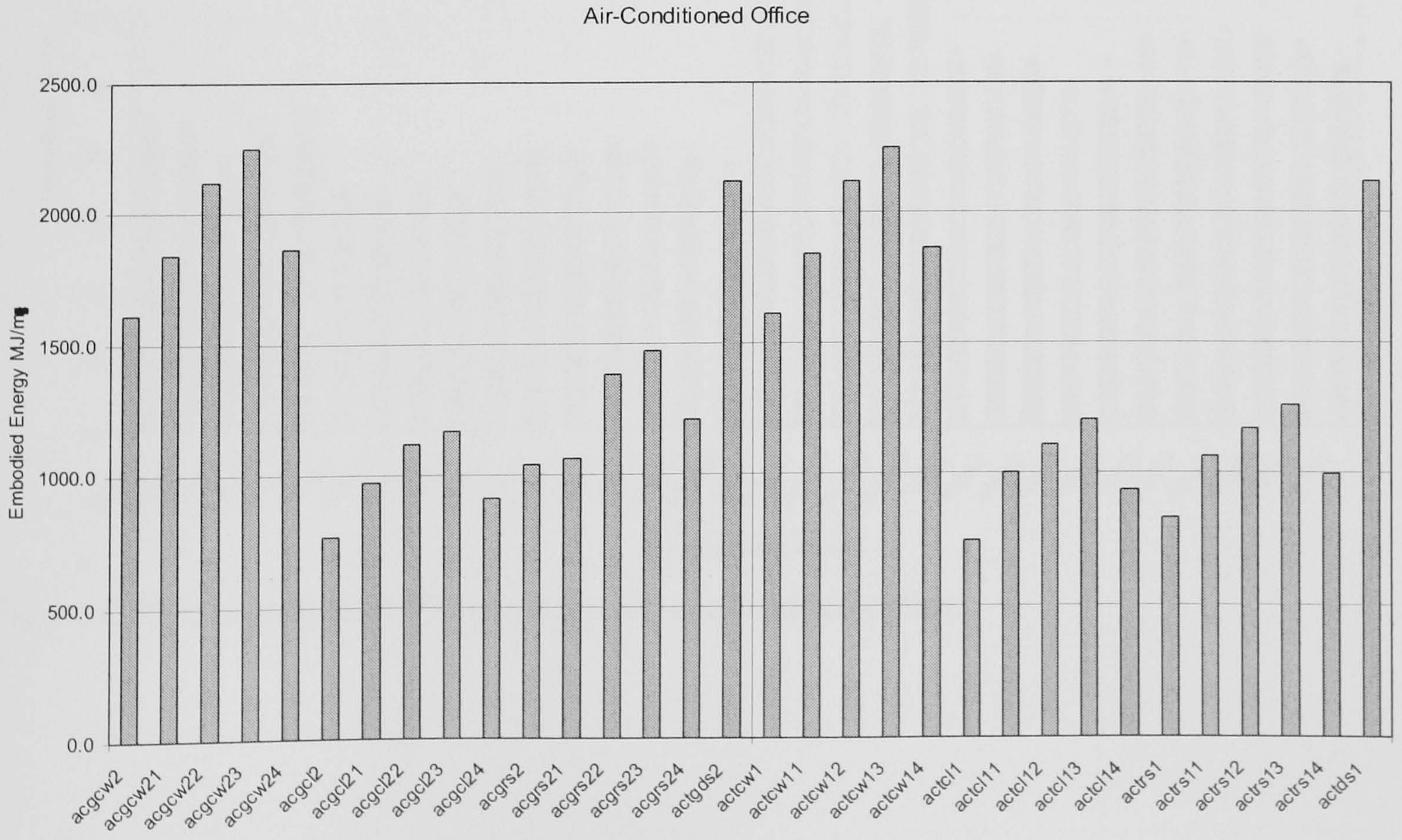


Figure C43 Embodied Energy of the facades in the air-conditioned office.

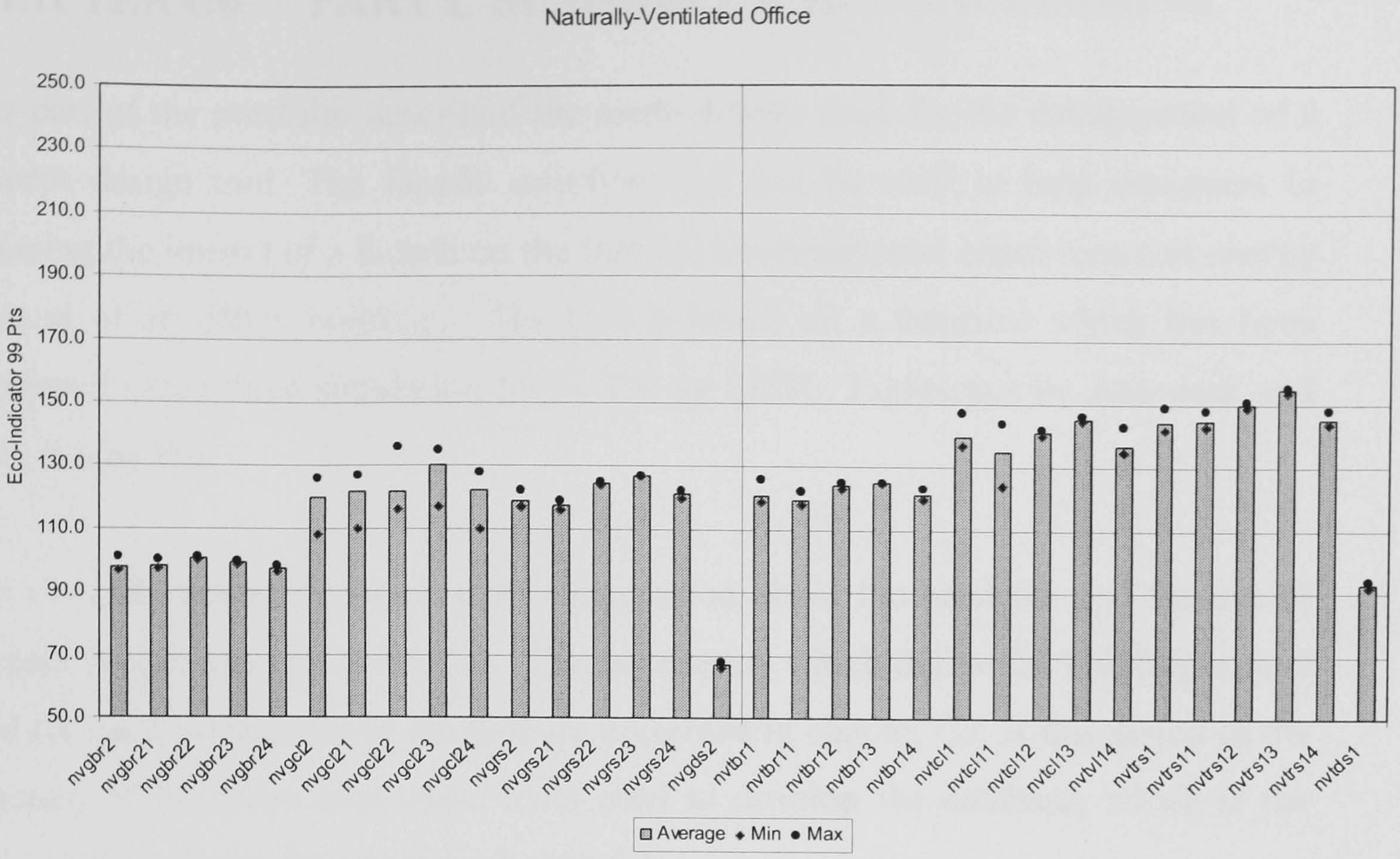


Figure C44 Eco-Indicator 99 points for naturally-ventilated office.

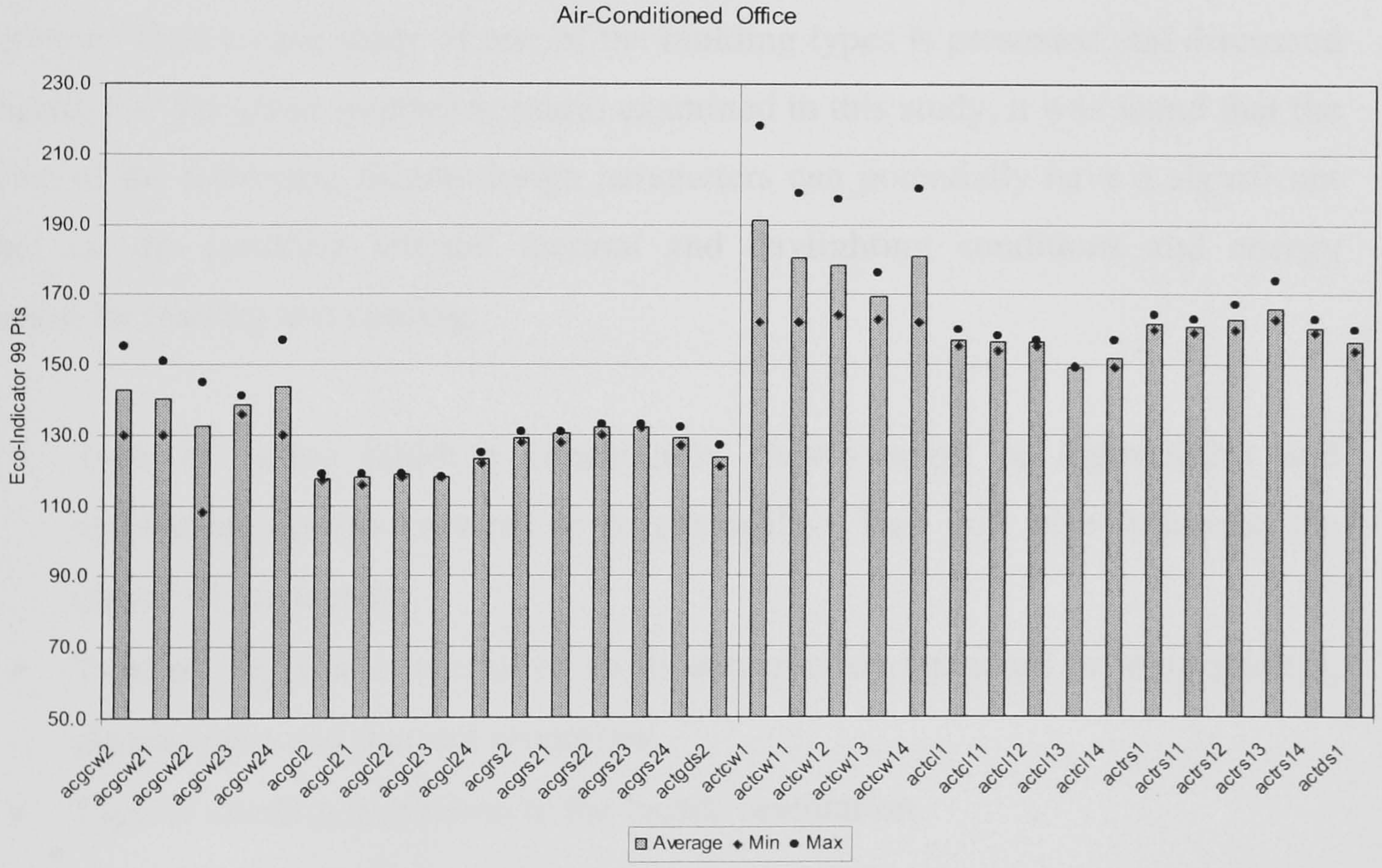


Figure C45 Eco-Indicator 99 points for air-conditioned office.

CHAPTER C6 PART C SUMMARY AND CONCLUSIONS

This part of the portfolio described the methodology used for the development of a concept design tool. The façade selection tool can be used to help designers in assessing the impact of a façade on the internal environmental conditions and energy demand of an office building. The tool is based on a database which has been developed using three simulation tools, Tas by EDSL, Lightscape by Autodesk and Sima Pro by Pré.

Part C of the portfolio begins with a discussion about the need for and the use of concept design tools (chapter C1). The parameters which define the building model used for the development of the tool are presented in chapter C2. A discussion of the selection of the three simulation tools used to develop the database, which is the basis of the tool, are discussed in chapter C3.

Chapter C4 presented a description of the façade selection tool, its options and operation. Then a case study of one of the building types is presented and discussed in detail. For the given weather scenario examined in this study, it was found that the choice of the following façade design parameters can potentially have a significant effect on the resulting internal thermal and daylighting conditions and energy demand for heating and cooling:

- Type of office building construction (heavyweight or lightweight) and ventilation system (natural or mechanical). This will also influence the choice of the façade.
- Type of the façade in relation to its construction (standard or high quality), glazing ratio and thermal properties.
- Type of shading in relation to the façade orientation.
- Internal heat gains.

The offices of naturally-ventilated Type 1 building had a lower environmental impact than the offices in the air-conditioned Type 2 building, reduced by 16% from 146.7 pts to 122.6 pts. This is due to lower consumption of energy by lighting and equipment as well as an absence of cooling load. However, the naturally ventilated offices required a larger heating load, 78.1 kW/m^2 in comparison to 25.4 kW/m^2 in the air-conditioned offices, to maintain similar internal temperatures during the heating season.

The application of appropriate shading can help to overcome overheating and reduce the cooling loads. However, the application of the horizontal metal louvres resulted in an increase in heating loads and a reduction in the daylight factor. Applying shading increases the embodied energy of the façade, in the case of the lightweight cladding, metal louvres increase the embodied energy by 52% from 769 MJ/m^2 to 1170 MJ/m^2. However, the large increases in embodied energy are not reflected in the overall environmental impact scores.

Controlling air infiltration and internal loads has a beneficial effect on both energy consumption and environmental impact as does improving the quality of the façade. In naturally ventilated offices improving the façade and reducing the energy consumption can result in a 17% improvement in the environmental impact, and a reduction in heating load of 21%. While similar changes in air-conditioned offices can reduce the environmental impact by 22%, and reduce the cooling load by 35%. Significant reductions in environmental impact can be made by carrying out these improvements even within the same façade type, for example the environmental impact of a curtain wall façade can be reduced from 191 pts to 142 pts.

The double-skinned façade, popular with architects in recent years, performs well in terms of internal conditions in the air-conditioned building type and provides environmental benefits resulting in a reduction of 16% of eco-points over the basic curtain wall. However, this building typology requires additional solar shading, such as internal blinds, in order to provide comfortable summer temperatures in the naturally-ventilated office.

The developed tool can directly help designers to realise potentially significant reductions in the energy consumption and environmental impact of office buildings by selecting the optimum façade design at the concept design stage. The parametric analysis may also help designers to take informed decisions about the concept design of façades for other building types and different climatic conditions.

OVERALL CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

CONCLUSIONS

This research has been carried out with the aim of reducing the environmental impact of buildings whilst creating a comfortable internal environment for occupants. This EngD Programme investigated the environmental impact of elements of the external envelope of buildings and their effect on environmental conditions inside those buildings.

This work has consisted of three research projects which investigated different aspects of the building facade and evaluated them with respect to their impact on the environment. The first of these projects was the assessment of the co-polymer ETFE for use as an alternative fenestration material for roofs and atria. The second project carried out a Life Cycle Analysis of a widely used building material, architectural float glass. Finally, the third project developed a computer based concept design tool to investigate the relationship between the facade choice, the internal environment and the environmental impact of a building.

The conclusions derived from this study are presented by section in a similar manner to that employed in the portfolio.

Part A: ETFE Foil Cushions

ETFE Foil is an appropriate technology for certain building applications. It is particularly appropriate where the area to be enclosed is large and high internal light levels are important. The physical characteristics of the materials used enable this approach to be used in a variety of situations where a large expanse of glass is not suitable. Further, it allows the weight of the structure to be greatly reduced whilst providing the same level of stability. ETFE Foils can improve the environmental performance of a building from two points-of-view; there is the opportunity to reduce the overall environmental burden incurred from the construction process itself and there is also the opportunity to reduce the burden of the building during its lifetime. This is all dependent, however, on the ability of architects and engineers to take advantage of both the flexibility and limitations of ETFE Foil cushions.

Part B: Life Cycle Analysis of Architectural Float Glass

It was calculated that the Pilkington float glass has an embodied energy of 13.4 ±0.5 GJ/tonne and an environmental impact of 243 ±11 eco-points per tonne. Both of these indicators suggest that the environmental burdens associated with this plant are in line with those that would be expected by a plant of this type in the UK. The small difference between the Pilkington float glass and the average flat glass value from the BRE, 13 GJ/tonne, is easily explained, most notably by slight differences in the LCA boundaries. Pilkington Glass used the results from this study to investigate their procurement and intend to carryout further such studies into their product range.

Part C: Concept Design Tool for Façade Selection

A Façade Selection tool was developed using three simulation tools, *Tas*, a dynamic thermal model, *Lightscape,* a lighting analysis tool and *SimaPro,* a lifecycle analysis tool. The application of the Façade Selection tool at the concept design phase of office construction will enable designers to use eight headline indicators to evaluate the suitability of a façade for a particular application. A parametric analysis of the database within the tool showed that using natural ventilation where possible can reduce the environmental impact of offices by up to 16%. Improving the standard of the façade and reducing the internal heat loads from lighting and equipment can reduce environmental impact by 17% in naturally-ventilated buildings and 22% in air-conditioned buildings.

RECOMMENDATIONS FOR FURTHER RESEARCH

The recommendations for further research are presented in three sections, which refer to the three parts of the portfolio.

Recommendations for Part A: ETFE Foil Cushions

The use of ETFE in buildings could be improved by lowering the thermal transmission through the cushions from the interior to the exterior of the building. This would reduce the amount of heating load required to keep the space at comfort temperature. There are several avenues of inquiry which could lad to improvements in this area:

1. The application of soft surface coating to ETFE in order to reduce the emissivity of the material
2. Design a new framing system, which incorporates thermal isolation. While this would not improve the thermal transmittance of the cushions it would help to reduce the thermal transmission through the roof as a whole.
3. Application of shading inside the cavity would allow the user to control the solar transmission and hence reduce unwanted solar gain.

Recommendations for Part B: LCA of Architectural Float Glass

The system for producing architectural float glass has been developed by commercial companies to optimised the cost of processing, but not necessarily to reduce the environmental impact of the process. The environmental impact of the process could be reduced by investigating the following areas:

1. Soda ash has a large environmental impact on the process, this could be reduced by changing the supply of soda ash from manufactured to natural soda ash. Ways should be sought to reduce the quantity of soda ash in the melt.
2. A reduction in the quantity of dolomite, which has a hazardous impact on human health, would help to reduce the environmental impact of the float glass manufacturing process.

3. Increasing the quantity of cullet in the melt would help to reduce the consumption f natural resources and energy. At present this process does not use any cullet from outside sources. If a reliable supply of cullet from secondary sources, such as curtain wall manufacturers and glaziers, could be supplied this would help to reduce the amount of waste glass which goes to landfill.

Recommendations for Part C: Development of Concept Design Tool for Facades

The investigation into the environmental and internal impacts of facade construction could have been expanded to consider other options. However, the size of this study did not allow for any further expansion. These topics were raised during this work as interesting questions which might merit further research:

1. Investigate the financial implications of the facade options in particular the impact of the select on the whole life cost. This would be interesting in the case of the high quality facades which have a higher initial outlay and but may result in lower whole life costs.
2. Include the element of internal shading, such as an internal blind, as this the application of this simple shading device would have a significant impact on the energy consumption of a building. However, this requires some study of buildings in use to assess user behaviour with regard to the implementation of shading systems.
3. An investigation of design for recycling in construction and an analysis of drivers for recycling in the construction industry.
4. Expansion for the study to include more complex variations of facade and building type. For example the retail sector consumes a similar proportion of the delivered energy in the UK.
5. Development of the tool to include the ability to compare two different facade types simultaneously.

GLOSSARY, REFERENCES, BIBLIOGRAPHY AND APPENDICIES

GLOSSARY

AIVC	Air Infiltration and Ventilation Centre
ASHVE	American Society for Heating and Ventilation Engineers (now ASHRAE).
ASHRAE	American Society of Heating Refrigerating and Air-Conditioning Engineers.
BBA	British Board of Agrément
BEPAC	Building Energy Performance Analysis club
BESTEST	Building Energy Simulation Tests
BRE	Building Research Establishment
BRECSU	Building Research Establishment Council Support Unit
BUWAL	Swiss Agency for the environment, forests and landscape
CIB	Conseil Internationale du Bâtiment
CIRIA	Construction Industry Research Information Agency
DETR	Department for the Environment Transport and the Regions (now DTRL)
DOE	Department of the Environment for England and Wales (replaced by DETR)
DTI	Department for Trade and Industry
DTRL	Department for Transport Local Government and the Regions
ETH-ESU	
ETSU	Energy Technology Support Unit
EU	European Union
IDEMAT	
IEA	International Energy Agency
LCA	lifecycle analysis
NPL	National Physical Laboratory
PTC	Pilkington Technology Centre
SPOLD	
VOC	volatile organic compound

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APPENDIX E1: PUBLISHED RESEARCH PAPERS.

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ETFE foil cushions in roofs and atria

S. Robinson-Gayle[a,b,*], M. Kolokotroni[a], A. Cripps[b], S. Tanno[b]

[a] *Brunel University, Cleveland Road, Uxbridge, Middlesex UB8-3PH, UK*
[b] *Buro Happold, Consulting Engineers, 17 Newman Street, London W1T-1PD, UK*

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stract

3uilding fenestration can be responsible for a significant impact on the environment created in a building, affecting, either /ersely or beneficially, both the health and perceptions of the occupants. Alternative to traditional fenestration solutions have :n available for a great many years, one of which is ethylenetetrafluoroethylene (ETFE) a co-polymer of PE and tetrafluo- :thylene which has been used for the past 20 years for atria and other overhead glazing. This study examines both the effects of 'FE manufacture and its use in buildings. This study has considered both its performance in terms of fitness for purpose and in nparison to glass, the common alternative. Some built examples of ETFE foil roofs are presented. It is concluded that ETFE is an appropriate technology for certain building applications, in particular those where the volume of space is large and high it levels are important. ETFE foils can improve the environmental performance of a building and may reduce the overall 'ironmental burden incurred from the construction process itself and the burden of the building during its lifetime. © 2001 evier Science Ltd. All rights reserved.

words: Atria; Roof; Environment; ETFE foil cushions

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ntroduction

'he impact of buildings on the environment is a well :ussed issue, with consensus at the moment on con- ıing to build new buildings whist trying to ensure t all new buildings have the minimum environmen- impact possible. Schemes such as Building Research ablishment Environmental Assessment Method EEAM (for which Buro Happold are assessors) e encouraged wider interest in these issues, but 'e is still much progress to be made.

he role of buildings is to moderate the environ- ıt, which often means excluding the external envi- nent in order to provide a suitable internal environment. Yet, it is possible to use the positive aspects of the external environment and provide a compromise between the inside and the outside. Atria have often been seen as an intermediary between the internal and external space particularly with regard to climate control. They can be used as a design element in climate adapting buildings, those that attempt to moderate the external environment rather than isolate it. Robertson [1] lists the following as features of climate adapting buildings:

- efficient daylighting;
- good orientation;
- efficient solar radiation control; and
- natural ventilation.

A wish to provide environmentally sensitive, 'healthy' and aesthetically pleasing buildings has increased the use of glass in buildings as atria and skylights. Yet this

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'orresponding author. Tel.: +44-0171-927-9700; fax: +44-0171- '701.

nail address: syreeta.robinson-gayle@burohappold.com (S. nson-Gayle).

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an substantially increase the embodied energy of uildings and there are many situations where glass is ot a viable option because of the geometry of the uilding. Hence, a plethora of alternatives to glass have een tried, mainly polycarbonates, but they have all ad limited success. What is required from a glass lternative is the ability to provide the benefits of using lass without the drawbacks, which includes the need o provide a flexible sealing system to take into account hermal expansion.

The present paper is part of a bigger project, which ttempts to evaluate ETFE as an alternative to glass. he project began in 1997 as part of the Construction esearch and Innovation Business Plan of the Departent of Environment Trade and Regions (DETR) [2]. he project details the state of the art in ETFE foil pplication as a building material, concentrating in articular on 'cushions'. The project is split into four arts:

- General information.
- Detailed physical property testing and thermal modelling.
- A study of buildings in use.
- A design guide to help promote best practice.

This paper discusses the findings of the general inormation guide that covers the physical properties, the tness for purpose and previous applications of ETFE il cushions.

What are ETFE foil cushions?

ETFE cushions are a multi-layer system that consists several layers of ETFE foil (100–200-μm thick) heat aled and clamped in a frame. They are inflated using small pump to a pressure of 250–400 Pa and topped intermittently.

ETFE was first used a roofing material in a zoo ilding in Burgers Zoo, Arnheim in the Netherlands 1981. It has subsequently been used in various ildings predominantly in the United Kingdom and rmany. The cushions allow a high performance flexe roof with double curvature to be constructed [3].

Why ETFE in buildings?

The basic function of ETFE is to modify the environnt inside a building to the benefit of its occupants, in ler to judge this it is necessary to compare the perties of ETFE with that of glass, which is the terial it seeks to replace.

3.1. Light transmission

This material is used primarily because of its ability to transmit light in the same manner as glass. Indeed, ETFE transmits 94–97% of visible light a higher percentage of visible light than ordinary 6-mm single glazing which only transmits 89%.

Design for natural daylighting takes into account not only the total percentage of light transmitted but also the range of frequencies transmitted, which is important for colour rendering, ETFE foil cushions performance is equivalent to that of glass. Another factor is picture transmission, although a high amount of light is transmitted the picture rendering is not equal to that of glass, because the surfaces of the cushion are curved. Although lettering would appear distorted, it is easy to see clouds below an atrium roof.

3.2. Sound transmission

ETFE foil cushions are, in effect, non-existent when it comes to sound, they transmit practically all sound with a R_w (dB) of 8. This can be viewed in different ways for different design questions. If the building is a library beside a motorway or train station this could be a problem, but if it is a leisure centre in a field this is a good solution as internal noise is transmitted out rather than reflected back into the building. In an atrium, footfall is not reflected around so the internal space can be very quiet, but conversely rain is easily audible.

3.3. Insulation

The thermal properties of a building are an important consideration, they impact on the thermal performance and ultimately the energy cost of the building. A well insulated building will be both easier to heat and easier to cool than a badly insulated building. The U value is an index measuring the heat flux through an element per unit of surface area and temperature difference. An ETFE foil roof will have a better rating for insulation, U value at 1.9 W/m^2K (horizontal) in comparison to single glazing at 6.3 W/m^2K (horizontal) and double glazing 3.2 W/m^2 (horizontal)[1].

3.4. Solar control

It is a feature of transparent materials that not only do they let in light, but they can let in too much light (glare) and heat. However, this is a similar problem for

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[1] Calculated from the vertical figures with reference to CIBSE Guide AJ-20.

ith glass and ETFE foil cushions and measures should taken to eliminate glare and the transmission of lar radiation inside.

5. *Physical properties*

ETFE foil is a co-polymer of ethylene and Teflon®. iis polymer displays characteristics of both of these iterials, being easily moulded blown and extruded e polyethylene and anti-adhesive like Teflon. Unlike her polymer roofing materials, ETFE is very stable d able to resist chemical and UV attack so that its tical properties are not diminished over time tests being run by the manufacturers and current tests ve run for 25 years.

The key properties of ETFE are given in Table 1.

i. *Environmental performance*

i.1. *Manufacture*

ETFE is manufactured from fluorspar, hydrogen sule and trichloromethane (CaF_2, H_2SO_4 and $CHCl_3$). e fluorspar or fluorite is the largest natural store of orine, it is found all over the world and is often ned in conjunction with limestone. These raw materils are used to make chlorodiflouromethane, a class substance under the Montreal treaty on ozone deting substances (which does not contribute to global rming). This undergoes pyrolysis at 700°C to give $_2 = CF_2$, which can be polymerised using US patent 4016345. The by-products of this process are $CaSO_4$, l and HF. The calcium sulfate and hydrogen fluoe are used to make more fluorspar and the other ste products are incinerated. The polymerisation icess uses water and a dispersing agent this process arried out at approximately 125°C.

The raw materials in glass are sand, soda, dolomite, estone and feldspar, with a certain amount of cullet iss chips) [6]. These are available as minerals in ious places, although soda is also manufactured. erefore, the main impacts of glass manufacture are those due to mining/quarrying, resource depletion and the energy costs of transportation.

le 1
sical properties of ETFE foil and glass

	ETFE foil [4]	Glass [5]
nate tensile strength nm^2)	40–46	50–100 (toughened) 10–20 (annealed)
ing range (°C)		
lass transition temp.)		600
nelting temp.)	150	1200
lness (N/mm^2)	31–33	5500
l stress (N/mm^2)	30–35^a	
ure mechanism	Plastic deformation	Brittle fracture

Yield stress is temperature-dependent.

Table 2
Embodied energy for ETFE foil and glass

Embodied energy	ETFE foil	6-mm float glass
EE (GJ/t)	26.5	20
EE per m^2 (MJ/m^2)	27.0	300

3.6.2. *Embodied energy*

This is a concept that takes into account the amount of energy used to produce material and includes the energy associated with mining, mineral purification and processing. The results of our calculations of the embodied energy for ETFE foil and glass are presented in Table 2.

Although the values of embodied energy per tonne of material is similar, it is very different when a suitable functional unit is compared, like area covered by roofing material.

3.6.3. *Processing*

ETFE is sold by manufacturers in granules, it is heated to its softening temperature of 170°C in the hopper of an extruder. The extrudate is then blow moulded into large sheets 50–150-μm thick. The sheets are heat welded together to form the three layer cushion. The pneumatic cushions are suspended in aluminium or steel frames. The finished cushions ready for installation on site require a tenth of the energy to transport when compared with similar construction in glass due to its much lower density.

The float glass process is well documented [6]. However, the most important feature is the very high heat input needed to cause the raw materials to combine. There are also very significant gaseous by-products, principally CO_2, SO_x and NO_x. There is virtually no solid waste in the process. The energy aspects of this are addressed through the embodied energy data presented in Table 2.

3.6.4. *Resource consumption in use*

The anti-adhesive nature of ETFE means that roofs and atria need to be cleaned less frequently than similar glass roofs. This leads to a reduction in the cost to the owner of the building, but also a reduction in the use of detergents and water to maintain the building.

Higher daylight factor due to greater transmittance of light can lead to a reduction of artificial light used in buildings. This directly reduces the energy consumption of the building and improves the atmosphere inside buildings.

A good U-value decreases the amount of heat lost hrough the roof, directly reducing the burden placed n the heating system of the building. However, care is eeded in the design to avoid overheating. For glass, here is no energy needed in use. ETFR foil cushions re kept inflated by using an electric fan, this uses a mall amount of energy, approximately 50 W per 1000 ^{2}.

.6.5. Recycling

The process used to manufacture the three layer ushions does not require any additives to the co-polyer system and other products are not mixed. The ushion can be directly removed from its aluminium ame and washed. Once the material is clean it can be ecycled by heating it to its softening temperature. The oftening temperature of ETFE is low so this is not a ery costly operation, the recycled ETFE can be added to the hopper with virgin ETFE.

Glass is also very recyclable and bottle glass is very ften reused or recycled. However, float glass process is ery sensitive to any impurities, which can result in atastrophic failure, so that in practice float glass is not ecycled to float glass. The fixings and frames used for lass cause problems when recycling, particularly those ade from aluminium, because aluminium causes inusions and bubbles to form inside the molten glass at cannot be removed. There is a very low tolerance f imperfections in float glass.

6.6. Fire by-products

The by-products of burning and incineration of ETFE e toxic fumes including CO and HF. On a small scale ese occur in a tiny amount so for example the ash d fume created by a building fire would be very substantial. In the event of a fire beneath an ETFE il cushion roof, the polymer would recoil from the mes and vent the fire. However, when using incineran as a disposal method, special precautions have to taken to avoid the discharge of fumes and the ntamination of water by waste [7].

Glass does not burn under building fire conditions, there are no issues relating to its by-products, alough if the fire is intense enough it will shatter so ere are design issues relating to overhead glazing in e conditions.

.7. Landfill

Due to the inert nature of ETFE, a foil roof which s disposed of, would create very little contamination hough there is a slow release of HF gas from the ls. Glass is very inert and will remain in the ground thousands of years as will ETFE foil. In most uations, reuse or recycling is preferable environmen- option to landfill.

4. Applications

As mentioned before, ETFE foil cushions have had a number of applications in building roofs over the last 10 years or so. Two examples in the UK are, the atrium of the Chelsea and Westminster Hospital occupied in 1992 and the Hampshire Health and Tennis Centre completed in 1994. Two photographs and some details of the buildings are presented in Figs. 1 and 2. The use of ETFE foil cushions in the two buildings presented here and a number of others have been surveyed and results will be reported in the future.

Project data, client: North West Thames RHA; structural engineers (building): Watermans; structural engineers (roof): Buro Happold; completion date: July 1992; project value: (roof) £1.6 million.

The hospital is built around a naturally ventilated central atrium. The atrium roof is a vaulted central nave along which all the departmental entrances are situated wards face in to the atrium and it acts as a light well. The overall size of this atrium is 116 m long by 85 m wide. There are three layer cushions with a white middle layer around the edges of the roof in order to reduce the solar gain and glare [8] and the central area has transparent cushions.

The Chelsea and Westminster hospital houses out-patient clinics, therapeutic units and a busy accident and emergency ward. It is in the centre of London and was built to replace the old Brompton Hospital, which is now a specialist unit. All access to wards is on

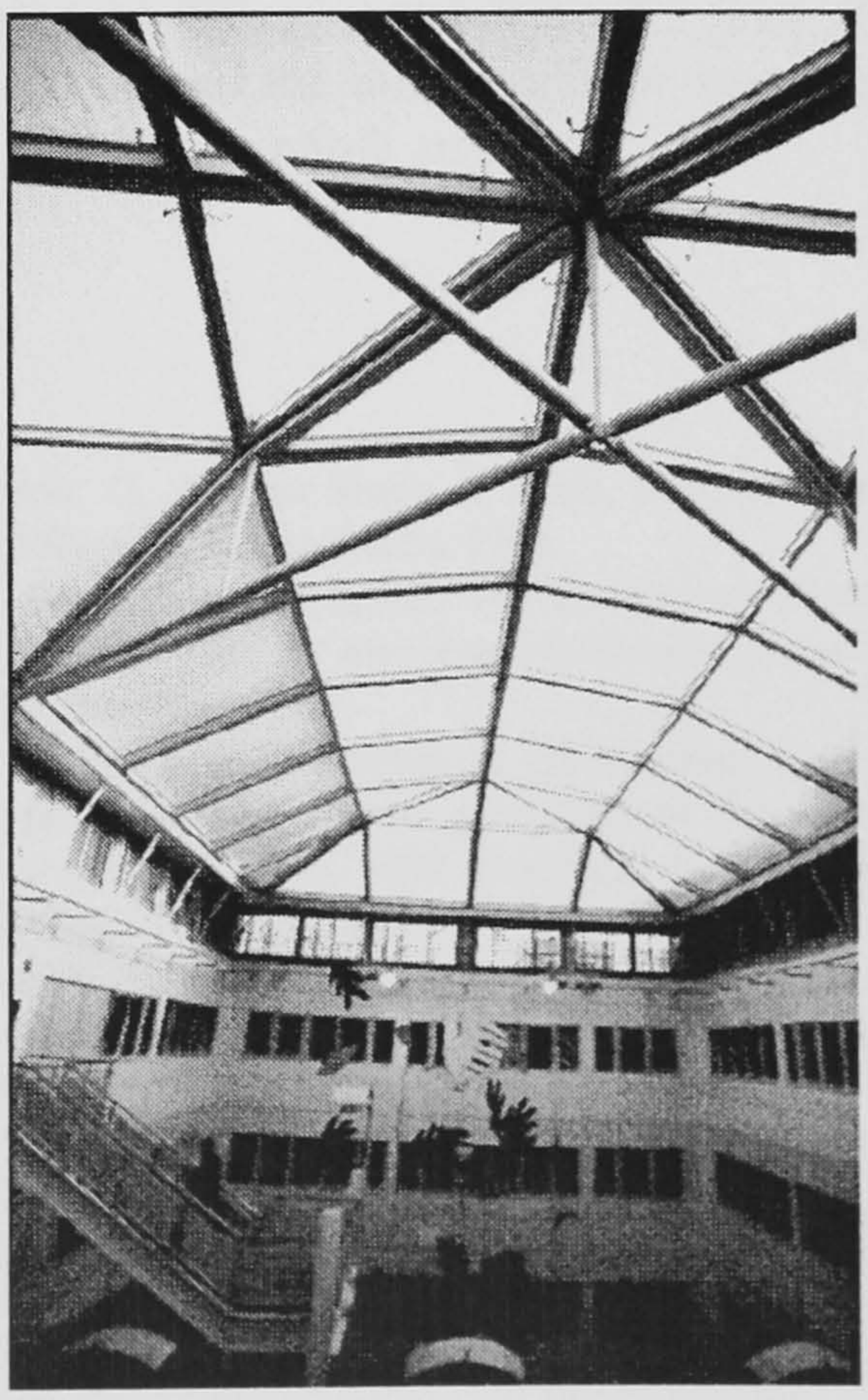

Fig. 1. View of the atrium of Chelsea and Westminster Hospital in London.

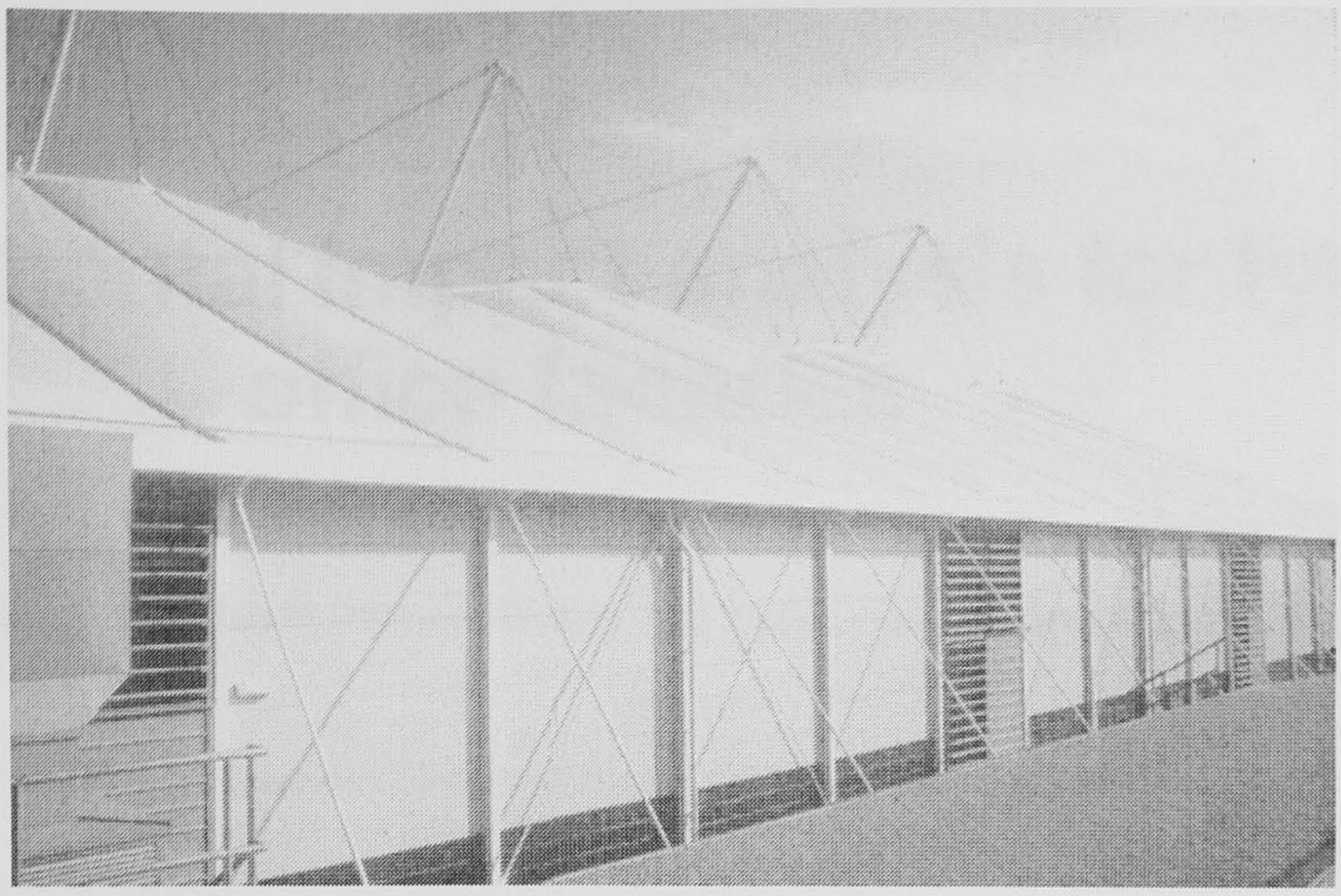

Fig. 2. External view of the roof of the Hampshire Health and Tennis Centre.

rridors suspended in the central atrium with the in reception area, a shop and restaurant/café area the ground floor level.

Project data, client: Tennis country club; architect: an Borland Associates; structural engineers: Buro ppold; services engineering: Buro Happold; project ue: £4.5 million.

The building is 6000 m^2 and consists of two central ildings with ETFE foil roofs. The roofs are triple er cushions 18 × 3 m. These, together with a system opposed eternal steel masts and pre-tensioned ca- s, form two ridged structure separated by a steel rtal frame, which serves as a central corridor giving cess to all of the tennis courts.

This building received the Lawn Tennis Association cility of the Year Award in 1994. In the case of the nis centre, the ETFE foil is particularly successful the white colour gives exceptionally good lighting for indoor courts. For such a large space the energy is very acceptable and the users we spoke to were delighted with it.

onclusions

TFE Foil is an appropriate technology for certain lding applications. This is the case particularly where volume of space is large and high light levels are ortant. The materials physical characteristics en- it to be used in a variety of situations where a e expanse of glass is not suitable, it allows the ght of the structure to be greatly reduced whilst viding the same level of stability. ETFE foils can rove the environmental performance of a building n two points of view: there is the opportunity to uce the overall environmental burden incurred from the construction process itself; and there is also the opportunity to reduce the burden of the building during its lifetime. This is all dependent, however, on the ability of Architects and Engineers to take advantage of both the flexibility and limitations of ETFE foil cushions.

Acknowledgements

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Environmental impact analysis for typical office facades

Maria Kolokotroni[1], Syreeta Robinson-Gayle[1,2], Stephen Tanno[2] and Andrew Cripps[2]

[1]Department of Mechanical Engineering, Brunel University, Uxbridge UB8 3PH, UK
E-mail: maria.kolokotroni@brunel.ac.uk

[2]Buro Happold, 17 Newman Street, London W1P 3HD, UK

The design of a building facade influences internal thermal and lighting conditions and energy use associated with the provision of these conditions. Key decisions about the building facade are usually taken during the concept design stage of a building, while decisions about the method of providing the environmental conditions are often made later in the design process. This dilemma is addressed by the development of a concept design tool that allows the design team to investigate the effect of facade design on the resulting internal environmental conditions, energy use and environmental impact. The concept design tool was developed by performing detailed thermal, lighting and environmental modelling for a number of generic office building facade designs and a range of parameters that affect directly the environmental performance of an office building. The results are presented in a user-friendly interface requiring a minimum number of inputs. Key parameter outputs (such as temperature, lighting levels, heating/cooling energy demand, embodied energy and eco-points) can then be viewed, while a more detailed analysis can also be created for specified facade designs. A parametric analysis of the summary result outputs for selected facade parameters indicates that natural ventilation and cooling can reduce the environmental impact of offices by up to 16%, although heating energy demand could increase significantly. Improving the construction standard of the facade and reducing the internal heat loads can reduce the environmental impact by up to 22%. Use of this tool at early design stages will benefit the design team through an improved understanding of the dynamics between facade design and building services and assist with a more integrated approach.

Keywords: curtain wall, design, design tool, environmental impact, facade, glazing, life cycle analysis, louvres

oduction

ling facade design is developed at a very early of the design process. It is often the basis for award of the contract to a particular firm of itects or developers. A detailed energy analysis e facade and its effect on the internal environ- of the building could be carried out when the cing strategy is being developed. However, led analysis requires information about the ing that may not have been decided on at such rly stage and relegates detailed energy analysis e latter stages of design. However, at latter n stages the potential for changes to the exter- ppearance of the building is severely restricted e plans submitted to the planning authorities. allows only small variations in the facade design ovide the best option since the overall facade typology is 'locked' into the design at an early stage by the nature of the process.

The greatest opportunity to evolve an environmentally efficient facade design is at the earliest stages of the design process. The difficulties of choosing the optimum facade solution can be summarized by the following questions:

- Which combinations of facade type and shading will provide the best performance in terms of internal conditions, environmental, energy and cost performance?
- If more stringent restrictions were imposed on one of the parameters, i.e. environmental performance, which facade would give the best performance?

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- If most of the parameters are fixed by the site, which options will fit within the performance constraints required by the client/brief?

This paper describes the rationale and methodology for developing a concept design tool for evaluating the effect of the facade design on the building internal thermal and lighting conditions, energy demand and environmental impact in office type buildings in England.

Q11 Recently, a number of concept design tools have been developed. Some focus on one technology such as night ventilation for cooling (Kolokotroni, 1998) and others on the integration of two or more environmental conditions provision in generic or specific types of buildings. For example, the LT method (Baker and Steemers, 1999) and Office Design Tool (Bunn, 1999) are two concept design tools developed in the UK. Both tools treat the building facade as a combination of solid and open (glass) areas, but do not consider the facade design in detail.

Through an extensive literature review, no single concept or simplified design tool was identified that would address the impact of various facade types of non-domestic buildings in terms of the provision of thermal and lighting conditions as well as energy demand and environmental impact. The authors are aware of two concept design tools aimed towards the optimization of thermal impact of facades in residential buildings: RESFEN (University of California, 1999) and OPTI (Gratia and De Herde, 2002). Both tools were developed by using advanced dynamic thermal simulation tools. RESFEN includes US weather data and is restricted to energy predictions. OPTI is based on Belgian weather data and outputs include internal thermal and lighting conditions as well as energy demand estimation. For facade systems suitable for non-domestic buildings, a simplified tool exists (Aarons and Glicksman, 2001) to assist the feasibility of double-facade systems. For this tool, an energy model was used to carry out calculations of internal comfort and lighting levels as well as energy demand.

In general, concept design models can be divided into two categories:

- Results are extracted from built-in databases derived from advanced modelling for a specified number of cases (in the form of parametric analysis) and weather data (usually country restricted)

- Results are calculated from built-in (usually energy and thermal) simplified or fast-to-run algorithms and appropriate databases for other variables of interest such as lighting and acoustics

It was decided to develop the tool described here using the 'database' approach because (1) the results would be based on detailed and advanced modelling, and therefore more accurate; and (2) user misinterpretation of results would be more difficult as the selection of cases is restricted by the development of the tool. The tool was developed by using three simulation models:

- Dynamic thermal simulation model provided energy demand and internal thermal conditions data

- Steady-state lighting simulation model calculated the lighting environment based on the optical properties associated with the facade. The lighting model shared a common model format with the dynamic thermal modelling tool

- Life Cycle Analysis (LCA) accounting tool calculated the impacts associated with the construction and use of the building based on information about the construction and energy use in the building over a fixed period

Method of tool development

This section describes the building model used to carry out the parametric analysis, which generated the datasets to be used in the concept design tool. The following parameters were considered:

- Office type

- Facade type

- Shading type

- Internal environmental conditions and energy practice

- External conditions

Office type

Two building types were modelled; the building types were developed from the information provided by Leighton and Pinney (1990), Saporito and Day (1997) and DETR (1998). A large database of office buildings in the UK was used to develop four office building typologies that are described in detail in the above three references in terms of construction and operational details. The present work used the two office types that most adequately reflected the construction typical in urban locations:

- Type 1: Naturally ventilated open-plan office. This is based on the traditional structure prevalent in UK cities, which is often refurbished to provide modern office space. This type of office building can range from 600 to 4000 m^2, typically open plan, but with some areas closed off such as meeting rooms. This building has a high thermal mass and is likely to be less than five stories high with medium internal heat loads

- Type 2: Air-conditioned prestige office. This type is usually a national or regional head office and typical size ranges from 4000 to 20 000 m^2. This building usually has low thermal mass, is more than five stories high and tends to have high internal heat loads

ie simulation results were based on a single office ace (6 m deep, 10 m long, 3 m high) with a single face)m) as an external facade. This office form was used various energy simulation experiments in the UK g. CIBSE, 2002b). All surrounding buildings were nsidered to be of similar heights, with a city aspect d a ground solar reflectance of 0.2. The building entation can be rotated through the cardinal points 0, 90, 180 and 270°. The construction of the floor/ ling slabs is used to change the thermal response of : building.

description of the characteristics of the facade types ;iven in Table 1, which lists the facade types accord- ; to building structure and ventilation system. Note it only the facade of the last category, 5, is different the two considered structures. Therefore, six differ- facade types were considered in total. In all cases, o systems were defined: standard (SS) and high qual- (HQS). These were achieved by altering the glazing operties and/or the *U*-value of the cladding panel. ese changes will influence the thermal properties and leakage characteristics of the facade. Two different leakage rates were selected to represent the quality the system: $HQS = 0.3\,ach^{-1}$ and $SS = 0.5\,ach^{-1}$. sponse factors for the materials were also specified. se are a measure of the thermal response of a mate- : the higher the response factor, the heavier weight building is. A response factor (F_r) less than 6 is con- red lightweight (Leighton and Pinney, 1990). All rnal surfaces were surrounded by other offices or ridors having the same internal temperature as the ce being considered. Therefore, there is no net heat v through internal surfaces. A description of the ide constructions is shown in Table 2.

Solar shading

Solar shading is a very important consideration when specifying a facade considering its environmental impact. Solar gains could increase heat gains considerably and be a source of glare. Four shading options were modelled for each facade type as follows (Figure 1):

- Type 1: horizontal overhang 75 cm deep with 0% transmittance
- Type 2: louvres 40 cm deep at 45° with 50% transmittance
- Type 3: louvres 10 cm deep at 45° with 0% transmittance
- Type 4: vertical fins 75 cm deep with 0% transmittance

These types are typically used for office buildings in the UK (Littlefair, 1999).

Internal environmental conditions and energy practice

The building occupancy, other internal heat gains, air exchange rate and temperature set points for each day were set as hourly values repeated for each day type. There are three day types: weekdays, Saturdays and Sundays. The occupied period was specified for each day type and it varies according to the building type. A Type 2 office has longer occupation hours with some use at the weekends. The controls were linked to the occupation of the building. A Type 2 office (air-conditioned) had both heating and cooling set points, while no cooling set point was specified for a Type 1 office (naturally ventilated). For a Type 1 office, the openings were used to control the internal summer temperature; these were scheduled according to the external temperature, wind speed and wind direction.

Internal and external heat gains

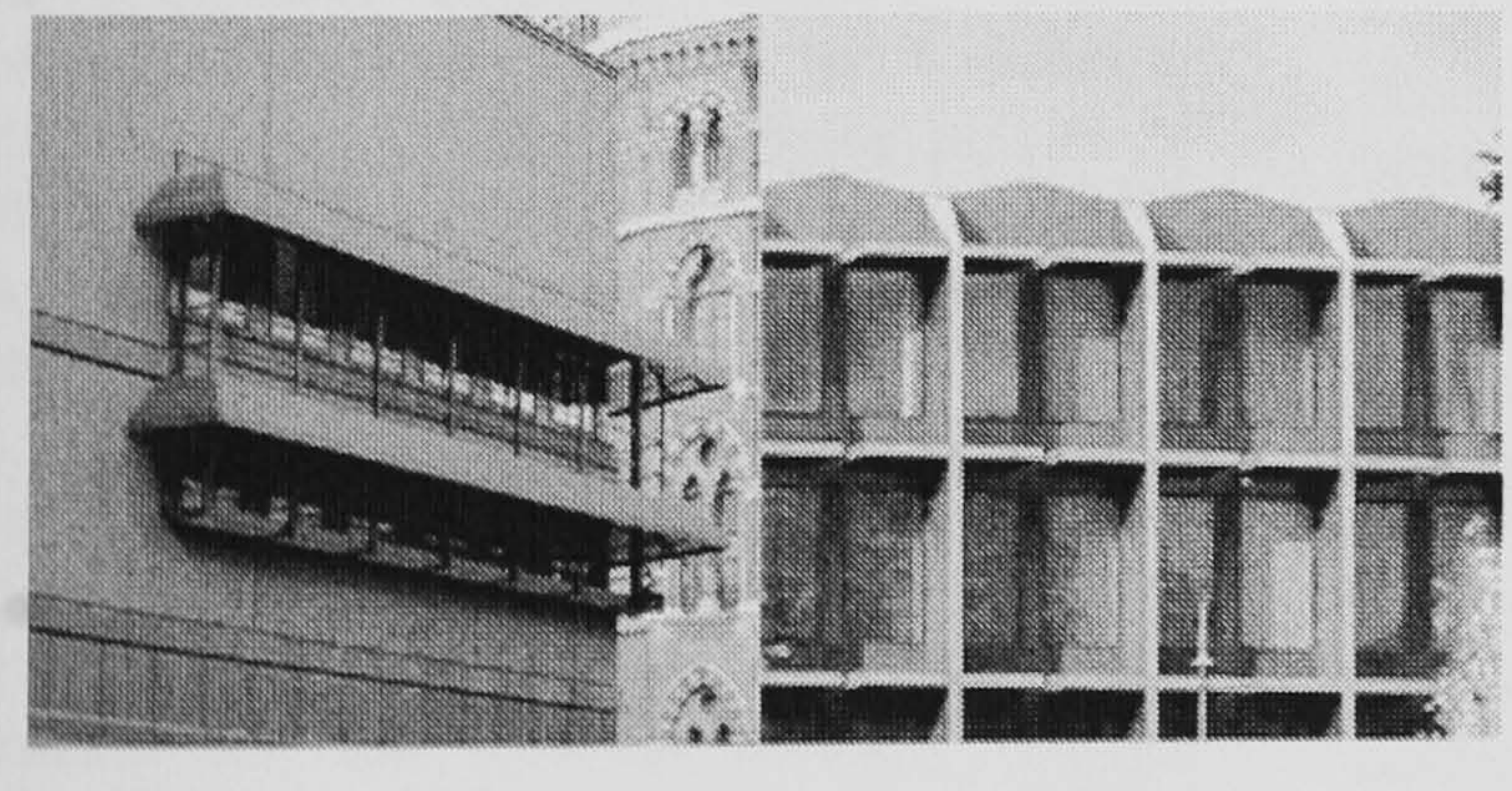
The internal gains were defined using the profiles in the ECON 19 energy survey (DETR, 1998) separately for each building type and are presented as a total value (W/m^2). Two modes available for the level of internal

Table 1 Facade types described by the building structure and ventilation system

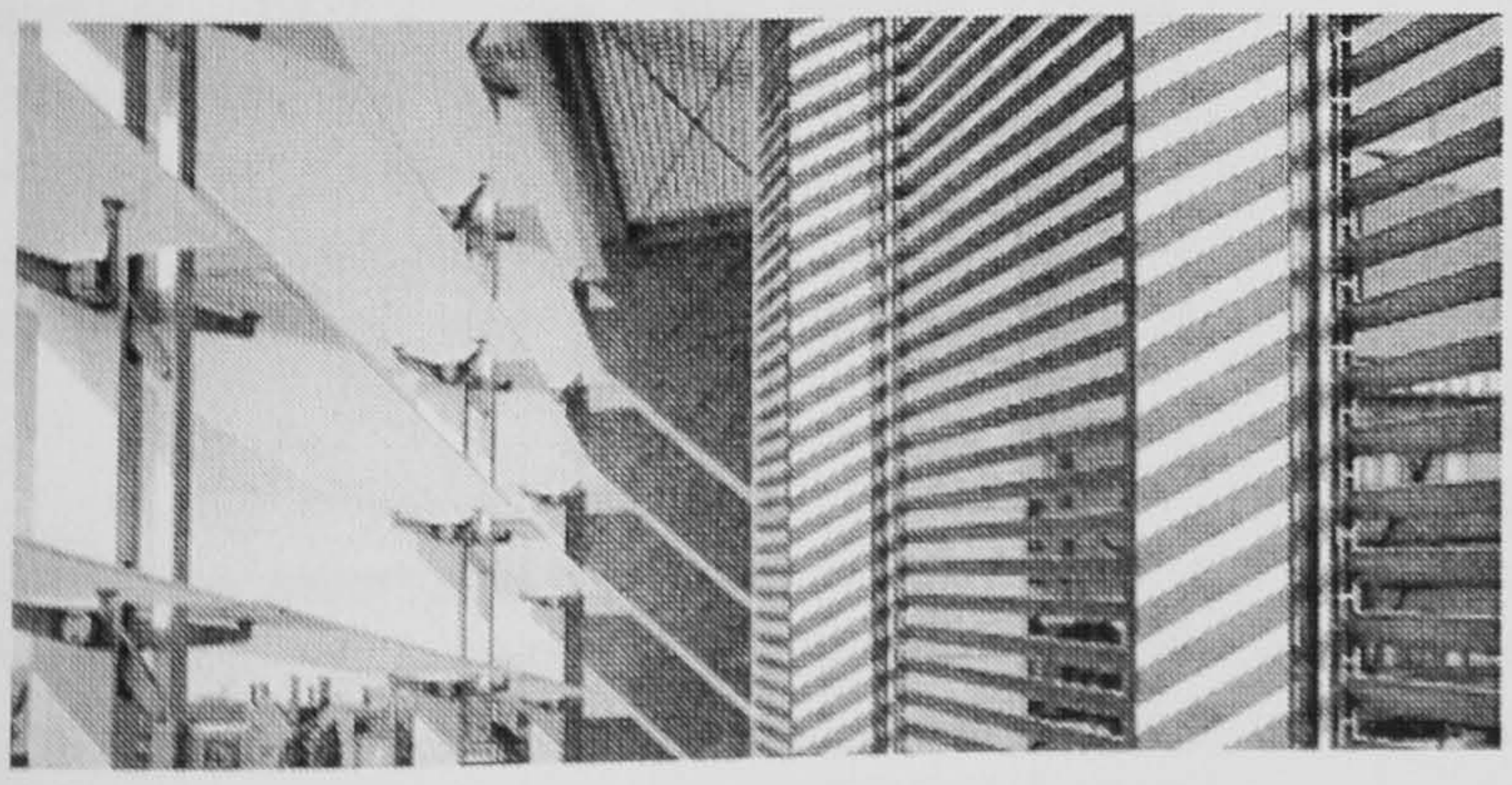
Category	Heavyweight masonry structure with natural ventilation	Lightweight steel-framed building with air-conditioning
1	Lightweight cladding with 50% glazing ratio	Lightweight cladding with 50% glazing ratio
2	Heavyweight cladding with 50% glazing ratio	Heavyweight cladding with 50% glazing ratio
3	Internal Weatherseal double-skinned facade	Internal Weatherseal double-skinned facade
4	External Weatherseal double-skinned facade	External Weatherseal double-skinned facade
5	Traditional masonry wall with 50% glazing ratio	Curtain walling

Table 2 Detailed descriptions of facade constructions

Element	Construction	U(W/m^{2}K)	Solar trans.	Light trans.	F_r
Floor type 1 building	Lightweight concrete, screed	1.4	–	–	3.1
Floor type 2 building	precast concrete plank	1.7	–	–	7.2
Internal walls	plasterboard, concrete, plasterboard	1.5	–	–	1.2
SS lightweight cladding	metal, insulation, metal	0.5	–	–	1.3
HQS lightweight cladding	metal, insulation, metal	0.3	–	–	1.3
SS heavyweight cladding	concrete, insulation, concrete	0.5	–	–	7.5
HQS heavyweight cladding	concrete, insulation, concrete	0.3	–	–	10.8
SS masonry cladding	brick, air cavity, insulation, block, plaster	0.5	–	–	5.2
HQS masonry cladding	brick, air cavity, insulation, block, plaster	0.3	–	–	5.5
Metal spandrel panel	aluminium, insulation and plasterboard	0.35	–	–	3.5
SS glazing	8-mm toughened glass, 12-mm air cavity, 8.4-mm laminated glass	1.7	0.4	0.78	–
HQS glazing	8-mm toughened glass, 12-mm argon filled cavity, 8.4-mm laminated glass	1.5	0.4	0.79	–
Double-skinned facade glazing (internal)	12-mm toughened glass, 0.2-m cavity, 8-mm float glass, 12-mm argon, 8.4-mm laminated glass	1.1	0.3	0.71	–
Double-skinned facade glazing (external)	12-mm toughened glass, 0.8-m cavity, 8-mm float glass, 12-mm argon, 8.4-mm laminated glass	1.1	0.3	0.71	–
Curtain wall glazing	10-mm toughened glass, 12-mm air cavity, 10.6-mm laminated glass	1.6	0.4	0.7	–



Horizontal overhang Vertical fins



Louvres

Figure 1 Types of solar shading considered

gains reflect the *energy practice* of the building occupants; these represent good (energy-efficient) and typical practices (Table 3). Solar gains were calculated hourly from the solar data and materials' properties to build a yearly figure for each configuration of facade types, orientations and shading options.

Ventilation rates

During the occupied period, it was assumed that the space had an occupancy rate of one person per 12 m^2, who required a ventilation rate of 8 l/s (McMullan, 1998). The background infiltration rate is assumed to be 0.5 ach^{-1} for SS construction and 0.3 ach^{-1} for HQS construction. Where mechanical ventilation is used, the rates (ach^{-1}) were set to reflect these requirements, but in the naturally ventilated building indoor air quality and summer temperatures were controlled by a combination of background ventilation, (i.e. through trickle vents), comfort ventilation through opening windows and night-time ventilation.

Lighting levels

A combination of average daylight factor (ADF) and distribution of daylight diagrams were used to assess the daylighting levels provided by the facade and the

Table 3 Building internal gains for both building types (DETR, 1998)

	Units	Type 1		Type 2	
		Typical practice	Good practice	Typical practice	Good practice
Lighting	W/m^2	15	12	20	12
Occupants	W/m^2	16	16	16	16
Equipment	W/m^2	12	10	18	15
Ventilation rate	$1/m^2$	N/A	N/A	4	4

rgy savings that can be made using a controlled
hting scheme. Lynes (1995) argued convincingly that
average daylight factor was a good basic guide for
effectiveness of a facade in reducing the artificial
hting costs. A room with a high average daylight
tor and a low uniformity will still result in an
dequate lighting solution. Distribution of daylight
grams provide a daylight factor profile and will
w the user to gauge the uniformity of the light
vided.

ather data

namic thermal simulations were carried out for a full
r. The weather data were selected using the guidance
CIBSE (1999a). The example weather years (EWY)
re used to provide dry bulb temperature, global solar
liation, cloud cover, wind speed and direction, and
tive humidity. The winter period (October–April)
modelled using data from Kew 1964/5 as this is the
in CIBSE EWY usually used for heating load calcu-
ons and its dry bulb temperature has a distribution
se to the long-term average. Summer (May–
tember) was modelled using data from Heathrow
0 (Levermore, 1998). It was considered necessary
se a weather year with higher than average dry bulb
peratures (Heathrow 1980 includes maximum dry
b temperatures reaching 31°C). While this work was
progress, new guidance was published (CIBSE,
2a) on the selection of EWYs. The new recommen-
ions propose Heathrow 1989 as the CIBSE design
mer year for the south-east of England. Average dry
b temperature for the summer months (April–
tember) for Heathrow 1989 is 15.9°C, while the
e average is 14.3°C for Heathrow 1980.
refore, the weather file used for summer calcula-
s here is cooler on average. However, it is warmer
the weather file recommended for Manchester,
an average summer dry bulb temperature of
°C.

ulations and user interface

ulations were carried out with the resulting 150
lels that combined all parameters described above.
nentioned above, a dynamic thermal model was
to predict internal environmental conditions and
gy requirements for heating and cooling, a steady-state daylighting model was used to predict daylight factors and an LCA model was used to calculate environmental impact. All simulation models used were commercially available and validated. A database was created with the simulation results and a user interface was written in Visual Basic to help users to interrogate it. A description of the available outputs for the user is presented below.

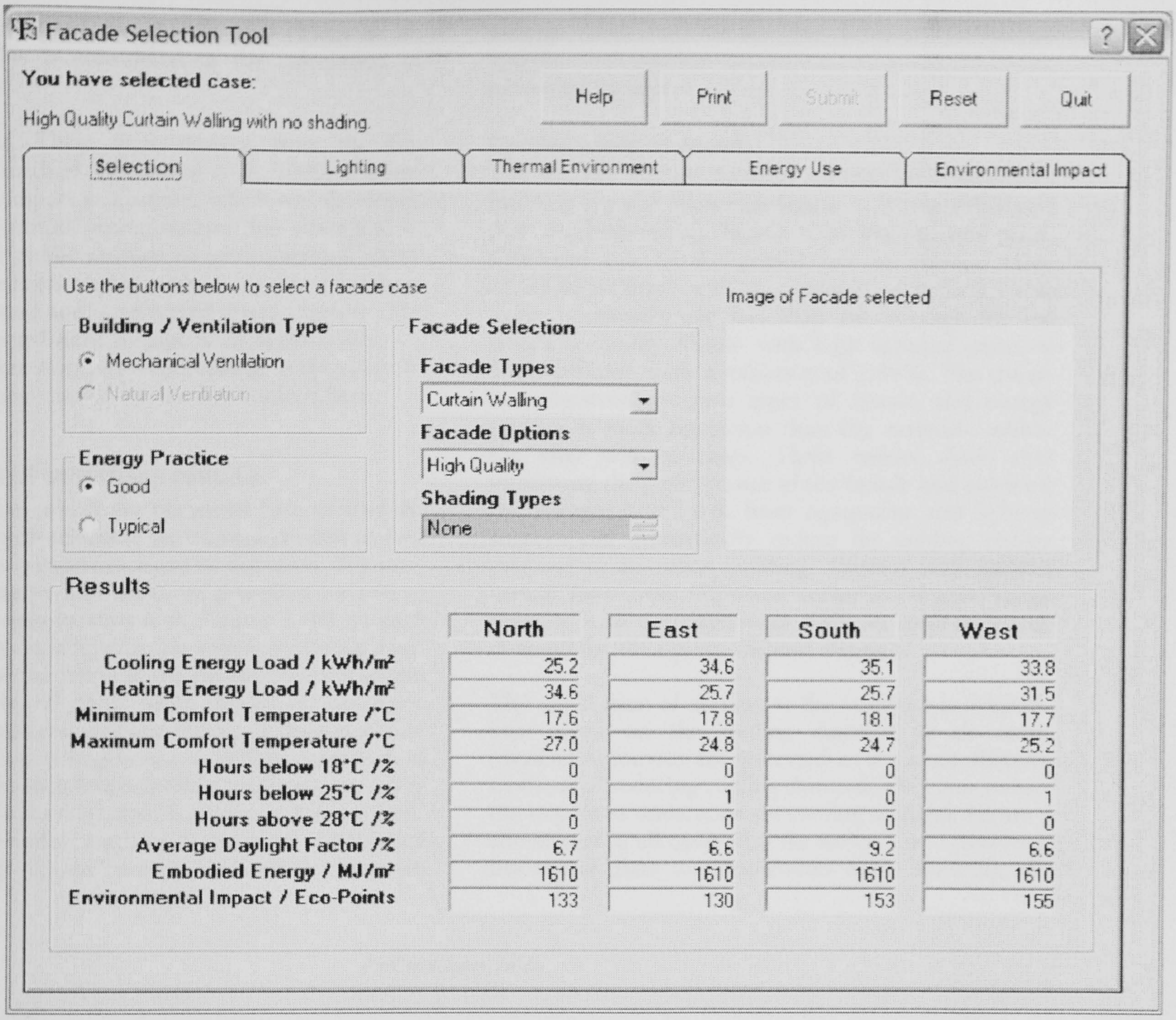
Description of output results

Two levels of information were contained within the output parameters. Key performance criteria were chosen for the first level (summary results), while more detailed information was provided at a second level. The second-level outputs are not described in detail here, but an example is presented below in the form of a case study. Second-level outputs included thermal comfort indicators (average hourly comfort internal temperature and relative humidity), daylight distribution diagrams, heating and cooling energy demand (for each month of the year and by category such as heating, cooling, humidification and dehumidification), and environmental impact indicators (eco-points arranged by subsystem of manufacture, in use phase and disposal of the materials to landfill and by the sphere in which those impacts occur such as human health, eco system damage and resource depletion).

The summary outputs are discussed in more detail below and some results are also shown. The initial screen of the tool (Figure 2) shows that the following parameters can be assessed very quickly describing the performance of a specific facade type throughout a whole year:

- Heating energy demand. This is annual energy (normalized per m^2 floor area) required to maintain the set internal minimum air temperature during operation hours throughout the year

- Cooling energy demand. This is annual energy (normalized per m^2 floor area) required to maintain the set internal maximum air temperature during operation hours throughout the year. It applies to a Type 2 office only



You have selected case:

High Quality Curtain Walling with no shading.

Use the buttons below to select a facade case

Building / Ventilation Type

● Mechanical Ventilation

○ Natural Ventilation

Energy Practice

● Good

○ Typical

Facade Selection

Facade Types

Curtain Walling

Facade Options

High Quality

Shading Types

None

Results

	North	East	South	West
Cooling Energy Load / kWh/m²	25.2	34.6	35.1	33.8
Heating Energy Load / kWh/m²	34.6	25.7	25.7	31.5
Minimum Comfort Temperature /°C	17.6	17.8	18.1	17.7
Maximum Comfort Temperature /°C	27.0	24.8	24.7	25.2
Hours below 18°C /%	0	0	0	0
Hours below 25°C /%	0	1	0	1
Hours above 28°C /%	0	0	0	0
Average Daylight Factor /%	6.7	6.6	9.2	6.6
Embodied Energy / MJ/m²	1610	1610	1610	1610
Environmental Impact / Eco-Points	133	130	153	155

Figure 2 Initial screen of the tool indicating the required input and presenting summary outputs

- Maximum comfort temperature. This comfort index (average of surface weighted radiant and room air temperature) was selected instead of air temperature because radiant temperature could play an important role in some facade types. For example, curtain wall facades can create a large cold or hot area within the space, which will significantly affect internal comfort. Comfort temperature is equivalent to dry resultant temperature (CIBSE, 1999a) for indoor air speeds below 0.1 m/s

- Numbers of hours that maximum temperature exceeds 25 and 28°C. This index is particularly important for naturally ventilated buildings for which recent research (CIBSE, 1999a; Brager and Dear, 2000) indicates that internal temperatures could be allowed to increase to a certain level and for a certain percentage of the year without affecting internal thermal comfort

- Minimum comfort temperature. For a similar reason as for maximum temperatures, the comfort temperature index is used to describe the provision of minimum comfort conditions

- Daylight levels. An average daylight factor is provided that is calculated using algorithms set out in CIBSE (1999b)

- Embodied energy (ee). The overall energy used in a facade is likely to dominate its efficiency, but this must be traded against the energy embedded in the building. The ee of a facade is a function of the materials used in its construction and it gives some indication of the impact of a building on the environment. However, it does not take into account the lifetime effects of the choices used (Yates *et al.*, 1994). This is considered in the calculation of eco-points

- Eco-points. These were derived from the Eco Indicator method (Goedkoop *et al.*, 2000) of environmental impact assessment, which was developed using an attitude questionnaire that attempted to assess the public attitude to environmental harm. The advantages of this method are that it has been widely tested and is respected internationally. The data collected have Europe-wide applicability, i.e. the data are normalized according to the environmental harm caused by one European citizen

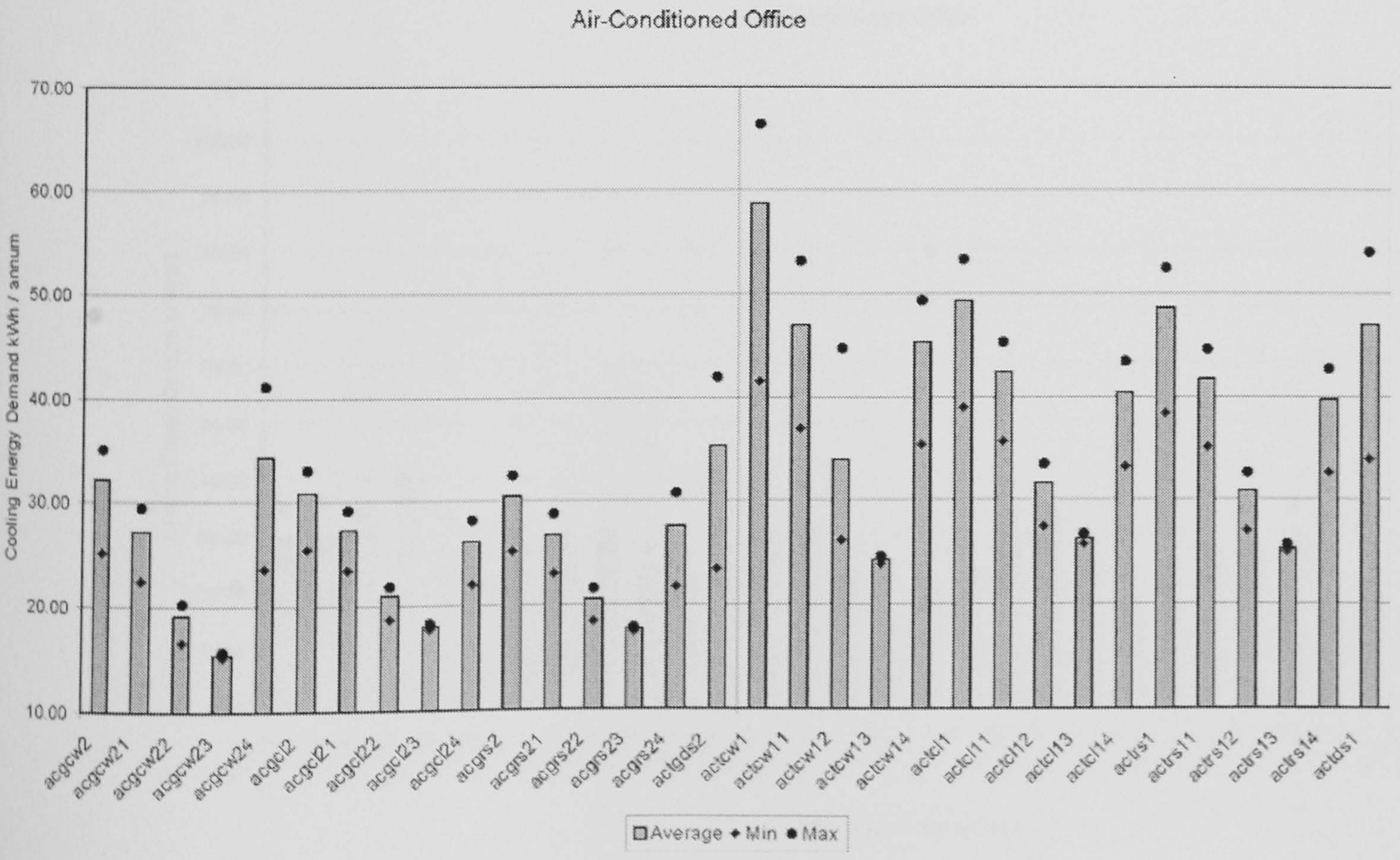
iscussion of summary results

me summary results are presented here so that the pact of facade selection on internal conditions and vironmental performance can be discussed. The sum- ry performance indicators are presented for two of e building options shown in Figures 3–10. In each ph, the high standard facade with low internal gains presented on the left with the standard facade system th high internal gains being shown on the right. ese combinations were selected for discussion as they e typically found in practice. A building case code is ed to refer to each facade/building option case. A key the code used in the graphs is shown in Table 4. Note t each case code is made up of five parts representing rious facade option choices. Each graph shows an average value (bar) for the four different orientations together with extreme values (maximum and minimum) presented by dots.

Cooling energy demand

The cooling energy demand for the air-conditioned building types is shown in Figure 3. It was calculated that the high-quality facade with low internal gains (left-hand side of the graph) has an average value of 25.65 kWh/m^2 with a variation of ±63%. This value is considerably less than the average for the standard quality facade with high internal gains of 39.50 kWh/m^2 with a variation of ±68%. The difference between the two types of facade and energy options is more significant than the variation within the two sets of cases. These results show that improving the performance of the facade and reducing the internal heat loads from equipment and lighting sources can dramatically reduce the cooling energy demand in an office building. Curtain wall facades benefit most from improved construction and energy practice with a reduction of 48% in cooling energy demand for the option without shading.

The application of shading to the facades has a significant effect on the cooling demand in all cases. Horizontal louvres are indicated as the most effective methods of reducing cooling demand. They also reduce the impact of orientation on cooling demand. Figure 3 shows that in all cases with the suffix 2 or 3 (denoting horizontal glass and horizontal metal louvres), the



re 3 Cooling energy demand in an air-conditioned office

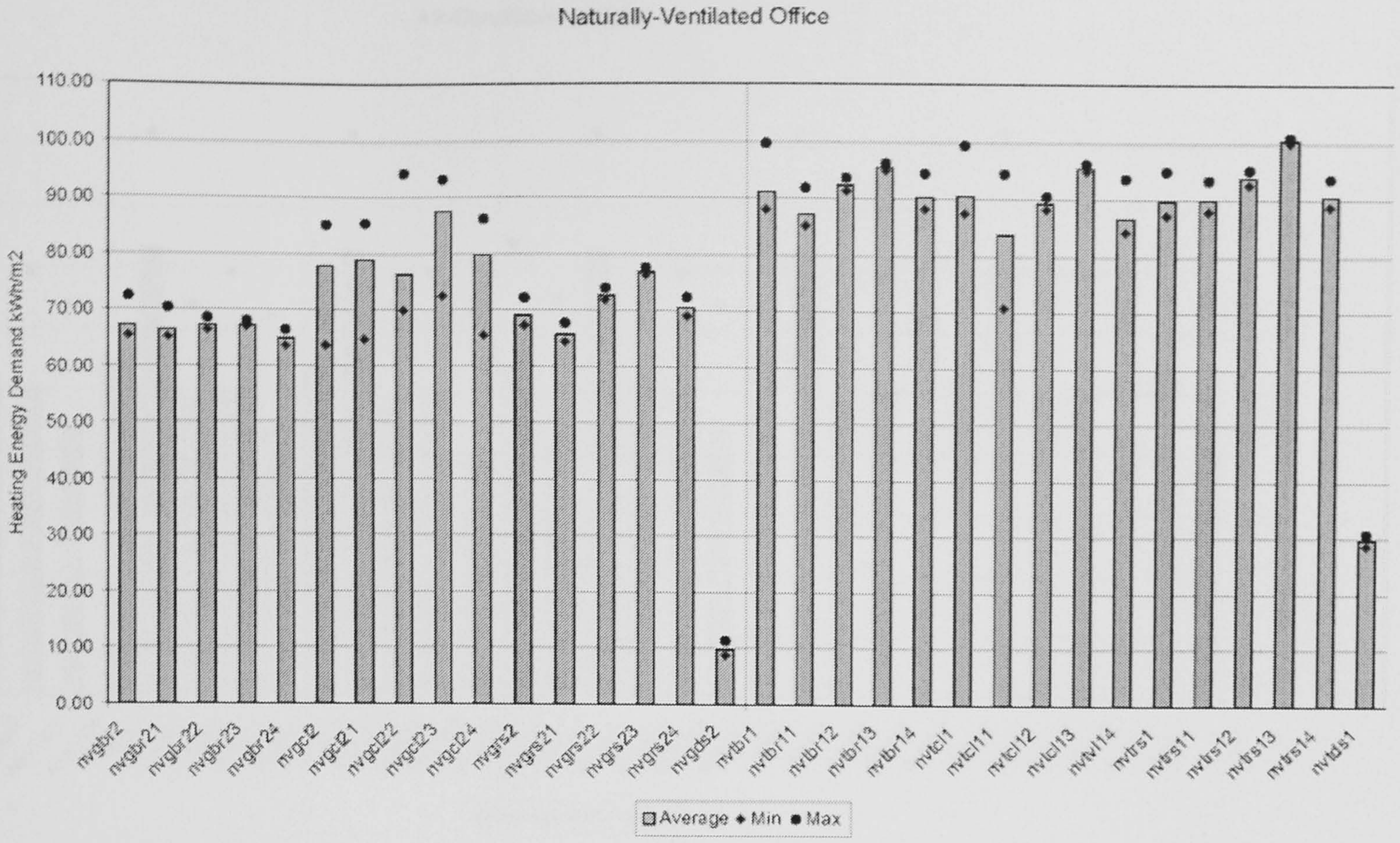


Figure 4 Heating energy demand in a naturally ventilated office

mean, minimum and maximum values begin to converge. The application of vertical louvres to a facade made solar control more complex and, in some instances, resulted in higher cooling demand than the facade without shading.

The construction of the facade also has an effect on cooling energy demand. Figure 3 shows that the cooling energy demand for lightweight metal cladding (cl), heavyweight concrete cladding (rs) and double-skinned (ds) facades are similar. This suggests that the

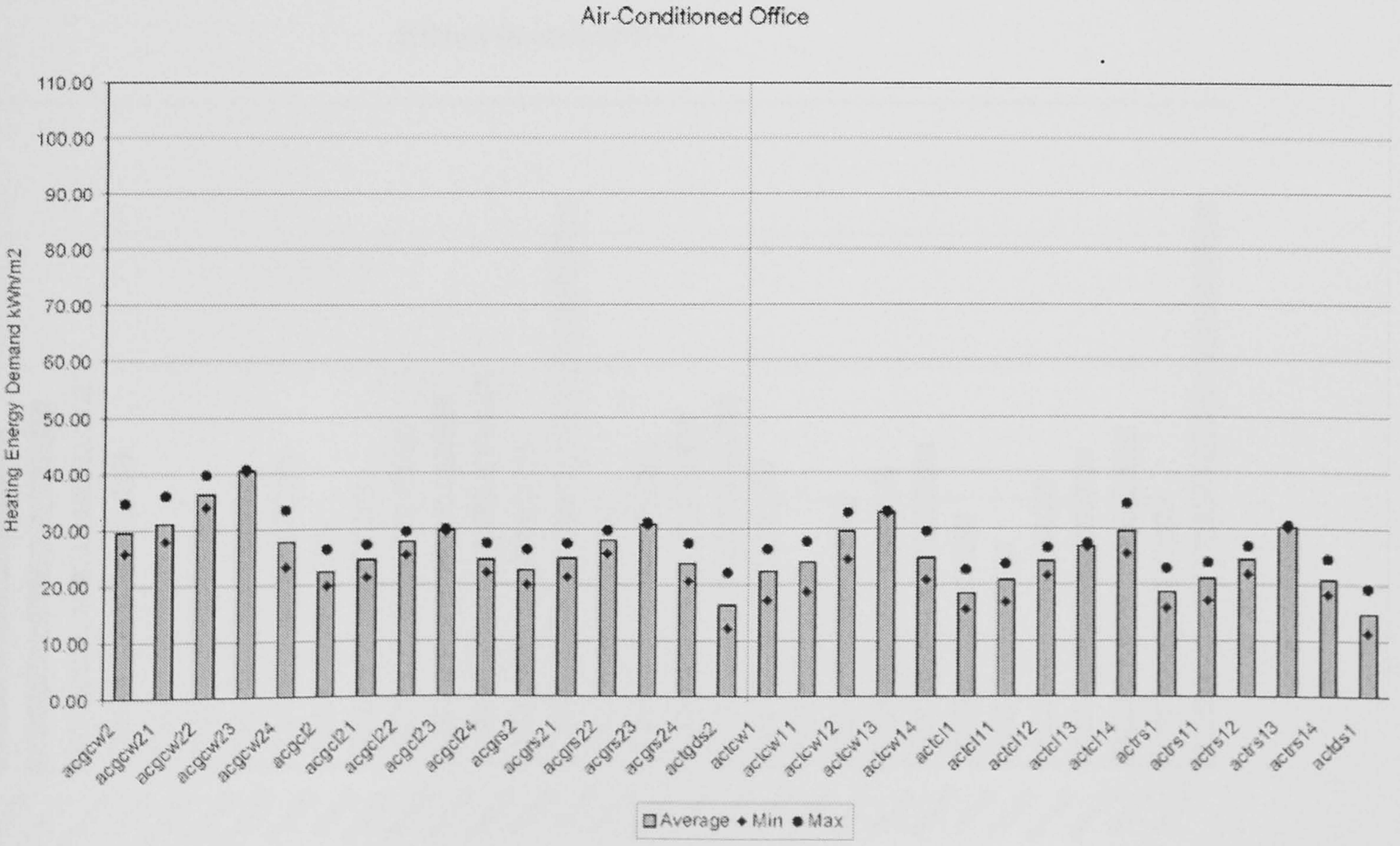
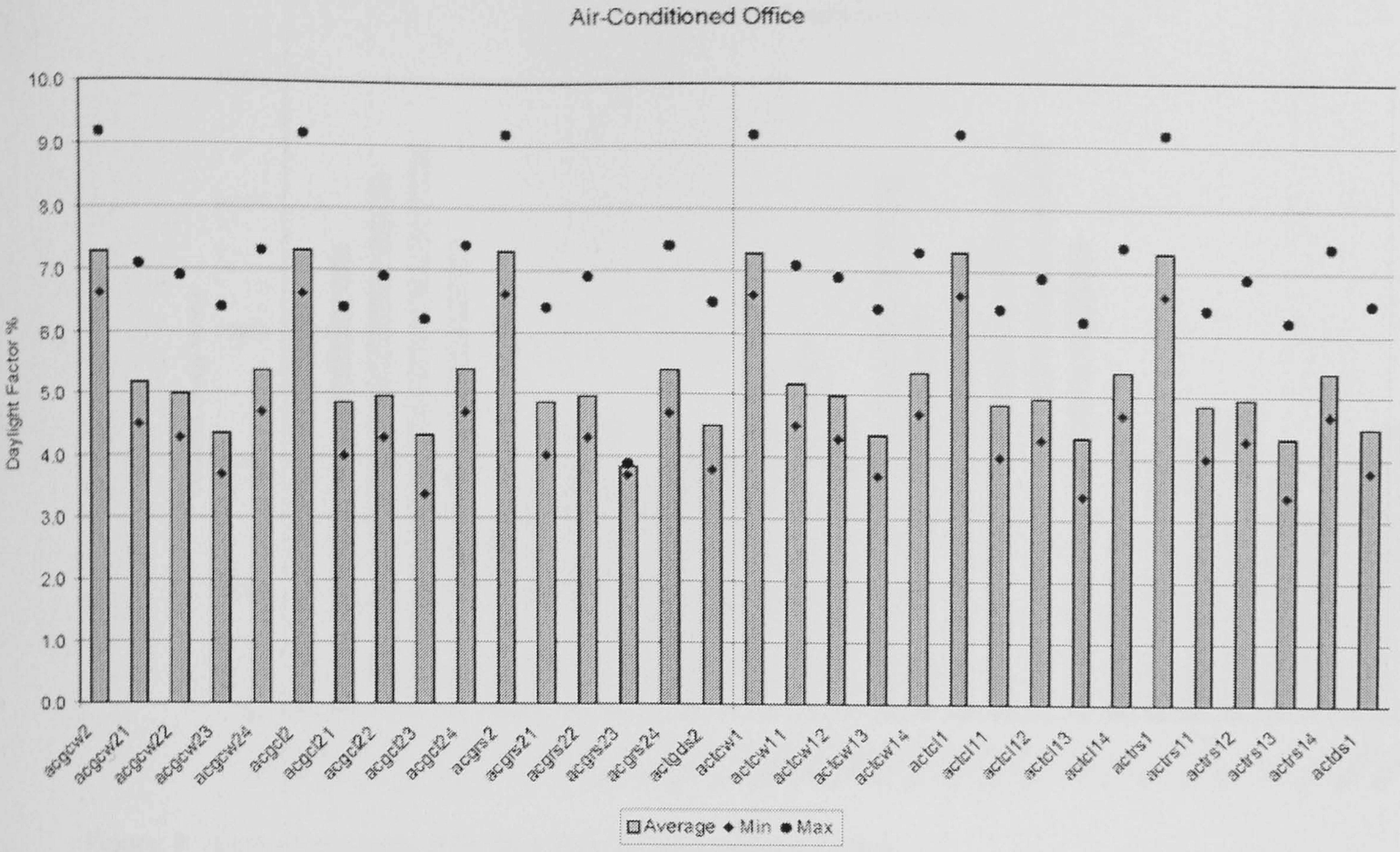
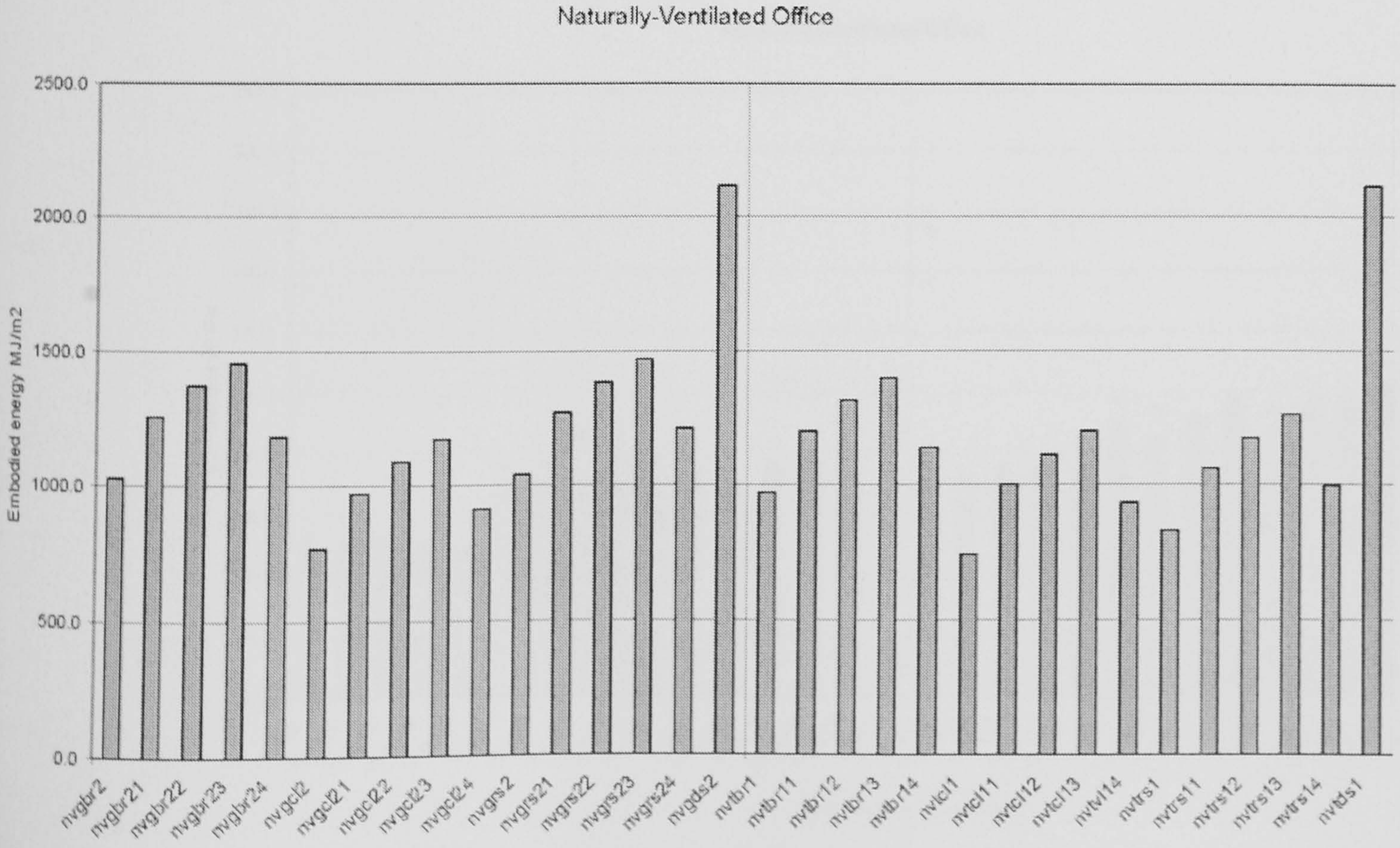


Figure 5 Heating energy demand in an air-conditioned office



gure 6 Average daylight factors for air-conditioned offices

lar heat gain has a larger impact than the radiative at gain through opaque facade materials. The curin wall (cw) has the largest cooling demand because e higher glazing ratio results in increased solar gains. This is particularly true in the case of standard construction. However, when the facade is heavily shaded by horizontal metal louvers, cooling energy demand falls below that of other facade types. This is because



ure 7 Embodied energy of the facades in a naturally ventilated office

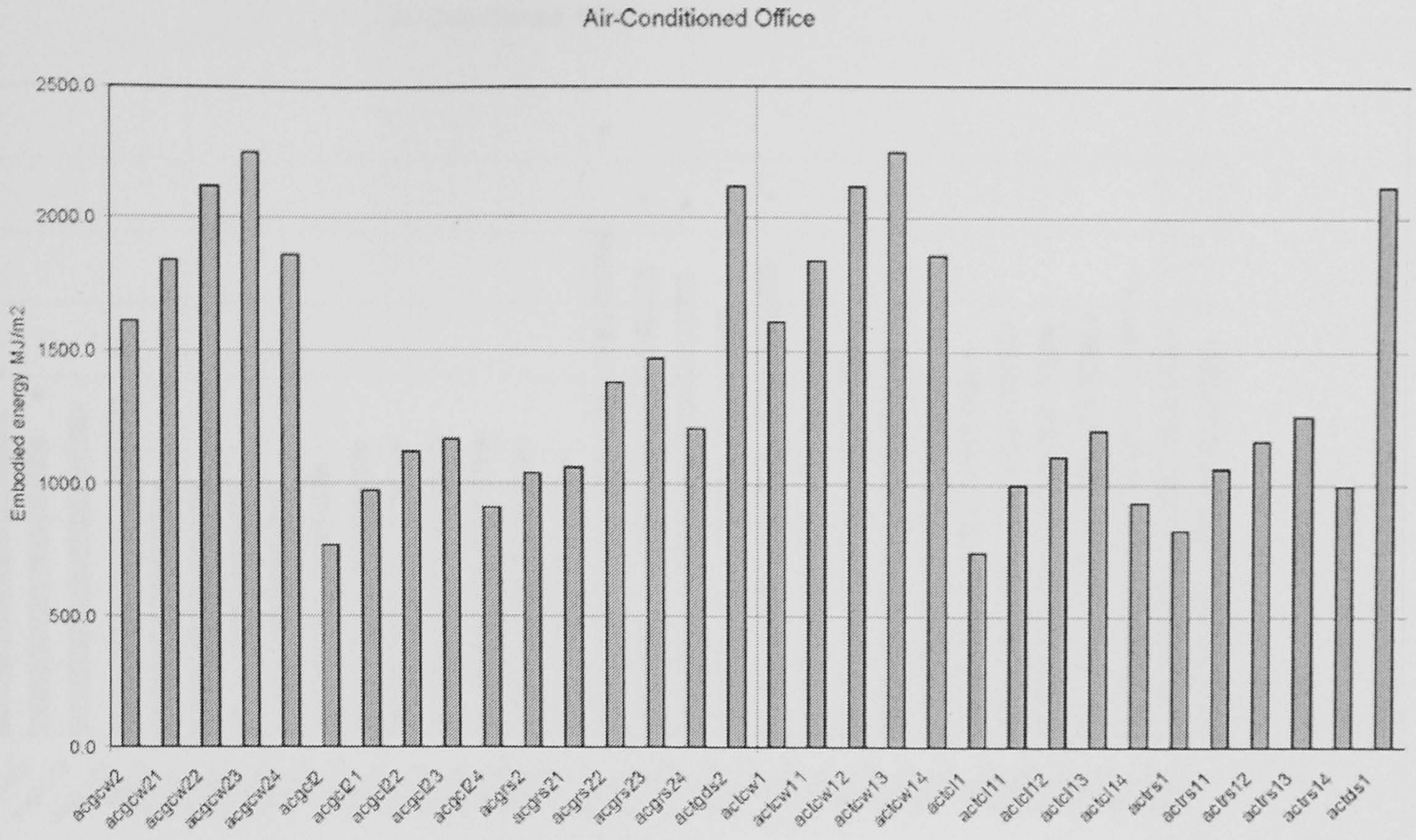


Figure 8 Embodied energy of the facades in an air-conditioned office

the shading is only applied to the glazing area and some of the heat load in the other offices occurs as radiation through the non-glazing elements.

Heating energy demand

There is a marked difference between the results for the naturally ventilated offices (Figure 4) and air-conditioned offices (Figure 5). The heating energy demand for the air-conditioned buildings (average 25.4 kWh/m^2) is less than one-third than that for naturally ventilated buildings (78.1 kWh/m^2). There are two reasons for the large difference. First, the naturally ventilated buildings have lower internal heat loads, a difference of up to 20 W/m^2/h, which must

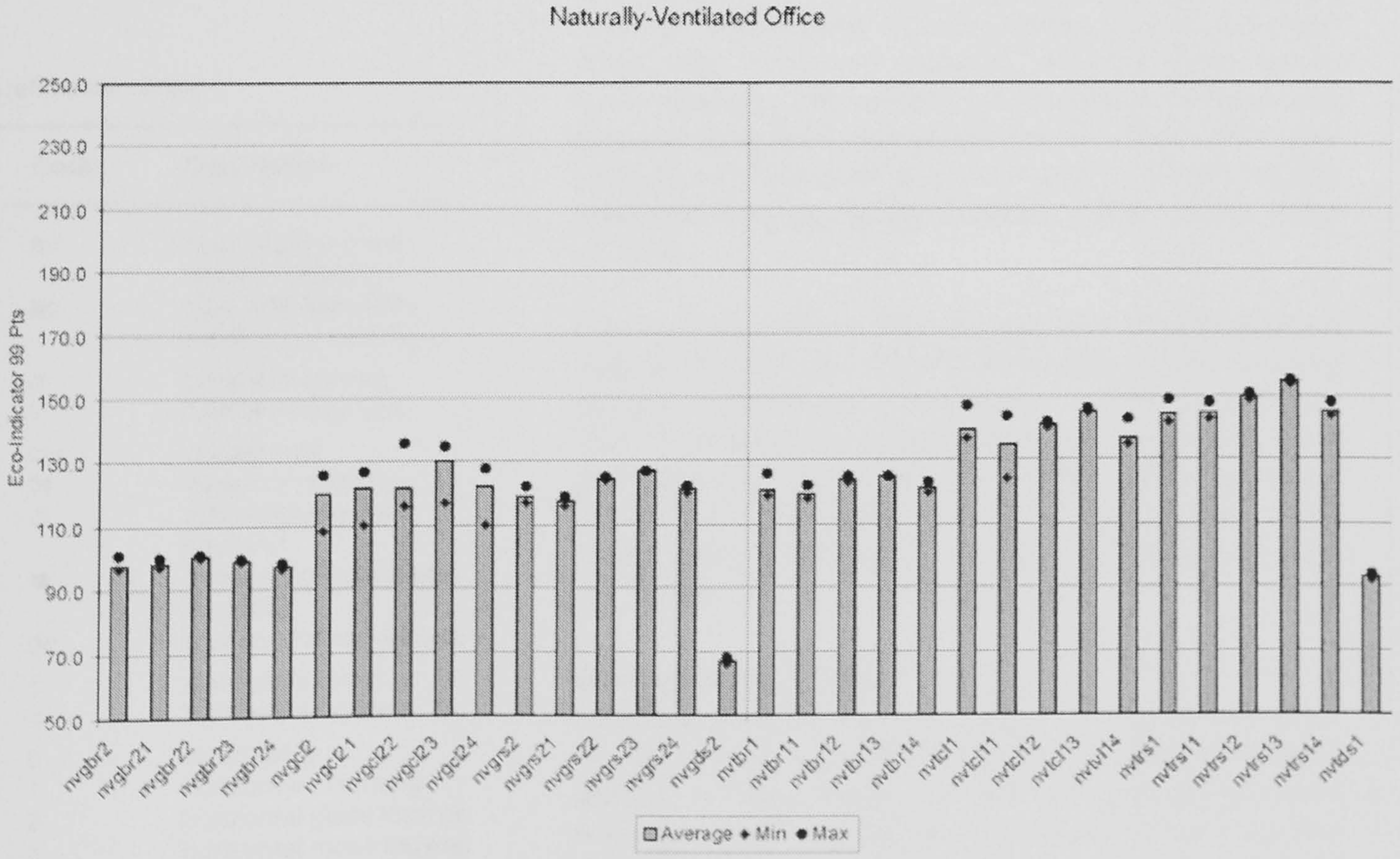
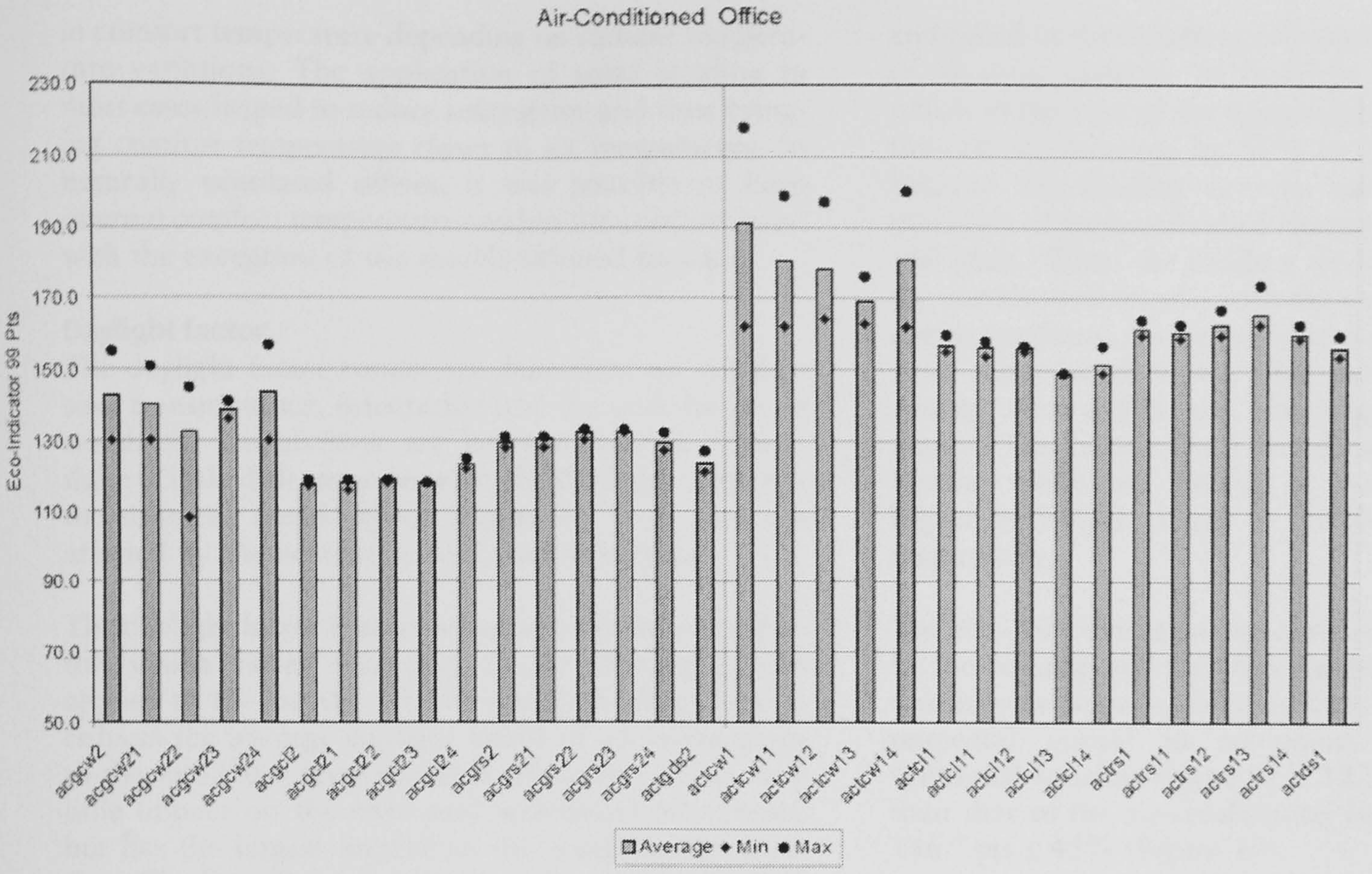


Figure 9 Eco-Indicator 99 points for a naturally ventilated office



igure 10 Eco-Indicator 99 points for an air-conditioned office

e compensated for by the heating system. Second, the ir infiltration rate in the air-conditioned buildings is wer due to the high air tightness associated with aled buildings. A reduction of the air infiltration rate duces the amount of uncontrolled external air, which as a temperature usually lower than the internal mperature during the heating season.

Table 4 Building case reference codes

Part of reference	Code	Description
Building type	nv	type 1 building with natural ventilation
	ac	type 2 building with mechanical ventilation
Energy conservation	g	good energy use
	t	typical energy use
Facade code	cw	curtain wall
	br	masonry cladding
	cl	lightweight metal cladding
	rs	heavyweight concrete cladding
	ds	double-skinned-facade
Facade standard	1	standard system
	2	high quality system
Shading code	0	no shading
	1	horizontal overhang
	2	horizontal glass louvres
	3	horizontal metal louvres
	4	vertical metal louvres

The application of shading types 1–3 to the facade increases the heating energy load and decreases the differences in loads due to orientation by reducing the amount of beneficial solar heat gain available during the heating season; the higher the solar shading factor, the higher the energy demand.

Improvements in thermal efficiency of the glazing as a result of high-quality facade construction do not overcome the effect of reduced internal heat loads. Consequently, these offices have higher heating energy demand than the lower quality facade offices with typical internal heat gain (Figures 4 and 5). However, the increased heating energy demand is low, in the order of 15%.

Figure 4 also shows that the use of a double-skinned facade system can significantly reduce the heating energy demand in a naturally ventilated building. This is reduced by a combination of increased solar gain into the space and the 'buffer' effect provided between the occupied space and the external wall, which reduces heat losses due to transmission through the facade.

Comfort temperature

Maximum and minimum comfort temperatures were similar in both naturally ventilated and air-conditioned offices. In most cases, this was because temperature was controlled through the heating and/or cooling system. However, set-point controls were based on air temperature and therefore variations were calculated in comfort temperature depending on radiant temperature variations. The application of solar shading in most cases helped to reduce solar gains and thus bringing comfort temperature closer to air temperature. In naturally ventilated offices, it was possible to keep internal comfort temperatures within the comfort band with the exception of the double-skinned facade.

Daylight factor

The daylight factor results are dependent on window size, transmittance, orientation and the desk height at which the calculations are being measured. Hence, there is little difference between the daylight factor for the different facade types (Figure 6). It is also not affected by the ventilation and cooling method.

The daylight factor is most sensitive to the shading factor, which varies according to the shading system applied to the facade. The overhang, shading Type 1, reduces the average daylight factor of all orientations to the minimum level required. However, it has very little impact on the east- and west-facing elevations, but has the largest impact on the south-facing elevation. Shading Type 2, the glass louvres with 50% transmittance, has the effect of reducing the daylight factor to a similar level as the overhang; however, this affects all elevations.

Shading Type 3, metal louvres with zero transmittance, has the effect of removing all the direct daylight and obstructing some of the diffuse daylight. This reduces the daylighting factor to an average of 4.3%, although there is a minimum of 3.5% for the north-facing elevation. These louvres have less effect on daylighting than on the heating energy demand because the daylight factor does not take into account direct solar transmission, i.e. direct sunlight. This is because the angle of direct sunlight has an effect on the lighting perceptions of the occupants, despite the level of background illumination in a room. It is also more difficult to derive an average for direct solar transmission.

The vertical louvres shown in solar shading Type 4 reduce the daylighting factor slightly by obstructing the glazing. They have a small impact on the average daylight factor because they are designed to reduce direct sunlight from a low angle, i.e. sunlight from the east or west at the beginning or end of the day.

Environmental impact

As mentioned above, two environmental impact indicators were calculated: embodied energy and eco-points. The embodied energy indicator (Figures 7 and 8) is a measure of the primary energy embodied in the construction of the facade. The indicator varies by facade type rather than by building type. All building types with masonry facade, heavy- and lightweight cladding have similar embodied energy: 1028, 1041 and 769 MJ/m^2, respectively. In each case, the energy embodied in the facade is increased by the application of shading systems, particularly the metal louvres, which in the case of the lightweight cladding increases the embodied energy by 52% to 1170 MJ/m^2. This is because the shading systems are constructed from materials of high embodied energy such as aluminium and glass. When the shading devices were applied to the curtain wall facade, with the exception of the horizontal overhang, they resulted in a larger increase than from other facade types. This was due to the larger glazing area and, hence, the larger area of shading device. The curtain wall facade and double-skinned facade, which are similar in construction, have a higher embodied energy at 1610 and 2120 MJ/m^2, respectively.

The eco-points indicator is sensitive to the energy used by the building and therefore might give different relationships between building options. The average environmental impact in eco-points of the naturally ventilated facades (Figure 9) is 122.6 pts ± 25% lower than that of the air-conditioned facades calculated as 146.7 pts ± 45% (Figure 10).

In naturally ventilated offices, improving the facade standard and reducing the internal heat load results in a reduction of 17% in the environmental impact. The double-skinned facade has the lowest environmental impact at 67 and 93 pts. This reflects the low heating energy consumption of this facade type. The masonry facade displays a low environmental impact with an average of 98.5 pts for the high-quality facade/low internal heat loads and 122.0 pts for the standard facade/high internal heat loads. This is despite a similar embodied energy to both the heavy- and lightweight cladding. The environmental impact of the light- and heavyweight cladding is similar, although the lightweight cladding shows greater volatility by orientation.

Improving the standard of the facade and reducing the internal heat loads can reduce the environmental impact by 22% in air-conditioned offices. The curtain wall facade has the largest environmental impact of the air-conditioned offices, an average of 159.8 pts when compared with the overall average of the air-conditioned facades of 146.7 pts.

The application of shading systems increased the embodied energy of the facades. In the naturally ventilated offices, the reduced energy consumption resulting from the shading resulted in very little difference between the eco-points of the various shading types. However, in the air-conditioned facades, the application of shading has a different effect on the different facade types. In the cooling-dominated facade, the curtain wall, the application of shading systems results in a reduction of the environmental impact. The same is true to a lesser extent for the lightweight cladding cade. However, in the heating-dominated heavy-eight facade system, the application of shading ypes 2–4 results in a higher environmental impact.

esults from a case study

case study is described here as a way to demonstrate ie type of summary and detailed results that the tool n provide. The user is required to select initially two put parameters: building type and facade type. For is case study, a Type 2 office is selected with a highly azed curtain wall facade (0.85 glazing ratio) and an sulated spandrel panel. The HQS, a 'best practice' ergy operation and no shading are selected. The uilding case reference code is thus acgcw2 (Figures , 5, 6, 8 and 10).

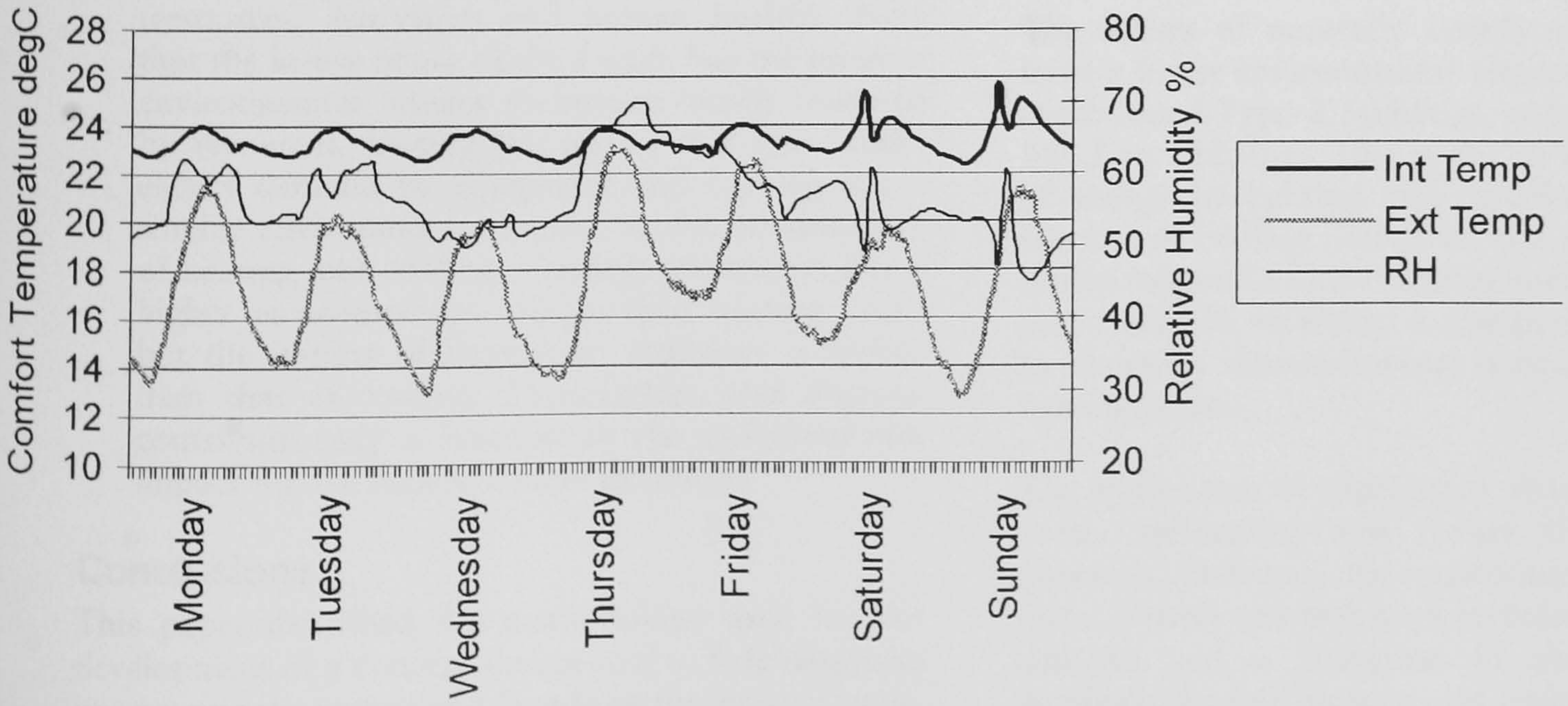
ummary output

or the inputs specified above, the summary output sults are shown in Figure 2 for four orientations. he annual cooling energy load ranges from 5.2 kWh/m^2 (for a north-facing facade) to 5.1 kWh/m^2 (for a south-facing facade), while the nnual heating load ranges from 25.7 kWh/m^2 (for st- and south-facing facades) to 34.6 kWh/m^2 (for a orth-facing facade). These can be easily converted to ergy consumption by making rule-of-thumb assump-ons about the type of fuel and air-conditioning system sed. For example, if the heating system is assumed to ave an efficiency of 75% from delivered gas to sup-ied heat, then the annual energy consumption for eating would be 18.9–26.3 kWh/m^2, while for a cool-g system with a coefficient of performance (COP) of the annual energy consumption for cooling would be 5–11.5 kWh/m^2. Note that these results do not clude energy required for the distribution of heating d cooling that can be a significant percentage and ould depend on the distribution system used. The overall environmental impact of the selected facade system would be 1610 MJ/m^2 embodied energy and the eco-points would range from 130 (an east-facing facade) to 155 (a west-facing facade). These values can be compared with alternative facade systems from within the tool to reach a decision about the relative environmental impact of the facade system selected.

Detailed output for the case study

Data available in the detailed output can be interrogated by the user for specific information. As mentioned above, standard tabular and graphical data are available. An example of graphical output for the south-facing facade is shown in Figures 11–13:

- Figure 11 shows the comfort temperature and relative humidity for 1 week in August. Note that similar weekly profiles are included in the tool for representative weeks for the 12 months of the year in addition to the coldest and warmest week. Note that comfort temperature and relative humidity are maintained within the set points of 18 and 24°C and 40–70% during the building operation times (8:00–18:00 hours weekdays, 11:00–13:00 hours Saturdays). The effect of high external temperatures and solar gains on the internal comfort temperatures can be also observed on Saturday and Sunday for this south-orientated office
- Figure 12 shows the heating, cooling, humidification and dehumidification loads for each month of the year for the discussed case study office (a south-facing facade). It also shows equipment and lighting energy load, which is very similar for each month



ure 11 Case study profiles of internal comfort temperature, relative humidity and external air temperature for a week in summer with highest weekly average external air temperature

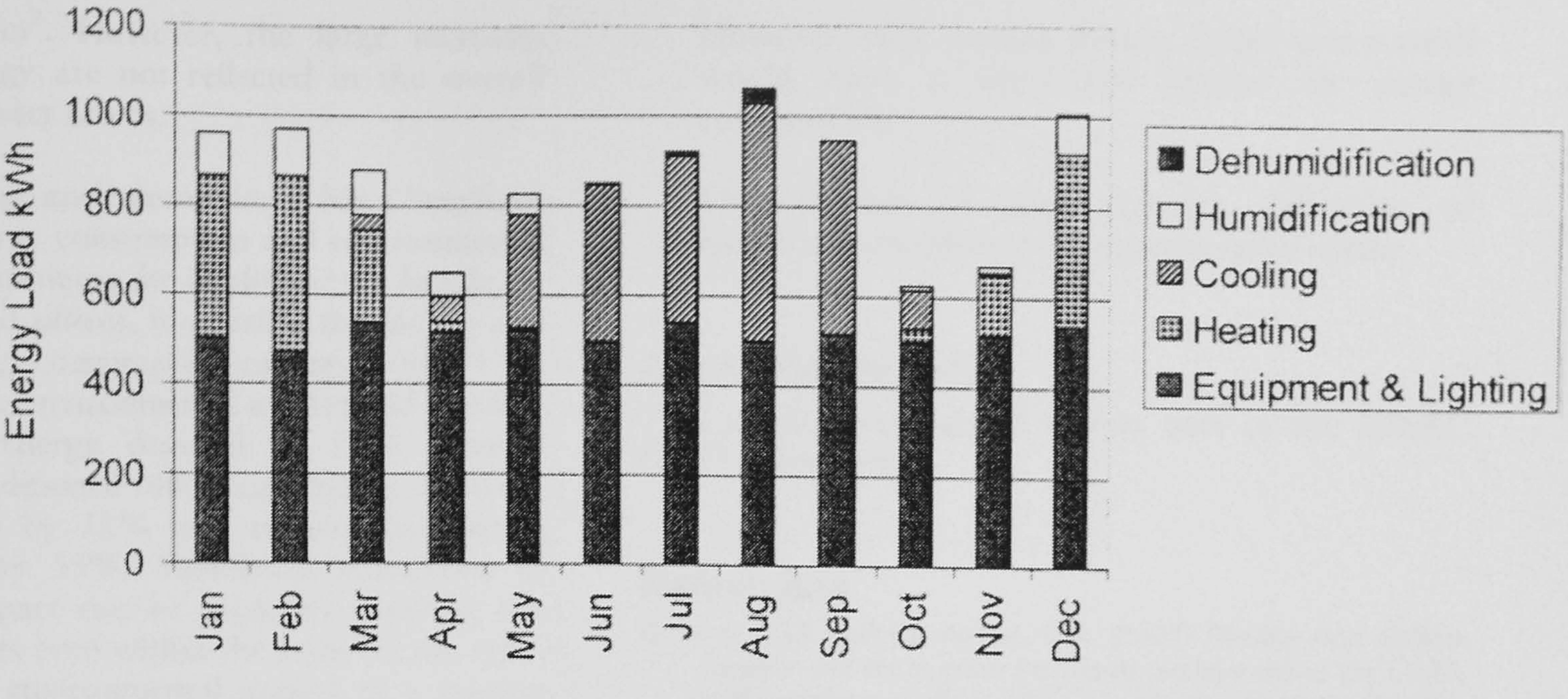


Figure 12 Case study profiles of energy loads for each month

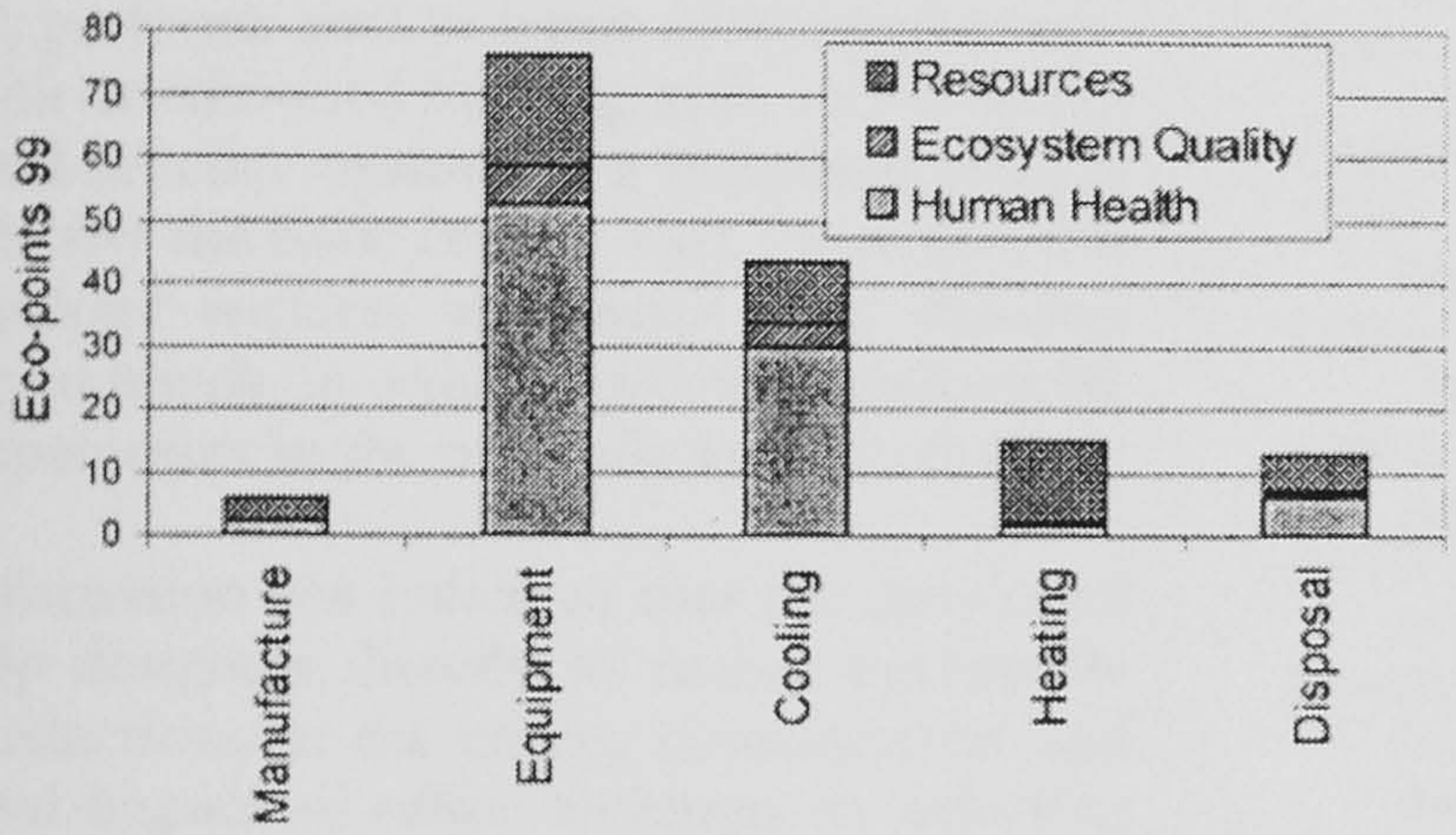


Figure 13 Case study profile for the environmental impact by subsystem and damage category

- Figure 13 shows the environmental impact in Eco-Indicator 99 points arranged by subsystem (manufacture, in-use and disposal) and damage category (resources, ecosystem and human health). Note that the in-use phase of the facade has the greatest environmental impact to human health followed by resources. During the use of this case study, energy demand by equipment and lighting has a similar environmental impact as the combination of heating and cooling. Cooling (electricity) has a higher environmental impact than heating (gas), but the impact of heating to resources is higher than that of cooling. Manufacture and disposal contribute only a fraction of the environmental impact for the facade system examined

Conclusions

This paper described the methodology used for the development of a concept design tool to help designers in assessing the impact of a facade on the internal environmental conditions, energy demand and environmental impact of an office building. For the given weather scenario examined, it was found that the choice of the following facade design parameters could potentially have a significant effect on the resulting internal thermal and daylighting conditions and energy demand for heating and cooling:

- Type of office building construction (heavy- or lightweight) and ventilation system (natural or mechanical). This will also influence the choice of the facade
- Type of facade in relation to its construction (standard or high quality), glazing ratio and thermal properties
- Type of shading in relation to the facade orientation
- Internal heat gains

The offices of naturally ventilated Type 1 building have a lower environmental impact than those in air-conditioned Type 2 buildings, reduced by 16% from 146.7 to 122.6 pts. This is due to lower consumption of energy by lighting and equipment as well as an absence of cooling. However, the naturally ventilated offices required a larger heating energy load, 78.1 compared with 25.4 kWh/m^2 in the air-conditioned offices, to maintain similar internal temperatures during the heating season.

The application of appropriate shading can help overcome overheating and reduce the cooling energy demands. However, the application of the horizontal metal louvres resulted in an increase in heating energy demand and a reduction in the daylight factor. Applying shading increases the embodied energy of the facade. In the case of the lightweight cladding, metal louvres increase the embodied energy by 52% from

69 to 1170 MJ/m². However, the large increases embodied energy are not reflected in the overall vironmental impact scores.

educing air leakage and internal loads has a beneficial ffect on both energy consumption and environmental npact, as does improving the quality of the facade. In aturally ventilated offices, improving the facade and ducing the energy consumption can result in a 17% nprovement in the environmental impact and a reducon in heating energy demand of 21%. Similar hanges in air-conditioned offices can reduce the environmental impact by 22% and reduce the cooling nergy demand by 35%. Significant reductions in nvironmental impact can be made by carrying out ese improvements even within the same facade type. or example, the environmental impact of a curtain all facade can be reduced from 191 to 142 pts.

he double-skinned facade, popular with architects in cent years, performs well in terms of internal conditions in the air-conditioned building type and provides vironmental benefits resulting in a reduction of 16% f eco-points over the basic curtain wall. However, this uilding typology requires additional solar shading, ich as internal blinds, in order to provide comfortable immer temperatures in the naturally ventilated office.

he above discussion has indicated that the developed ol can help designers directly to realize potentially gnificant reductions in the energy consumption and vironmental impact of office buildings by selecting e optimum facade design at the concept design stage. se of the tool could improve the understanding of the ynamics between facade design and building services, d assist with a more integrated approach. The parametric analysis could also help designers take informed cisions about the concept design of facades for other uilding types and different climatic conditions.

he tool has been discussed with designers within the thors' organizations who have commented positively its educational value in promoting a better understanding of the complex interaction between facade, ilding services and internal environment using a st-response interface.

hrough discussions with designers, the following pics were raised that merit further development:

- Financial implications of the facade options, particularly the impact of the selection on the whole life cost, particularly for the high-quality facades with a higher initial outlay but which may result in lower whole life costs
- Internal shading has not been considered, as this requires user-behaviour scheduling of its use. However, such shading devices under user control would have a significant impact on energy consumption
- Consideration of more complex variations of facade and building type, e.g. the retail sector

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APPENDIX B1: LIST OF FLOWS FROM THE LIFECYCLE ANALYSIS OF ACHITECTURAL FLOAT GLASS.

Bottom Level Inventory of Pilkington Float Glass.

	Units	Glass lifecycle	Building	Preparation	Process	Float Glass Process	Raw
hate (BaSO4, in ground)	kg	3.8E-01	7.2E-05	0.0E+00	3.7E-01	0.0E+00	
O3, ore)	kg	4.0E-03	8.2E-05	0.0E+00	1.5E-03	0.0E+00	
l2O3.4SiO2.H2O, in ground)	kg	3.6E-02	1.8E-05	0.0E+00	3.5E-02	0.0E+00	
phate (CaSO4, ore)	kg	7.8E-02	7.6E-02	0.0E+00	5.5E-04	0.0E+00	
r, ore)	kg	7.3E-05	1.3E-09	0.0E+00	7.0E-05	0.0E+00	
nd)	kg	5.1E-01	4.3E-01	0.0E+00	7.8E-02	0.0E+00	
nd)	kg	6.2E+01	4.5E-01	0.0E+00	2.0E+01	0.0E+00	
ore)	kg	1.8E-02	1.7E-02	0.0E+00	3.6E-04	0.0E+00	
aCO3.MgCO3, in ground)	kg	1.8E+02	0.0E+00	0.0E+00	0.0E+00	0.0E+00	
ecified)	kg	1.1E+01	1.0E+01	0.0E+00	7.5E-02	0.0E+00	
)	kg	1.2E+00	1.2E-03	0.0E+00	1.1E+00	0.0E+00	
e (FeSO4, ore)	kg	1.8E-03	4.7E-06	0.0E+00	6.0E-04	0.0E+00	
e)	kg	1.2E-04	2.1E-09	0.0E+00	1.1E-04	0.0E+00	
ound)	kg	1.1E+00	4.0E-01	0.0E+00	6.5E-01	0.0E+00	
aCO3, in ground)	kg	3.1E+02	1.8E+00	0.0E+00	5.1E-01	0.0E+00	
(Mn, ore)	kg	4.3E-05	7.6E-10	0.0E+00	4.1E-05	0.0E+00	
(in ground)	kg	2.5E+02	3.6E-01	0.0E+00	2.3E+02	0.0E+00	
re)	kg	2.5E-05	4.4E-10	0.0E+00	2.4E-05	0.0E+00	
d)	kg	4.7E+01	3.3E-01	0.0E+00	4.6E+00	0.0E+00	
, ore)	kg	6.2E-01	9.2E-03	0.0E+00	5.9E-01	0.0E+00	
und)	kg	6.7E+02	3.0E-04	0.0E+00	1.3E-02	0.0E+00	
re)	kg	1.8E-06	3.3E-11	0.0E+00	1.8E-06	0.0E+00	
ride (NaCl, in ground or in sea)	kg	3.5E+02	1.1E-03	0.0E+00	2.0E-02	0.0E+00	
n ground)	kg	1.3E-02	0.0E+00	0.0E+00	4.0E-05	0.0E+00	
	kg	1.5E-04	0.0E+00	0.0E+00	1.5E-04	0.0E+00	
ore)	kg	9.1E-04	2.2E-05	0.0E+00	8.8E-04	0.0E+00	
)	kg	2.7E-06	4.9E-11	0.0E+00	2.6E-06	0.0E+00	
	MJ elec	2.7E+02	9.3E-01	0.0E+00	1.5E+02	3.1E+02	
ecified)	kg	2.1E-02	5.5E-05	0.0E+00	7.1E-03	0.0E+00	
	kg	1.9E-01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	
	kg	1.7E+00	1.7E+00	0.0E+00	5.2E-03	0.0E+00	
III)	m2a	2.6E-01	2.1E-02	0.0E+00	7.9E-02	0.0E+00	
IV)	m2a	5.8E-02	2.6E-02	0.0E+00	1.1E-02	0.0E+00	
IV)	m2a	1.1E-02	3.0E-05	0.0E+00	3.7E-03	0.0E+00	
, general purpose)	kg	2.4E+01	0.0E+00	2.4E+01	0.0E+00	0.0E+00	
unspecified)	kg	1.4E-01	9.0E-02	0.0E+00	3.0E-02	0.0E+00	
	kg	1.3E-03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	
al)	litre	3.2E+03	3.0E+01	0.0E+00	2.1E+02	0.0E+00	
etwork	litre	3.0E+01	0.0E+00	0.0E+00	2.8E+00	2.5E+00	
	litre	2.7E-02	0.0E+00	0.0E+00	1.1E-04	0.0E+00	

Bottom Level Inventory of Pilkington Float Glass.

ified Origin	litre	3.2E+03	3.0E+01	0.0E+00	2.1E+02	0.0E+00	
	litre	3.3E-04	0.0E+00	0.0E+00	1.1E-06	0.0E+00	
	kg	2.2E-01	3.4E-03	0.0E+00	1.3E-02	0.0E+00	
g)	m3	1.2E-04	0.0E+00	0.0E+00	1.2E-04	0.0E+00	
de (CH3CHO)	g	2.0E-01	9.4E-05	0.0E+00	3.0E-02	0.0E+00	
(CH3COOH)	g	2.1E+00	4.0E-04	0.0E+00	1.4E+00	0.0E+00	
H3COCH3)	g	1.9E-01	9.3E-05	0.0E+00	2.2E-02	0.0E+00	
C2H2)	g	2.0E-01	1.3E-03	0.0E+00	1.7E-01	0.0E+00	
nspecified)	g	1.3E-02	5.9E-05	0.0E+00	8.5E-03	0.0E+00	
pecified)	g	3.0E+01	1.0E-02	0.0E+00	2.6E+01	0.0E+00	
pecified)	g	3.0E-01	1.3E-03	0.0E+00	2.3E-01	0.0E+00	
pecified)	g	6.2E-04	1.1E-08	0.0E+00	6.0E-04	0.0E+00	
(Al)	g	3.6E+00	2.5E-02	0.0E+00	3.2E+00	0.0E+00	
NH3)	g	4.3E+02	3.3E-03	0.0E+00	7.7E-02	0.0E+00	
Sb)	g	6.5E-04	4.9E-06	0.0E+00	6.2E-04	0.0E+00	
rbable Organic Halogens)	g	8.1E-12	2.1E-14	0.0E+00	2.7E-12	0.0E+00	
ydrocarbons (unspecified)	g	2.0E-01	1.0E-02	0.0E+00	2.1E-02	0.0E+00	
)	g	2.4E-02	8.3E-05	0.0E+00	8.3E-03	0.0E+00	
)	g	4.3E-02	3.0E-04	0.0E+00	3.9E-02	0.0E+00	
de (C6H5CHO)	g	1.1E-07	2.0E-12	0.0E+00	1.1E-07	0.0E+00	
6H6)	g	4.4E+00	4.0E-03	0.0E+00	3.9E+00	0.0E+00	
rene (C20H12)	g	1.8E-03	4.3E-06	0.0E+00	6.5E-04	0.0E+00	
le)	g	6.8E-04	5.0E-06	0.0E+00	6.3E-04	0.0E+00	
	g	3.2E-01	2.4E-03	0.0E+00	3.2E-01	0.0E+00	
r)	g	6.3E-02	4.8E-04	0.0E+00	6.2E-02	0.0E+00	
4H10)	g	1.3E+01	6.9E-03	0.0E+00	7.9E+00	0.0E+00	
H3CH2CHCH2)	g	7.5E-02	1.3E-04	0.0E+00	9.3E-03	0.0E+00	
Cd)	g	4.4E-02	4.3E-05	0.0E+00	5.6E-03	0.0E+00	
a)	g	6.0E-01	3.1E-03	0.0E+00	4.5E-01	0.0E+00	
xide (CO2, fossil)	g	1.1E+06	4.2E+03	0.0E+00	6.7E+05	7.6E+04	
noxide (CO)	g	3.5E+02	9.0E+00	0.0E+00	2.2E+02	0.0E+00	
rafluoride (CF4)	g	9.0E-05	1.6E-09	0.0E+00	8.7E-05	0.0E+00	
Matter (unspecified, as Cl)	g	4.0E-03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	
l2)	g	4.0E-03	0.0E+00	0.0E+00	1.7E-07	0.0E+00	
(Cr III, Cr VI)	g	3.1E-02	4.9E-04	0.0E+00	1.1E-02	0.0E+00	
	g	4.5E-02	3.1E-05	0.0E+00	6.1E-03	0.0E+00	
)	g	7.2E-02	1.1E-03	0.0E+00	1.4E-02	0.0E+00	
N-)	g	2.9E-03	6.6E-06	0.0E+00	1.1E-03	0.0E+00	
specified)	g	1.1E-08	2.9E-10	0.0E+00	1.0E-08	0.0E+00	
H6)	g	7.6E+01	4.1E-02	0.0E+00	3.2E+01	0.0E+00	
H5OH)	g	3.7E-01	1.9E-04	0.0E+00	4.3E-02	0.0E+00	

Bottom Level Inventory of Pilkington Float Glass.

e (C8H10)	g	7.5E-02	1.3E-04	0.0E+00	9.3E-03	0.0E+00
2H4)	g	1.2E+02	1.3E-02	0.0E+00	1.1E+02	0.0E+00
-)	g	2.4E-04	1.1E-08	0.0E+00	1.9E-05	0.0E+00
)	g	3.7E-03	0.0E+00	0.0E+00	1.2E-05	0.0E+00
de (CH2O)	g	1.6E+00	1.2E-03	0.0E+00	9.9E-01	0.0E+00
d Matter (unspecified)	g	3.7E-03	4.2E-07	0.0E+00	3.5E-14	0.0E+00
(CF3Br)	g	8.5E-03	2.7E-05	0.0E+00	1.0E-03	0.0E+00
7H16)	g	7.4E-01	1.3E-03	0.0E+00	8.0E-02	0.0E+00
H14)	g	1.4E+00	1.8E-03	0.0E+00	1.6E-01	0.0E+00
ns (except methane)	g	4.2E+02	1.5E+00	0.0E+00	1.5E+02	0.0E+00
ns (unspecified)	g	6.6E+02	6.1E+00	0.0E+00	9.7E-01	0.0E+00
2)	g	5.0E+01	5.7E-09	0.0E+00	2.1E+01	5.6E-01
hloride (HCl)	g	2.1E+01	3.4E-01	0.0E+00	1.6E+01	0.0E+00
luoride (HF)	g	8.1E-01	2.7E-02	0.0E+00	6.0E-01	0.0E+00
ulphide (H2S)	g	4.9E+00	3.6E-03	0.0E+00	3.9E+00	0.0E+00
	g	1.6E-02	1.2E-04	0.0E+00	1.6E-02	0.0E+00
	g	1.8E+00	1.1E-02	0.0E+00	1.4E+00	0.0E+00
La)	g	1.2E-03	8.0E-06	0.0E+00	1.0E-03	0.0E+00
	g	1.3E-01	1.4E-02	0.0E+00	4.1E-02	0.0E+00
(Mg)	g	1.3E+00	8.9E-03	0.0E+00	1.1E+00	0.0E+00
(Mn)	g	6.5E-02	5.0E-03	0.0E+00	5.7E-02	0.0E+00
	g	4.0E-03	0.0E+00	0.0E+00	0.0E+00	0.0E+00
)	g	7.0E-03	9.2E-05	0.0E+00	2.7E-03	0.0E+00
pecified)	g	5.8E-02	5.0E-02	0.0E+00	5.9E-04	0.0E+00
H4)	g	2.1E+03	4.7E+00	0.0E+00	8.0E+02	0.0E+00
H3OH)	g	6.3E-01	3.2E-04	0.0E+00	7.2E-02	0.0E+00
n (Mo)	g	2.2E-02	2.1E-05	0.0E+00	3.6E-03	0.0E+00
e (C10H8)	g	9.2E-08	0.0E+00	0.0E+00	9.2E-08	0.0E+00
	g	8.7E-01	1.1E-03	0.0E+00	1.1E-01	0.0E+00
ides (NOx as NO2)	g	8.2E+03	1.2E+01	0.0E+00	7.2E+03	6.6E+03
e (N2O)	g	5.8E+00	2.7E-02	0.0E+00	1.8E+00	0.0E+00
tter (unspecified)	g	3.8E-02	8.7E-05	0.0E+00	1.1E-02	0.0E+00
(unspecified)	g	4.2E+04	1.3E+02	0.0E+00	4.0E+01	0.0E+00
5H12)	g	1.5E+01	6.6E-03	0.0E+00	1.1E+01	0.0E+00
5OH)	g	8.6E-07	1.5E-11	0.0E+00	8.3E-07	0.0E+00
(P)	g	3.2E-02	2.7E-04	0.0E+00	2.9E-02	0.0E+00
Pentoxide (P2O5)	g	5.8E-05	1.5E-07	0.0E+00	1.9E-05	0.0E+00
romatic Hydrocarbons (PAH, unspecified)	g	9.8E-02	3.6E-05	0.0E+00	9.1E-02	0.0E+00
K)	g	6.2E-01	3.0E-03	0.0E+00	5.7E-01	0.0E+00
3H8)	g	2.0E+01	1.3E-02	0.0E+00	9.5E+00	0.0E+00
hyde (CH3CH2CHO)	g	3.1E-07	5.5E-12	0.0E+00	3.0E-07	0.0E+00

Bottom Level Inventory of Pilkington Float Glass.

cid (CH3CH2COOH)	g	4.1E-04	7.2E-09	0.0E+00	3.9E-04	0.0E+00	
CH2CHCH3)	g	3.9E-01	1.7E-03	0.0E+00	2.0E-01	0.0E+00	
Sc)	g	4.3E-04	2.7E-06	0.0E+00	3.4E-04	0.0E+00	
e)	g	2.5E-02	5.7E-05	0.0E+00	1.1E-02	0.0E+00	
	g	5.4E+00	4.0E-02	0.0E+00	4.9E+00	0.0E+00	
)	g	1.2E+00	2.1E-03	0.0E+00	3.1E-01	0.0E+00	
Sr)	g	6.8E-02	4.9E-04	0.0E+00	6.3E-02	0.0E+00	
ides (SOx as SO2)	g	8.3E+03	1.2E+01	0.0E+00	6.4E+03	5.9E+03	
cified)	g	2.9E-06	3.1E-08	0.0E+00	1.9E-08	0.0E+00	
)	g	3.4E-04	2.5E-06	0.0E+00	3.1E-04	0.0E+00	
)	g	7.3E-04	5.1E-06	0.0E+00	6.4E-04	0.0E+00	
	g	2.4E-04	1.6E-06	0.0E+00	2.0E-04	0.0E+00	
i)	g	1.3E-01	8.9E-04	0.0E+00	1.1E-01	0.0E+00	
6H5CH3)	g	2.4E+00	1.2E-03	0.0E+00	1.9E+00	0.0E+00	
)	g	6.8E-04	4.9E-06	0.0E+00	6.3E-04	0.0E+00	
V)	g	3.4E+00	2.0E-03	0.0E+00	4.0E-01	0.0E+00	
tmosphere as steam	g	4.0E+05	0.0E+00	0.0E+00	4.0E+05	4.0E+05	
H4(CH3)2)	g	3.3E-01	7.4E-04	0.0E+00	6.8E-02	0.0E+00	
	g	7.2E-01	5.9E-03	0.0E+00	5.4E-02	0.0E+00	
Zr)	g	1.5E-03	3.8E-06	0.0E+00	4.8E-04	0.0E+00	
nd Halogenes (unspecified)	kBq	1.2E-03	0.0E+00	0.0E+00	1.2E-03	0.0E+00	
14)	kBq	3.9E-01	0.0E+00	0.0E+00	3.9E-01	0.0E+00	
s134)	kBq	1.5E-05	0.0E+00	0.0E+00	1.5E-05	0.0E+00	
s137)	kBq	1.5E-05	0.0E+00	0.0E+00	1.5E-05	0.0E+00	
58)	kBq	1.5E-05	0.0E+00	0.0E+00	1.5E-05	0.0E+00	
60)	kBq	1.5E-05	0.0E+00	0.0E+00	1.5E-05	0.0E+00	
cified)	kBq	3.7E+01	0.0E+00	0.0E+00	3.7E+01	0.0E+00	
1)	kBq	8.7E-05	0.0E+00	0.0E+00	8.7E-05	0.0E+00	
3)	kBq	1.7E-04	0.0E+00	0.0E+00	1.7E-04	0.0E+00	
85)	kBq	2.3E+00	0.0E+00	0.0E+00	2.3E+00	0.0E+00	
10)	kBq	1.5E-02	1.1E-04	0.0E+00	1.5E-02	0.0E+00	
Po210)	kBq	2.6E-02	2.0E-04	0.0E+00	2.6E-02	0.0E+00	
(K40)	kBq	4.0E-03	3.1E-05	0.0E+00	3.9E-03	0.0E+00	
n (Pa234m)	kBq	2.1E-04	0.0E+00	0.0E+00	2.1E-04	0.0E+00	
Substance (unspecified)	kBq	1.5E+03	1.5E+03	0.0E+00	1.2E-04	0.0E+00	
a226)	kBq	1.8E-02	2.9E-05	0.0E+00	1.8E-02	0.0E+00	
a228)	kBq	2.0E-03	1.6E-05	0.0E+00	2.0E-03	0.0E+00	
220)	kBq	6.1E-02	4.8E-04	0.0E+00	6.1E-02	0.0E+00	
222)	kBq	1.8E+03	2.0E-03	0.0E+00	1.8E+03	0.0E+00	
226)	kBq	1.6E-03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	
h228)	kBq	1.7E-03	1.3E-05	0.0E+00	1.7E-03	0.0E+00	

Bottom Level Inventory of Pilkington Float Glass.

h230)	kBq	3.0E-03	0.0E+00	0.0E+00	3.0E-03	0.0E+00	
h232)	kBq	1.1E-03	8.4E-06	0.0E+00	1.1E-03	0.0E+00	
h234)	kBq	2.1E-04	0.0E+00	0.0E+00	2.1E-04	0.0E+00	
3)	kBq	4.5E+00	0.0E+00	0.0E+00	4.5E+00	0.0E+00	
J234)	kBq	5.3E-03	0.0E+00	0.0E+00	5.3E-03	0.0E+00	
J235)	kBq	4.0E-05	0.0E+00	0.0E+00	4.0E-05	0.0E+00	
J238)	kBq	9.1E-03	2.4E-05	0.0E+00	9.1E-03	0.0E+00	
133)	kBq	3.2E+01	0.0E+00	0.0E+00	3.2E+01	0.0E+00	
(Al)	g	4.8E+00	9.7E-04	0.0E+00	4.7E+00	0.0E+00	
)	g	1.9E-03	3.9E-07	0.0E+00	1.9E-03	0.0E+00	
Cd)	g	8.9E-07	1.3E-08	0.0E+00	8.4E-07	0.0E+00	
a)	g	1.9E+01	3.9E-03	0.0E+00	1.9E+01	0.0E+00	
	g	1.5E+01	3.0E-03	0.0E+00	1.4E+01	0.0E+00	
(Cr III, Cr VI)	g	2.4E-02	4.9E-06	0.0E+00	2.3E-02	0.0E+00	
	g	9.0E-07	1.5E-08	0.0E+00	8.6E-07	0.0E+00	
)	g	4.5E-06	7.4E-08	0.0E+00	4.3E-06	0.0E+00	
	g	9.7E+00	1.9E-03	0.0E+00	9.3E+00	0.0E+00	
	g	2.1E-05	3.4E-07	0.0E+00	2.0E-05	0.0E+00	
(Mn)	g	1.9E-01	3.9E-05	0.0E+00	1.9E-01	0.0E+00	
g)	g	1.6E-07	2.3E-09	0.0E+00	1.6E-07	0.0E+00	
	g	6.8E-06	1.1E-07	0.0E+00	6.4E-06	0.0E+00	
)	g	7.6E-05	1.4E-09	0.0E+00	7.3E-05	0.0E+00	
cified)	g	3.0E-02	4.8E-04	0.0E+00	2.8E-02	0.0E+00	
s (P)	g	2.4E-01	4.4E-06	0.0E+00	2.3E-01	0.0E+00	
	g	2.9E+00	5.8E-04	0.0E+00	2.8E+00	0.0E+00	
	g	7.3E-02	1.5E-05	0.0E+00	7.0E-02	0.0E+00	
(Am241)	kBq	3.9E+00	0.0E+00	0.0E+00	3.9E+00	0.0E+00	
(Am243)	kBq	8.5E-02	0.0E+00	0.0E+00	8.5E-02	0.0E+00	
s135)	kBq	1.9E+03	0.0E+00	0.0E+00	1.9E+03	0.0E+00	
s137)	kBq	5.3E-03	0.0E+00	0.0E+00	5.3E-03	0.0E+00	
m244)	kBq	7.9E+00	0.0E+00	0.0E+00	7.9E+00	0.0E+00	
m245)	kBq	8.8E-04	0.0E+00	0.0E+00	8.8E-04	0.0E+00	
9)	kBq	1.2E-04	0.0E+00	0.0E+00	1.2E-04	0.0E+00	
(Np237)	kBq	1.2E+00	0.0E+00	0.0E+00	1.2E+00	0.0E+00	
(Pd107)	kBq	4.3E-04	0.0E+00	0.0E+00	4.3E-04	0.0E+00	
(Pu239)	kBq	1.5E+03	0.0E+00	0.0E+00	1.5E+03	0.0E+00	
(Pu240)	kBq	2.1E+03	0.0E+00	0.0E+00	2.1E+03	0.0E+00	
(Pu241)	kBq	4.9E+05	0.0E+00	0.0E+00	4.9E+05	0.0E+00	
(Pu242)	kBq	7.9E+00	0.0E+00	0.0E+00	7.9E+00	0.0E+00	
a226)	kBq	1.0E+01	0.0E+00	0.0E+00	1.0E+01	0.0E+00	
(Sm151)	kBq	1.8E+00	0.0E+00	0.0E+00	1.8E+00	0.0E+00	

Bottom Level Inventory of Pilkington Float Glass.

Se79)	kBq	1.4E-03	0.0E+00	0.0E+00	1.4E-03	0.0E+00	
(Sr90)	kBq	2.8E+02	0.0E+00	0.0E+00	2.8E+02	0.0E+00	
n (Tc99)	kBq	5.8E-02	0.0E+00	0.0E+00	5.8E-02	0.0E+00	
h230)	kBq	1.0E+01	0.0E+00	0.0E+00	1.0E+01	0.0E+00	
)	kBq	2.4E-03	0.0E+00	0.0E+00	2.4E-03	0.0E+00	
J234)	kBq	6.3E+00	0.0E+00	0.0E+00	6.3E+00	0.0E+00	
J235)	kBq	1.1E-01	0.0E+00	0.0E+00	1.1E-01	0.0E+00	
J238)	kBq	1.8E+00	0.0E+00	0.0E+00	1.8E+00	0.0E+00	
(Zr93)	kBq	7.6E-03	0.0E+00	0.0E+00	7.6E-03	0.0E+00	
	g	4.4E+01	2.6E-02	0.0E+00	7.7E-03	0.0E+00	
specified)	g	1.6E-03	0.0E+00	0.0E+00	1.6E-03	0.0E+00	
unspecified)	g	2.1E-03	3.7E-08	0.0E+00	2.0E-03	0.0E+00	
specified)	g	5.7E-01	9.0E-04	0.0E+00	1.0E-01	0.0E+00	
specified)	g	5.3E-02	8.3E-05	0.0E+00	9.2E-03	0.0E+00	
(Al3+)	g	3.2E+00	4.3E-01	0.0E+00	2.6E+00	0.0E+00	
Hydroxide (Al(OH)3)	g	1.8E-05	0.0E+00	0.0E+00	1.8E-05	0.0E+00	
NH4+, NH3, as N)	g	2.6E+00	1.4E-02	0.0E+00	4.6E-01	0.0E+00	
rbable Organic Halogens)	g	7.7E-03	2.2E-05	0.0E+00	8.8E-04	0.0E+00	
ydrocarbons (unspecified)	g	2.5E+00	5.3E-03	0.0E+00	5.6E-01	0.0E+00	
s3+, As5+)	g	7.5E-03	8.7E-04	0.0E+00	5.0E-03	0.0E+00	
++)	g	1.0E+01	5.7E-02	0.0E+00	1.3E+00	0.0E+00	
	g	6.9E+01	1.4E-02	0.0E+00	6.6E+01	0.0E+00	
C6H6)	g	5.7E-01	9.8E-04	0.0E+00	1.0E-01	0.0E+00	
chemical Oxygen Demand)	g	2.2E+00	2.6E-01	0.0E+00	2.9E-01	0.0E+00	
(H3BO3)	g	2.3E-02	0.0E+00	0.0E+00	2.3E-02	0.0E+00	
)	g	7.1E-02	1.1E-04	0.0E+00	1.3E-02	0.0E+00	
Cd++)	g	2.0E-03	2.8E-05	0.0E+00	4.8E-04	0.0E+00	
a++)	g	1.5E+02	2.7E-01	0.0E+00	3.2E+01	0.0E+00	
s (CO3--, HCO3-, CO2, as C)	g	2.9E-01	0.0E+00	0.0E+00	4.0E-02	0.0E+00	
e++)	g	8.1E-04	6.9E-06	0.0E+00	3.3E-04	0.0E+00	
s++)	g	3.2E-03	0.0E+00	0.0E+00	4.7E-05	0.0E+00	
Cl-)	g	3.3E+04	1.2E+01	0.0E+00	4.4E+02	0.0E+00	
d Matter (unspecified, as Cl)	g	1.1E+01	9.0E-04	0.0E+00	1.1E+01	0.0E+00	
l2)	g	3.7E-03	0.0E+00	0.0E+00	7.0E-08	0.0E+00	
(CHCl3)	g	1.2E-05	2.1E-10	0.0E+00	1.1E-05	0.0E+00	
(Cr III)	g	5.1E-02	9.2E-07	0.0E+00	4.9E-02	0.0E+00	
(Cr III, Cr VI)	g	2.0E-02	9.7E-03	0.0E+00	1.7E-03	0.0E+00	
(Cr VI)	g	9.9E-07	3.3E-08	0.0E+00	9.2E-07	0.0E+00	
l, Co II, Co III)	g	3.1E-03	5.7E-08	0.0E+00	3.0E-03	0.0E+00	
mical Oxygen Demand)	g	7.9E+00	7.1E-01	0.0E+00	3.5E+00	0.0E+00	
u+, Cu++)	g	2.3E-02	2.6E-03	0.0E+00	1.1E-02	0.0E+00	

Bottom Level Inventory of Pilkington Float Glass.

CN-)	g	9.0E-02	2.3E-04	0.0E+00	2.9E-02	0.0E+00
Matter (unspecified)	g	1.8E+02	2.5E-01	0.0E+00	1.4E+01	0.0E+00
Organic Carbon (DOC)	g	3.9E+00	2.8E-03	0.0E+00	3.7E+00	0.0E+00
(C10H16N2O8, EDTA)	g	3.9E-05	0.0E+00	0.0E+00	3.9E-05	0.0E+00
ne (C6H5C2H5)	g	9.6E-02	1.7E-04	0.0E+00	9.8E-03	0.0E+00
F-)	g	7.7E-01	5.4E-04	0.0E+00	6.3E-01	0.0E+00
yde (CH2O)	g	1.5E-07	2.7E-12	0.0E+00	1.4E-07	0.0E+00
ethane (C2Cl6)	g	2.1E-11	3.7E-16	0.0E+00	2.0E-11	0.0E+00
(N2H4)	g	1.8E-05	0.0E+00	0.0E+00	1.8E-05	0.0E+00
ons (unspecified)	g	4.2E-02	3.8E-02	0.0E+00	1.4E-04	0.0E+00
te (ClO-)	g	3.5E-03	6.3E-08	0.0E+00	3.4E-03	0.0E+00
us Acid (HClO)	g	3.5E-03	6.3E-08	0.0E+00	3.4E-03	0.0E+00
Dissolved Matter (unspecified)	g	9.6E+00	9.1E-06	0.0E+00	2.1E-03	0.0E+00
	g	4.0E-01	6.9E-04	0.0E+00	3.8E-02	0.0E+00
, Fe3+)	g	4.0E+00	8.4E-01	0.0E+00	2.6E+00	0.0E+00
+, Pb4+)	g	5.2E-02	2.5E-03	0.0E+00	4.6E-02	0.0E+00
lts (Lithine)	g	2.0E-06	0.0E+00	0.0E+00	2.0E-06	0.0E+00
n (Mg++)	g	5.4E+00	2.4E-02	0.0E+00	2.3E+00	0.0E+00
e (Mn II, Mn IV, Mn VII)	g	3.3E-01	4.3E-04	0.0E+00	1.3E-01	0.0E+00
g+, Hg++)	g	3.8E-03	2.2E-05	0.0E+00	1.7E-06	0.0E+00
specified)	g	2.4E+00	1.3E-01	0.0E+00	2.2E-03	0.0E+00
Chloride (CH2Cl2)	g	3.4E-02	6.0E-07	0.0E+00	3.2E-02	0.0E+00
m (Mo II, Mo III, Mo IV, Mo V, Mo VI)	g	3.4E-03	2.9E-06	0.0E+00	1.9E-03	0.0E+00
(C4H9NO)	g	1.9E-04	0.0E+00	0.0E+00	1.9E-04	0.0E+00
+, Ni3+)	g	3.2E-02	2.5E-03	0.0E+00	1.4E-02	0.0E+00
O3-)	g	1.4E+00	2.2E-02	0.0E+00	1.1E-01	0.0E+00
O2-)	g	9.1E-04	3.4E-05	0.0E+00	8.4E-04	0.0E+00
s Matter (Kjeldahl, as N)	g	9.1E-03	0.0E+00	0.0E+00	9.1E-03	0.0E+00
s Matter (unspecified, as N)	g	2.3E+00	8.4E-03	0.0E+00	2.8E-01	0.0E+00
cified)	g	1.3E+01	7.4E-02	0.0E+00	9.7E+00	0.0E+00
ssolved Matter (chlorinated)	g	4.0E-03	0.0E+00	0.0E+00	0.0E+00	0.0E+00
ssolved Matter (unspecified)	g	5.6E-03	9.7E-08	0.0E+00	1.7E-03	0.0E+00
((COOH)2)	g	7.8E-05	0.0E+00	0.0E+00	7.8E-05	0.0E+00
H5OH)	g	5.4E-01	1.1E-03	0.0E+00	9.9E-02	0.0E+00
s (PO4 3-, HPO4--, H2PO4-, H3PO4, as P)	g	5.3E-02	2.3E-02	0.0E+00	2.7E-02	0.0E+00
s (P)	g	1.8E-02	2.9E-05	0.0E+00	2.9E-03	0.0E+00
s Pentoxide (P2O5)	g	1.7E-03	4.5E-06	0.0E+00	5.7E-04	0.0E+00
Aromatic Hydrocarbons (PAH, unspecified)	g	5.3E-02	1.1E-04	0.0E+00	5.5E-03	0.0E+00
(K+)	g	3.2E+01	4.0E-02	0.0E+00	3.5E+00	0.0E+00
Rb+)	g	4.0E-02	6.9E-05	0.0E+00	3.8E-03	0.0E+00
ecified)	g	5.8E+00	3.5E+00	0.0E+00	1.6E+00	0.0E+00

Bottom Level Inventory of Pilkington Float Glass.

le Oils and Fats	g	1.9E+01	3.7E-02	0.0E+00	1.8E+00	0.0E+00
Se II, Se IV, Se VI)	g	3.2E-03	2.9E-06	0.0E+00	1.7E-03	0.0E+00
xide (SiO2)	g	1.2E-02	2.2E-07	0.0E+00	1.2E-02	0.0E+00
)	g	2.4E-03	4.2E-06	0.0E+00	2.3E-04	0.0E+00
a+)	g	1.4E+03	2.4E+00	0.0E+00	1.6E+02	0.0E+00
(Sr II)	g	2.4E+01	4.6E-02	0.0E+00	2.5E+00	0.0E+00
(SO4--)	g	2.4E+03	4.6E+00	0.0E+00	8.5E+01	0.0E+00
(S--)	g	7.0E-02	1.8E-04	0.0E+00	7.3E-03	0.0E+00
SO3--)	g	1.3E-04	1.9E-05	0.0E+00	1.1E-04	0.0E+00
d Matter (unspecified, as S)	g	2.8E-06	6.6E-09	0.0E+00	7.6E-07	0.0E+00
Matter (unspecified)	g	7.0E+02	4.8E-01	0.0E+00	2.3E+02	0.0E+00
ecified)	g	4.1E-08	4.4E-10	0.0E+00	2.7E-10	0.0E+00
ethylene (C2Cl4)	g	5.0E-08	9.1E-13	0.0E+00	4.9E-08	0.0E+00
Sn4+)	g	5.3E-06	0.0E+00	0.0E+00	5.3E-06	0.0E+00
Ti3+, Ti4+)	g	1.3E-01	2.3E-06	0.0E+00	1.2E-01	0.0E+00
Organic Carbon)	g	8.2E+01	2.5E-01	0.0E+00	5.6E+01	0.0E+00
6H5CH3)	g	4.8E-01	9.7E-04	0.0E+00	8.7E-02	0.0E+00
ane (1,1,1-CH3CCl3)	g	1.1E-07	2.0E-12	0.0E+00	1.1E-07	0.0E+00
hylene (C2HCl3)	g	3.1E-06	5.6E-11	0.0E+00	3.0E-06	0.0E+00
Glycol (C6H14O4)	g	3.9E+00	7.0E-05	0.0E+00	3.7E+00	0.0E+00
(V3+, V5+)	g	7.6E-03	2.9E-06	0.0E+00	6.1E-03	0.0E+00
tile Organic Compounds)	g	1.4E+00	2.4E-03	0.0E+00	1.3E-01	0.0E+00
pecified)	litre	5.0E+01	1.4E-01	0.0E+00	1.8E+01	0.0E+00
emically Polluted	litre	1.2E+03	7.1E+00	0.0E+00	1.6E+01	0.0E+00
H4(CH3)2)	g	3.8E+00	6.5E-03	0.0E+00	3.9E-01	0.0E+00
)	g	1.2E-01	4.4E-03	0.0E+00	8.9E-02	0.0E+00
(Sb124)	kBq	8.8E-04	0.0E+00	0.0E+00	8.8E-04	0.0E+00
s134)	kBq	7.7E-04	0.0E+00	0.0E+00	7.7E-04	0.0E+00
s137)	kBq	1.1E-03	0.0E+00	0.0E+00	1.1E-03	0.0E+00
58)	kBq	2.5E-03	0.0E+00	0.0E+00	2.5E-03	0.0E+00
60)	kBq	1.6E-03	0.0E+00	0.0E+00	1.6E-03	0.0E+00
1)	kBq	9.6E-05	0.0E+00	0.0E+00	9.6E-05	0.0E+00
e (Mn54)	kBq	1.3E-04	0.0E+00	0.0E+00	1.3E-04	0.0E+00
m (Pa234m)	kBq	3.9E-03	0.0E+00	0.0E+00	3.9E-03	0.0E+00
e Substance (unspecified)	kBq	1.3E+01	1.3E+01	0.0E+00	1.1E-06	0.0E+00
a224)	kBq	2.0E-01	3.5E-04	0.0E+00	1.9E-02	0.0E+00
a226)	kBq	7.8E+00	6.9E-04	0.0E+00	7.5E+00	0.0E+00
a228)	kBq	4.0E-01	6.9E-04	0.0E+00	3.8E-02	0.0E+00
10m)	kBq	3.8E-03	0.0E+00	0.0E+00	3.8E-03	0.0E+00
h228)	kBq	8.0E-01	1.4E-03	0.0E+00	7.5E-02	0.0E+00
h230)	kBq	3.6E-01	0.0E+00	0.0E+00	3.6E-01	0.0E+00

Bottom Level Inventory of Pilkington Float Glass.

Th234)	kBq	3.9E-03	0.0E+00	0.0E+00	3.9E-03	0.0E+00
3)	kBq	4.6E+01	0.0E+00	0.0E+00	4.6E+01	0.0E+00
U234)	kBq	1.3E-01	0.0E+00	0.0E+00	1.3E-01	0.0E+00
U235)	kBq	5.6E-03	0.0E+00	0.0E+00	5.6E-03	0.0E+00
U238)	kBq	1.2E-01	0.0E+00	0.0E+00	1.2E-01	0.0E+00
	m2	1.0E+02	0.0E+00	1.0E+02	1.0E+02	1.0E+02
tter (total)	kg	2.7E-01	2.0E-01	0.0E+00	3.9E-02	0.0E+00
tter (unspecified)	kg	2.2E-01	1.5E-01	0.0E+00	3.9E-02	0.0E+00
tter: Iron Scrap	kg	4.6E-04	0.0E+00	0.0E+00	4.6E-04	0.0E+00
ous)	kg	7.9E-02	8.4E-05	0.0E+00	8.0E-03	0.0E+00
ation)	kg	2.5E-02	2.1E-04	0.0E+00	2.7E-03	0.0E+00
pal and industrial)	kg	7.8E-02	8.4E-04	0.0E+00	3.3E-03	0.0E+00
	kg	3.1E+02	2.6E-01	0.0E+00	6.9E+00	0.0E+00
cified)	kg	2.8E+02	1.8E-01	0.0E+00	3.1E-02	0.0E+00
Radioactive (class C)	kg	1.1E-04	0.0E+00	0.0E+00	1.1E-04	0.0E+00
adioactive (class A)	kg	2.8E-02	4.2E-05	0.0E+00	6.1E-03	0.0E+00
l (inert)	kg	2.5E+01	7.0E-02	0.0E+00	5.9E+00	0.0E+00
	kg	5.8E+00	0.0E+00	0.0E+00	5.8E+00	0.0E+00
ineral (inert)	kg	3.8E+00	6.0E-06	0.0E+00	4.9E-04	0.0E+00
oxic Chemicals (unspecified)	kg	5.5E-02	1.5E-03	0.0E+00	4.2E-06	0.0E+00
ctive	kg	7.9E-04	6.7E-06	0.0E+00	3.2E-04	0.0E+00
ctive (unspecified)	kg	3.1E-03	0.0E+00	0.0E+00	4.6E-05	0.0E+00
and Ash (unspecified)	kg	1.5E+00	9.6E-03	0.0E+00	8.9E-01	0.0E+00
y Energy	MJ	1.3E+04	4.8E+01	0.0E+00	1.0E+04	0.0E+00
	kg	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
otal)	litre	3.2E+03	3.0E+01	0.0E+00	2.1E+02	0.0E+00

APPENDIX C1: THERMAL AND ENERGY SIMULATION.

APPENDIX C2: DETERMINING INTERNAL ILLUMINANCE.

APPENDIX C3: FAÇADE MANUFACTURING METHODS.

APPENDIX C4: CODE FOR VISUAL BASIC TOOL.

APPENDIX C1: THERMAL AND ENERGY SIMULATION

This chapter describes the theory of heat balance calculations and the dynamic thermal model used in the development of the Façade design tool. There is an explanation of the heat balance method, and the tools which are suitable for carrying out this type of simulation are discussed. There is a further discussion of applicable weather data. Some definitions of appropriate terms are presented first.

Thermal Environment

The dynamic thermal model provides a representation of the storage of heat within the building fabric, the flow of heat into and out of the structure.

Heat Flux

The heat flux is the total flow of heat during a heat exchange over an appropriate time and area.

Transient conduction

This describes the process by which a fluctuation of the heat flux at one boundary of a solid material is transmitted to another boundary of the material, having changed in magnitude and shifted in time due to the material's thermal inertia. In the building fabric transient conduction is a function of thermal capacitance, temperature, heat flux excitations, hygro-thermal properties of the materials and the relative position of the materials. The external thermal excitations are in the form of known time series weather data, hence the modelling objective is to determine the intra-fabric temperature and moisture distribution, which can be described as the dynamic variation of heat flux at the material's exposed surfaces.

The thermophysical properties of a material which can be used to determine the intra-fabric behaviour include: conductivity, density, and specific heat capacity. These properties are time dependent because of material temperature and moisture levels, these properties may also be directional if the material is anisotropic.

Heat Balance Method

The heat balance method for calculating the net space sensible loads is based on the first law of thermodynamics (the theory of energy conservation). The heat balance method allows the net instantaneous sensible heating or cooling load on the space air mass to be calculated. A heat balance equation is written for each enclosing surface and for the room air. This set of equations can be solved for the unknown surface and air temperatures. The temperatures can be used to calculated the convective heat flow to or from the space air mass.

The space in the building under consideration is described by an enclosure bounded by a number of discrete surfaces (walls, floors, windows and ceiling). At any time, θ, each of the surfaces is assumed to be at some uniform temperature $T_{i\theta}$. Also the space air mass is assumed to be at some uniform temperature $T_{a\theta}$. At any plane the flux leaving the boundary and the flux entering the boundary are assumed to be equal, thus at the inside surface of any room wall the heat flow into the surface - because of convection from room air, radiation from internal sources (such as people and equipment) and net radiation from interchange between the surface and all other surfaces in the room - is balanced by the conductive flux leaving the surface to penetrate the solid.

Similarly the conductive flux leaving the exterior surface of the wall to penetrate the solid and enter the room is balanced by the absorbed solar radiation, net long wave radiant flux from the surroundings and the convective flux from the external air. A heat balance for the room air volume requires the air condition system to remove the net heat added to the volume by convection from interior surfaces and interior heat sources (light, people and equipment) and by mass transfer due to infiltration. Thus at the *i*th surface at time *q*, the energy (per unit area) balance is:

$$q_{i,\theta} = h_i\left(T_{a,\theta} - T_{i,\theta}\right) + \sum_{k=1}^{n} g_{i,k}\left(T_{k,\theta} - T_{i,\theta}\right) + R_i \qquad \text{(AC- 1)}$$

Where:

i = surface number

n = number of surfaces

$q_{i,\theta}$ = rate of heat conducted into surface i at the inside surface at time θ (W)

h_i = convective heat transfer coefficient at interior surface i (W/m^2-K)

g_{ik} = linearised radiation heat transfer factor between interior surface i and interior surface k (W/m^2-K)

$T_{a,\theta}$ = inside air temperature

$T_{i,\theta}$ = average temperature of interior surface i at time θ (°C)

$T_{k\theta}$ = average temperature of interior surface k at time θ (°C)

The first term represents the heat gain due to convection from the room air , the summation represents radiative interchange and the last term represents R_i all other radiant energy absorbed by the surface.

The left side of equation (AC-1) $q_{i,\theta}$ represents the net transfer to the surface from the air and surroundings. It must match the heat conducted into the solid surface.

$$q_{i,t} = \sum_{j=1}^{m} X_j T_{i,\theta-j} - \sum_{j=0}^{m} Y_j T_{oi,\theta-j} + CR_i q_{i,\theta-i} \qquad \text{(AC- 2)}$$

Where:

i = inside surface

o = outside surface

j = the number of non-zero CTF values

m = time index variable

T = temperature

θ = time

X = cross CTF values

Y = interior CTF values

The X (cross CTF) value refers to the current and previous flow of energy through the wall due to the outside conditions and the CR (flux history) coefficients refer to the current and previous heat flux to the zone. This equation is a simplification of the strict heat balance calculation technique. This equation must be solved for every surface in a room, but it cannot be solved independently of equation (AC-1) because the energy changes occurring within the room have an effect on the internal conditions and interior surface temperature $T_{i,\theta}$ is represented in both equations. So the equations AC-1 and AC-2 must be solved for all surfaces simultaneously to calculate the space internal load. There are several possible ways of modelling this process, including numerical finite series and time series methods.

However, the most common method of modelling the equations, due to greater computational speed and little loss of generality, is the conduction transfer function method (CTF). This method is developed from the final term of equation (AC-2). This is based on the assumption (Stephenson and Mitalas 1967) that the characteristics of any physical system can be described by giving the relationship between an excitation and the systems response to it. This relationship is described by the transfer coefficients, which are generally referred to as response factors. A response factor is calculated for each specific wall configuration; this reduces the amount of calculation required. The response factor is dependent on the physical properties of the materials of the wall and only needs to be calculated once. The response factors are used to relate the output function at a given time to the value of one or more of the driving functions at the given time and a set period immediately preceding the excitation (ASHRAE, 1997).

As well as calculating the energy balance through the materials of the wall surfaces an energy balance for the zone air must also be calculated.

$$q_\theta = \left[\sum_{i=1}^{m} h_{ci} \left(T_{i,\theta} - T_{a,\theta} \right) \right] A_i + \rho C_P \quad Q_{i,\theta} \left(T_{o,\theta} - T_{a,\theta} \right) + \rho \quad C_P Q_{v,\theta} \left(T_{v,\theta} - T_{a,\theta} \right) + q_{s,\theta} + q_{l,\theta} + q_{e,\theta}$$

(AC- 3)

Where:

$T_{a,\theta}$ = inside air temperature at time θ (°C)

$T_{o,\theta}$ = outside air temperature at time θ (°C)

$T_{v,\theta}$ = ventilation air temperature at time θ (°C)

ρ = air density (kg/m^3)

C_P = specific heat of air (J/kg-K)

$Q_{i,\theta}$ = volume flow rate of outdoor air infiltrating into the room at time θ (m^3/s)

$Q_{v,\theta}$ = volume rate of flow of ventilation air at time θ (m^3/s)

$q_{s,\theta}$ = rate of solar heat coming through the windows and convected into the room air at time θ (W)

$q_{l,\theta}$ = rate of heat from the lights convected into the room air at time θ (W)

$q_{e,\theta}$ = rate of heat from equipment and occupants convected into the room air at the time θ (W)

APPENDIX C2: DETERMINING INTERNAL ILLUMINANCE.

The methods for determining the internal luminance and the energy balance equation are explained as is the radiosity solution method. Some basic terms are explained first:

Local and Global illumination

Local illumination algorithms describe how an individual surface reflects or transmits light. Given a description of the light arriving at a surface the mathematical algorithms predict the intensity, spectral colour and distribution of the light leaving the surface. The next task is to determine from where the light arriving at the surface originates. Simple rendering algorithms only deal with light which comes directly from light sources.

In order to produce more accurate images it is important to take into account both light sources and the interaction of other surfaces in the room with those light sources and each other. For example some surfaces absorb and block the transmission of light, casting shadows onto other surfaces; while some surfaces are shiny, and reflections of other surfaces are visible in them. An algorithm has been developed which takes into account the interactivity between surfaces and this is known as a global illumination algorithm.

Radiance

The relevant quantity used to describe radiant energy transfer is radiance, denoted by L. Radiance is defined as the amount of energy travelling at some point in a specified direction, per unit time, per unit area perpendicular to the direction of travel, per unit solid angle, as shown in Figure AC1.

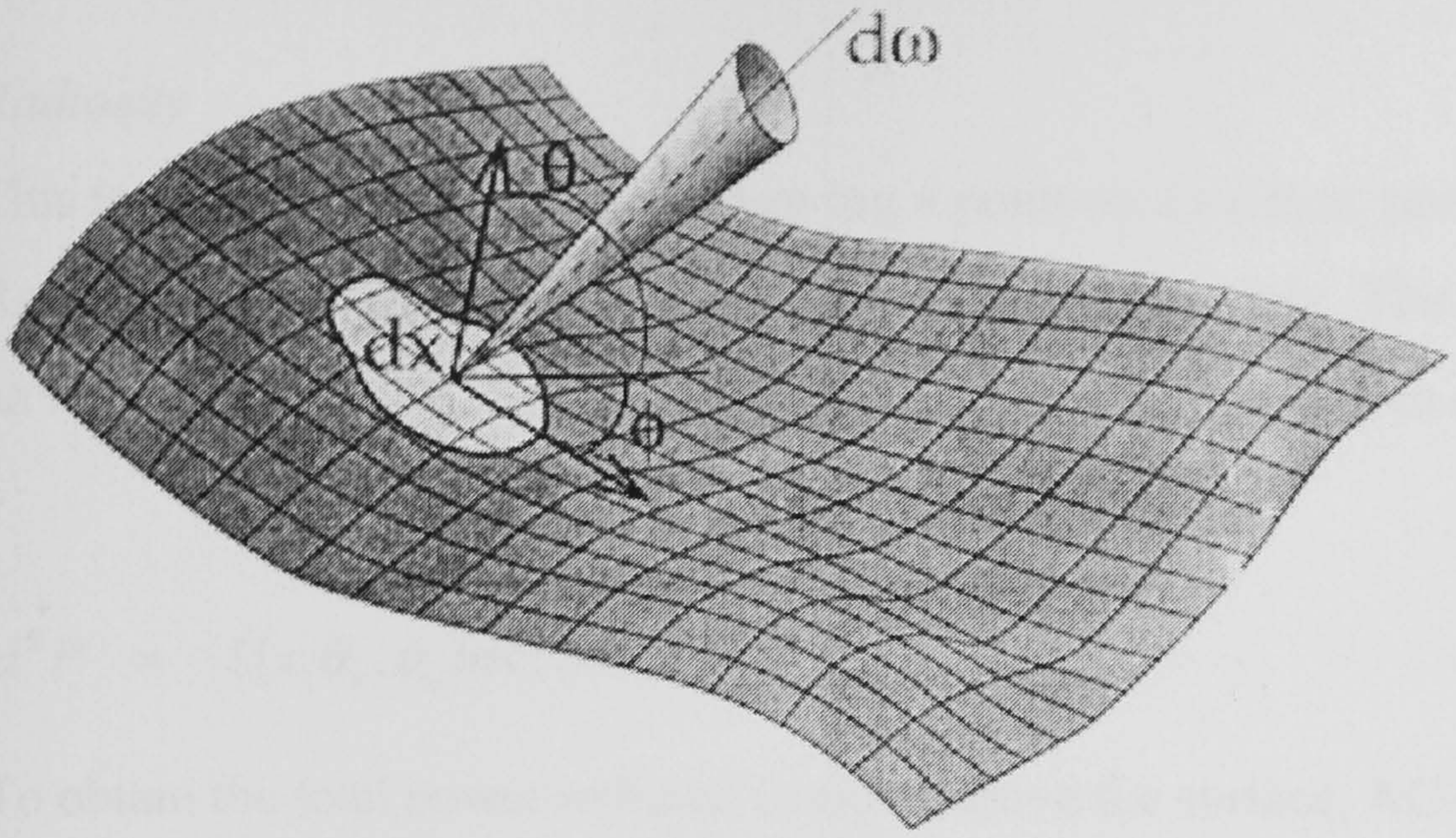

Figure AC1 A diagrammatic representation of radiance.

Therefore, in the situation shown the energy radiated in the small solid angle *dω*, from the differential area dx^2, during the time interval *dt* is:

$$L(x,\theta,\phi) \quad \underbrace{dx\cos\theta}_{projected \quad area} \quad d\omega dt \tag{AC-4}$$

and the power (energy per unit time) radiated in the same condition is:

$$d^2P = L(x,\theta,\phi)dx\cos\theta d\omega \tag{AC-5}$$

An important property of radiance is that for any two mutually visible points *x* and *y* in space, the radiance leaving point *x* in the direction of point *y* is the same as radiance impinging on point *y* from the direction of point *x*, i.e. radiance is conserved along the path from *x* to *y*. Most light receivers are sensitive to radiance; this property explains that a given surface produces the same visual impression due to its emitted radiance at all viewing distances. It also means that a knowledge of the radiance leaving all surfaces in a scene is sufficient to render a picture. When a visible surface is identified, its emitted radiance in the direction of the viewer is all that is needed to evaluate the effect produced on the receiver.

Radiosity

This is defined as the total power leaving a point on a surface, per unit area of the surface. Radiosity (*B*) is a function of position on the surfaces only. The power radiated through an infinitesimal solid angle dω from an infinitesimal surface area *dx* is given by AC-6.

$$d^2P \ = \ L(x,\theta_x,\phi_x)dx\cos\theta_x d\omega_{xy} \qquad \text{(AC-6)}$$

To obtain the total power radiated from *dx* above the surface, AC-6 is integrated over the upper hemisphere Ω:

$$\begin{aligned} dP \ &= \ \int_\Omega d^2 P \\ &= \ \int_\Omega L(x,\theta,\phi)\cos\theta d\omega \qquad \text{(AC-7)} \end{aligned}$$

Since radiosity is defined per unit area, the radiosity at point *x* is defined as :

$$\begin{aligned} B(x) &= \ \frac{dP}{dx} \\ &= \ \int_\Omega L(x,\theta,\phi) \ \cos\theta d\omega \qquad \text{(AC-8)} \end{aligned}$$

Ideal diffuse Reflectors

An ideal diffuse reflector has a uniform bi-directional reflectance distribution function (BRDF), i.e. a surface where the direction of the reflected radiation does not depend on the direction of the light source. As a consequence the reflected radiance is the same in all directions, and the appearance of the surface does not change with the viewing angle. When light is reflected in a uniform manner, the surface is easily characterised by its directional hemispherical reflectance, which is also independent of direction. This dimensionless constant which corresponds to the intuitive meaning of reflectance is called the diffuse reflectance.

Ideal Specular Reflectors

An ideal specular reflector reflects light only in the minor direction given by Snell's Law. The out-going direction is contained in the line of incidence, and the outgoing polar angle is equal to the incident polar angle. The BDRF in this case is not well-behaved.

Global Illumination Model

In general the energy equilibrium for a set of radiating surfaces is expressed by the following integral equation:

$$\underbrace{L(x,\theta_0,\phi_0)}_{\textit{total radiance}} = \underbrace{L_e(x,\theta_0,\phi_0)}_{\textit{emitted radiance}} + \underbrace{\int_\Omega \rho_{bd}(x,\theta_0,\phi_0,\theta,\phi)L_i(x,\theta,\phi)\cos\theta d\omega}_{\textit{reflected radiance}} \qquad \text{(AC-9)}$$

where:

$L(x,\theta_0,\phi_0)$ is the radiance leaving point x in direction (θ_0, ϕ_0);

$L_e(x,\theta_0,\phi_0)$ is the emitted radiance, a property of the surface at point x;

$L_i(x,\theta,\phi)$ is the incident radiance impinging on point x from direction θ, ϕ;

Ω is the set of directions (θ, ϕ) in the hemisphere covering the surface at point x ;

$\rho_{bd}(x,\theta_0,\phi_0,\theta,\phi)$ is the bidirectional reflectance distribution function (BRDF) describing the reflective properties of the surface at point x.

Equation AC-19 represents the energy balance at point x as it expresses the outgoing radiance in terms of the various sources of radiant energy. The first term on the right-hand side is the emissivity of the surface. This term is non-zero only for surfaces that generate light themselves, even if no other surface is present. For visible light this is only the case for light sources. For heat transfer simulations all surfaces usually exhibit some emissivity, which depends on material's properties and their temperature. The second term on the right hand side of the equation expresses the effect of light reflection: the reflected radiance is an integral over all possible incoming directions of the incoming flux density (or irradiance) multiplied by the bidirectional reflectance distribution function.

The global illumination equation is an integral equation with the unknown radiance function *L* appearing under an integral on the right-hand side, as well as on the left-hand side. Thus the equation is difficult to solve, since the computation of the radiance at a particular point requires knowledge of the incoming radiances from all directions. In general, integral equations can rarely be solved analytically, and numerical methods are used instead to compute approximate solutions. Radiosity and ray tracing are two methods of performing a numerical approximation of the global illumination equation.

Ray Tracing

Ray tracing was one of the first global illumination algorithms to be developed. The algorithm works by tracing the rays backward from each pixel in the screen to the 3D model. This means that only the information needed to construct the visible image is computed. Ray tracing is a versatile algorithm because it can accurately model a number of lighting effects, including specular reflections and refraction through transparent materials. However, the main disadvantage of this algorithm is that ray tracing in a complex environment can be computationally expensive. Another important disadvantage of using ray tracing is that it does not account for diffusing surfaces, because only light which arrives directly from the light source is accurately accounted for.

Radiosity

The radiosity method was originally developed in the 1950s as a method of computing radiant heat exchanges between surfaces. This method was adapted in the 1980s by a group at Cornell University (Goral *et al.* 1984). A radiosity equation is first derived from the general global illumination equation (AC-9) which assumes that all surfaces are ideally diffuse. Where all surfaces are ideally diffuse radiosity can be used in place of radiance as the relevant variable. This substitution reduces the global illumination equation to a simpler energy balance equation.

Radiosity is the total power leaving a surface at a given point per unit area on the surface. In terms of the radiance leaving the surface, radiosity is described by the following integral:

$$B(x) \equiv \int_{\Omega} L(x,\theta,\phi)\cos\theta d\omega \qquad \text{(AC-10)}$$

In the case of an ideal diffuse surface radiance is a function of position only:

$$L(x,\theta,\phi) \equiv L(x) \qquad \text{(AC-11)}$$

and can therefore be moved outside the integral

$$B(x) \equiv L(x) \int_{\Omega} \cos\theta d\omega \qquad \text{(AC-12)}$$

$$= L(x) \int_0^{\pi} \int_0^{2\pi} \cos\theta \sin\theta d\theta d\phi \qquad \text{(AC-13)}$$

$$= \pi L(x) \qquad \text{(AC-14)}$$

Thus radiosity and radiance can be used interchangeably to characterise the light leaving diffuse surfaces.

The radiosity method is described diagrammatically in Figure AC-1. The radiosity solution relies on the discretisation of all surfaces into smaller components. The illumination and radiative energy for each of these smaller surfaces is calculated by calculating the interaction between each surface and each of the other surfaces. These values are represented by "form factors".

The form factor describes the fraction of energy which leaves one surface (Patch) and arrives at a second surface, F_{ij} is the proportion of the total power leaving patch P_i that is received by P_j. F_{ij} takes into account the distance between the surfaces and their orientation in space relative to each other. This method assumes that a single point on each surface is representative of all the points on the surface. To increase the accuracy of the calculation the number of patches must be increased until a representative number of patches have been calculated. Form factors present a symmetrical relationship, such that :

$$\forall(i,j) \quad A_i F_{ij} \;=\; A_j F_{ji} \qquad \text{(AC-15)}$$

This reciprocal relationship means that an unknown form factor can be derived from a known form factor. The form factors also display additivity, which is that two disjoint patches receive the sum of their individual powers if they are joined. Hence it is possible to divide a surface into a number of small patches, calculate F and subsequently join the form factors together to calculate the power received by the entire surface.

The form factors for each surface in a scene are calculated and stored in a grid, this grid is referred to as the "radiosity matrix" and it works just like a 2-dimensional table. Each element in this matrix contains a form factor for the interaction from the surface indexed by the column and the surface indexed by the row.

The stored form factors are used to calculate the radiosity in every patch of model using the following equation:

$$B_i \;=\; E_i \;+\; \rho_i \sum B_j F_{ij} \qquad \text{(AC-16)}$$

where:

B_i is the radiosity of the surface i

E_i is the emissivity of surface i

ρ is the reflectivity of surface i

B_j is the radiosity of the surface j

F_{ij} is the form factory of surface j relative to surface i

E_i is the energy emitted by the surface

$\sum B_j F_{ij}$ is the energy reaching this surface from other surfaces

$\rho_i \sum B_j F_{ij}$ is the energy reflected by the surface.

The whole process of calculating the radiosity of a solution is presented diagrammatically in Figure AC-2. The selection of linear radiosity calculations are solved to give a set of patch radiosities which describe a particular model. This numerical description of the model can be used for various purposes; however it is usually used to construct a visual image of the scene. The final step in producing such an image is called visualisation or rendering. In this step every patch is assigned a colour based on its radiosity. The radiosity for all surface combinations are solved and held in a 2D grid. This result is one of the useful features of the radiosity solution, which is the ability to view any 2D scene in a 3D solution, which gives the effect of being able to move through the solution. The computational effectiveness of the radiosity solution has led to its choice for this study.

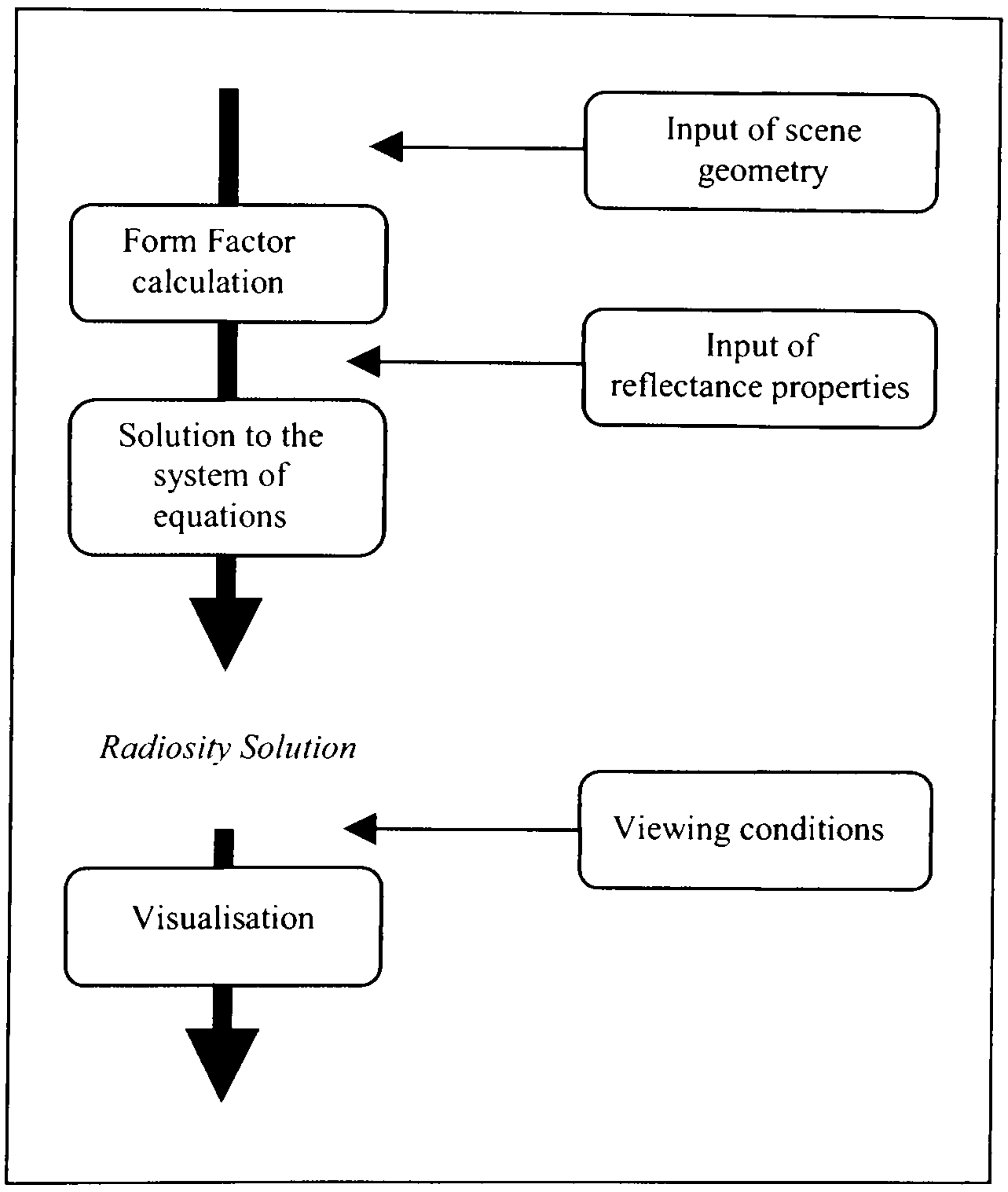

Figure AC-2 Diagram of the radiosity algorithm for image

Attempts are being made to integrate the two main methods (Dischler 1999) these attempts are mainly being driven by the computer graphics industry, which uses the ability to predict accurately lighting in order to provide photo realistic backgrounds for computer games.

APPENDIX C3: FAÇADE MANUFACTURING METHODS.

The starting point of this LCA is the raw materials, which are processed into feedstock materials. This materials feed stock is separately processed into façade components and pre-assembled into façade elements (with the exception of the traditional masonry façade where walls are delivered to the construction site as bricks and manufactured into a wall on site).

Glazing systems

The manufacture of glass produces large sheets, often 6m by 3m, which are cut to the to the appropriate size. The off-cuts are returned to the glazing manufacturer where they are used as cullet in the glass manufacturing process. The glass has any off-line processes carried out, such as toughening, laminating or the addition of hard and soft coatings. Toughened glass can be tested by being heat soaked in a kiln order to reduce the likelihood of fracture from the expansion of nickel sulphide inclusions. The completed panes are washed and hollow aluminium spacer bars filled with desiccant are bonded between two panes of glass using a butyl adhesive. The edges are sealed with silicone to produce a double glazing panel. If the double glazing panel includes a heavy gas filling, a hole is made in the silicone seal and the panes are filled with the insulating gases the air is evacuated and the silicone is resealed. The double glazing panels can be stored for site fixing or shipped to another façade component manufacturer for pre assembly.

Lightweight Cladding

Metal composite panels can be manufactured using two methods; continuous production and batch production (Brookes, 1998). The composite metal panels consist of two sheets of metal separated by an insulation core material. Different insulation cores may be used in order to achieve various thermal insulation values. The most popular types of core are mineral wool, honeycombed paper, polystyrene and polyurethane (with fame retardants). The continuous production line involves one layer of the sheet metal being fed through onto a table with the core material laid onto it and the top layer of sheet metal sandwiched on top. This material is then passed through an oven to cure the core material or the adhesives then the material is cut to size as it exits the oven. The rolled sheet metal used for the panels can be anodised (aluminium) or powder coated to protect it from the environment and give the desired finish. These cladding elements are then installed onto framework on site.

Heavyweight Cladding

Pre-cast concrete cladding is manufactured by pouring wet concrete into a mould. The moulds are either made from steel or timber; this is factory dependent with different fabricators favouring different methods. Steel forms have the advantage of greater accuracy, whereas timber forms, manufactured from softwoods, allow greater versatility and tend to be cheaper. Large concrete panels are reinforced with steel in order to reduce the depth of concrete required and increase the strength. The size of concrete panels is usually limited by the structural framework of the building and the transportation.

Panels are cast horizontally either face down or face up depending on the final surface finish required. Face up casting is used so that finishes, such as sand blasting can be applied while the cast is still in the mould, and face down casting is used so that facing materials, brick as shown in Figure P3-4, can be applied. The amount of steel reinforcement is calculated and the steel is shaped into the correct pattern for the particular form. If the concrete panels are faced the facing material is placed into the form before the reinforcement and concrete are added. The form is kept moving at carefully controlled temperatures in order to promote curing. It is possible to cast insulation materials into the concrete rather than adding it to the back face of the concrete. Devices for lifting and fixing the concrete panels are usually pre added during the casting process. Once they are complete the pre-cast panels are stored on site until enough panels have been manufactured to provide some float then they are delivered to site where they are fixed to the structure and glazed.

Curtain Walling

Curtain wall manufacture is dependent on the glazing manufacturing process. The framework for the glazing, which is typically aluminium, is extruded into lengths.. The surface can either be anodised or powder coated. When the appropriate surface finish has been applied the lengths of aluminium are cut to size. Any panels which need to be included in the design are rolled, or pressed into the correct form. At this stage there are two options, the framework, solid panels and glazing can be transported to site where they are constructed (stick system), or the curtain wall can be pre-assembled into units in the factory and transported to site as a finished article (unitised system). If the unitised curtainwall method is chosen the frame is bolted together, gaskets are inserted and the frame is glazed in the factory. The units are transported to site where they are installed into prefixed brackets. However, even in designs that utilise mainly unitised curtain walling systems there can be areas, atria for example, which have to be glazed on-site.

Masonry

The materials are transported to site where they are constructed into the form desired. Inner and outer leaves of brickwork are laid with the mortar and in some cases the addition of a polymeric dam proof course. Ties are used between courses to give the two leaves of brick stability and cause them to have composite action. Sills are added and lintels are put in above door ways and windows. A timber form of the correct dimensions is often placed in the structure to simulate the window opening. When the brickwork is completed the timber "window" is removed and the space is glazed.

Timber forms and other site equipment for mixing mortar and moving the bricks and blocks once they are on site have not been included in the inventory analysis of the masonry systems.

Shading Systems

The shading systems are usually designed at the same time as the façade. These systems are often developed by different companies and supplied to the main façade contractor. Aluminium is typically used to manufacture solid shading systems, while systems such as the glass louvres use safety toughened glass with aluminium brackets. Stubs are included in the design of the façade to assist the fixing of shading systems to the external face of the building. In some instances the stubs for the shading systems go through the façade to the structure of the building. The shading is erected on site by the system company after the construction of the other façade elements.

APPENDIX C4: CODE FOR VISUAL BASIC TOOL.

```
Option Explicit
Public wbkObj As Workbook
Public filename As String
Dim Folder As String
Dim num(10) As String
Dim a As String
Dim b As String
Dim c As String
Dim d As String
Dim e(10) As String
Dim i As Integer
Dim j As Integer
Dim k As Integer
Dim Weather As Variant

Private Sub cmdEU_Click()

If LstDir2.Text = "" Then
  MsgBox ("Please select a direction. "), , "Error"
  MSChart2.Visible = False
   Exit Sub
End If

Dim arrenergy(1 To 12, 1 To 6)


MSChart2.ChartType = VtChChartType2dBar
MSChart2.Stacking = True
MSChart2.Legend.Location.LocationType = VtChLocationTypeBottom
MSChart2.Legend.VtFont.Size = 8
MSChart2.Plot.SeriesCollection(1).LegendText = "Internal Loads"
MSChart2.Plot.SeriesCollection(2).LegendText = "Heating"
MSChart2.Plot.SeriesCollection(3).LegendText = "Cooling"
MSChart2.Plot.SeriesCollection(4).LegendText = "Humidification"
MSChart2.Plot.SeriesCollection(5).LegendText = "Dehumidification"
MSChart2.TitleText = LstDir2.Text


With MSChart2.Plot.Axis(VtChAxisIdY)
  .AxisTitle.VtFont.Name = "Arial"
  .AxisTitle.VtFont.Size = 10
  .AxisTitle.VtFont.Effect = VtFontStyleBold
  .AxisTitle.Text = "Energy Load KWh/m" & Chr$(178)
  .ValueScale.Auto = False
  .ValueScale.Minimum = 0
  .ValueScale.Maximum = 1600
  .ValueScale.MajorDivision = 8
  .ValueScale.MinorDivision = 2
End With

If LstDir2.Text = "North" Then
  j = 3
ElseIf LstDir2.Text = "East" Then
```

```
  j = 17
ElseIf LstDir2.Text = "South" Then
  j = 31
ElseIf LstDir2.Text = "West" Then
  j = 45
End If

For i = 1 To 12

arrenergy(i, 1) = wbkObj.Worksheets(3).Range("D" & i + j).Value 'Labels
arrenergy(i, 2) = wbkObj.Worksheets(3).Range("K" & i + j).Value 'Series 1
arrenergy(i, 3) = wbkObj.Worksheets(3).Range("G" & i + j).Value 'Series 2
arrenergy(i, 4) = wbkObj.Worksheets(3).Range("H" & i + j).Value 'Series 3
arrenergy(i, 5) = wbkObj.Worksheets(3).Range("I" & i + j).Value 'Series 4
arrenergy(i, 6) = wbkObj.Worksheets(3).Range("J" & i + j).Value 'Series 5
Next i

MSChart2.ChartData = arrenergy
MSChart2.Visible = True
End Sub
```

Private Sub cmdEI_Click()

```
'turn off the screen  update property

MSChart3.Visible = False
MSChart4.Visible = False
FrmMain.AutoRedraw = False

If OptEI(0).Value = True Then
   Call chartEI1
   If complete = 5 Then
   MSChart3.Visible = True
   End If
Else
   Call chartEI2
   If complete = 5 Then
   MSChart4.Visible = True
   End If
End If

'turn on the screen  update property
FrmMain.AutoRedraw = True
End Sub
```

Private Sub chartEI2()

```
complete = 1
  With FrmMain.MSChart4
     .Height = 5535
     .Width = 9375
     .Top = 720
     .Left = 240
     .ChartType = VtChChartType2dBar
     .Legend.Location.LocationType = VtChLocationTypeRight
     .Plot.SeriesCollection(1).LegendText = "Human Health"
     .Plot.SeriesCollection(2).LegendText = "Eco System"
     .Plot.SeriesCollection(3).LegendText = "Resource"
```

```
        .ShowLegend = True
    End With


    MSChart4.Plot.Axis(VtChAxisIdY).ValueScale.Auto = False
    With MSChart4.Plot.Axis(VtChAxisIdY)
        .ValueScale.Minimum = 0
        .ValueScale.Maximum = 240
        .ValueScale.MinorDivision = 2
        .ValueScale.MajorDivision = 12
    End With

    MSChart4.Plot.Axis(VtChAxisIdY2).AxisScale.Hide = True

Dim arrenv(1 To 4, 1 To 4)
For i = 1 To 4
arrenv(i, 1) = wbkObj.Worksheets(3).Range("B" & ((i - 1) * 9 + 63)).Value 'Labels
arrenv(i, 2) = wbkObj.Worksheets(3).Range("D" & ((i - 1) * 9 + 66)).Value 'Series 1
arrenv(i, 3) = wbkObj.Worksheets(3).Range("D" & ((i - 1) * 9 + 67)).Value 'Series 2
arrenv(i, 4) = wbkObj.Worksheets(3).Range("D" & ((i - 1) * 9 + 68)).Value 'Series 3
Next i


MSChart4.ChartData = arrenv
complete = 5

End Sub
```

Private Sub chartEl1()

```
complete = 1

Dim arrenv(1 To 4, 1 To 6)

    With FrmMain.MSChart3
        .Height = 5535
        .Width = 9375
        .Top = 720
        .Left = 240
    End With

    'format graph
    With FrmMain.MSChart3
        .ChartType = VtChChartType2dBar
        .Legend.Location.LocationType = VtChLocationTypeRight
        .Plot.SeriesCollection(1).LegendText = "Incidental loads"
        .Plot.SeriesCollection(2).LegendText = "Cladding"
        .Plot.SeriesCollection(3).LegendText = "Mechnical Ventilation"
        .Plot.SeriesCollection(4).LegendText = "Heating"
        .Plot.SeriesCollection(5).LegendText = "Waste"
        .ShowLegend = True
    End With

    MSChart3.Plot.Axis(VtChAxisIdY).ValueScale.Auto = False
    With MSChart3.Plot.Axis(VtChAxisIdY)
```

```
      .ValueScale.Minimum = 0
      .ValueScale.Maximum = 240
      .ValueScale.MinorDivision = 2
      .ValueScale.MajorDivision = 12
   End With

   MSChart3.Plot.Axis(VtChAxisIdY2).AxisScale.Hide = True


For i = 1 To 4
arrenv(i, 1) = wbkObj.Worksheets(3).Range("B" & ((i - 1) * 9 + 63)).Value 'Labels
arrenv(i, 2) = wbkObj.Worksheets(3).Range("I" & ((i - 1) * 9 + 65)).Value 'Series 1
arrenv(i, 3) = wbkObj.Worksheets(3).Range("E" & ((i - 1) * 9 + 65)).Value 'Series 2
arrenv(i, 4) = wbkObj.Worksheets(3).Range("F" & ((i - 1) * 9 + 65)).Value 'Series 3
arrenv(i, 5) = wbkObj.Worksheets(3).Range("G" & ((i - 1) * 9 + 65)).Value 'Series 4
arrenv(i, 6) = wbkObj.Worksheets(3).Range("H" & ((i - 1) * 9 + 65)).Value 'Series 5
Next i

MSChart3.ChartData = arrenv
complete = 5

End Sub

Private Sub cmdTE_Click()

MSChart1.Visible = False

   With MSChart1.Plot.Axis(VtChAxisIdY)
      .AxisTitle.VtFont.Name = "Small Fonts"
      .AxisTitle.VtFont.Size = 9
      .AxisTitle.Text = "Temperature" & Chr$(176) & "C"
   End With

   With FrmMain.MSChart1.Plot.Axis(VtChAxisIdX)
      .AxisTitle.VtFont.Name = "Small Fonts"
      .AxisTitle.VtFont.Size = 10
   End With
   MSChart1.Legend.Location.LocationType = VtChLocationTypeBottom
   MSChart1.Legend.VtFont.Size = 8
   MSChart1.ColumnCount = 6
   MSChart1.SeriesColumn = 1


If OptTE(0).Value = True Then
   Call Month
Else
   Call Season
End If

If complete = 5 Then
   MSChart1.Visible = True
Else
   MSChart1.Visible = False
End If

End Sub
```

Private Sub Season()

```
'format graph
  With FrmMain.MSChart1
     .ChartType = VtChChartType2dLine
     .Plot.SeriesCollection(1).LegendText = "North"
     .Plot.SeriesCollection(2).LegendText = "East"
     .Plot.SeriesCollection(3).LegendText = "South"
     .Plot.SeriesCollection(4).LegendText = "West"
     .Plot.SeriesCollection(5).LegendText = "External"
     .Plot.SeriesCollection(3).SecondaryAxis = False
  End With
     MSChart1.Plot.Axis(VtChAxisIdY2).AxisScale.Hide = True
     MSChart1.TitleText = lstSeason.Text
     MSChart1.Plot.Axis(VtChAxisIdY2).AxisTitle.Visible = False

'select season
If lstSeason.ListIndex = -1 Then
  MsgBox ("Please select season. "), , "Error"
  complete = 1
  Exit Sub

ElseIf lstSeason.Text = "Summer" Then
  j = 2026
  With MSChart1.Plot.Axis(VtChAxisIdY)
     .ValueScale.Auto = False
     .ValueScale.Minimum = 0
     .ValueScale.Maximum = 30
     .ValueScale.MajorDivision = 6
  End With
  With MSChart1.Plot.Axis(VtChAxisIdY2)
     .ValueScale.Auto = False
     .ValueScale.Minimum = 0
     .ValueScale.Maximum = 30
     .ValueScale.MajorDivision = 6
  End With

ElseIf lstSeason.Text = "Winter" Then
  j = 2194
  With MSChart1.Plot.Axis(VtChAxisIdY)
     .ValueScale.Auto = False
     .ValueScale.Minimum = -10
     .ValueScale.Maximum = 25
     .ValueScale.MajorDivision = 7
  End With
  With MSChart1.Plot.Axis(VtChAxisIdY2)
     .ValueScale.Auto = False
     .ValueScale.Minimum = -10
     .ValueScale.Maximum = 25
     .ValueScale.MajorDivision = 7
  End With

End If
```

```
'get data
Dim arrweather(1 To 168, 1 To 6)

For i = 1 To 168
arrweather(i, 1) = wbkObj.Worksheets(2).Range("E" & i + j).Value 'Labels
arrweather(i, 2) = wbkObj.Worksheets(2).Range("G" & i + j).Value 'Series 1
arrweather(i, 3) = wbkObj.Worksheets(2).Range("K" & i + j).Value 'Series 2
arrweather(i, 4) = wbkObj.Worksheets(2).Range("O" & i + j).Value 'Series 3
arrweather(i, 5) = wbkObj.Worksheets(2).Range("S" & i + j).Value 'Series 4
arrweather(i, 6) = wbkObj.Worksheets(2).Range("H" & i + j).Value 'Series 5
Next i
MSChart1.ChartData = arrweather
complete = 5

'turn on screen update
End Sub


Private Sub Month()

'turn off the screen  update property
FrmMain.AutoRedraw = False

    With FrmMain.MSChart1.Plot.Axis(VtChAxisIdY)
        .ValueScale.Auto = False
        .ValueScale.Maximum = 30
        .ValueScale.Minimum = 0
        .ValueScale.MinorDivision = 1
        .ValueScale.MajorDivision = 6

    End With
With MSChart1
    .ChartType = VtChChartType2dLine
    .Legend.Location.LocationType = VtChLocationTypeBottom
    .Plot.SeriesCollection(1).LegendText = "Internal Temperature"
    .Plot.SeriesCollection(2).LegendText = "External Temperature"
    .Plot.SeriesCollection(3).LegendText = "Relative Humidity"
    .Plot.SeriesCollection(3).SecondaryAxis = True
    .ShowLegend = True
End With

    MSChart1.Title = lstDir.Text & " " & lstWeather.Text

With MSChart1.Plot.Axis(VtChAxisIdY2)
    .AxisScale.Hide = False
    .ValueScale.Auto = False
    .ValueScale.Maximum = 90
    .ValueScale.Minimum = 30
    .ValueScale.MinorDivision = 1
    .ValueScale.MajorDivision = 6
    .AxisTitle.VtFont.Name = "Small Fonts"
    .AxisTitle.VtFont.Size = 9
    .AxisTitle.Text = "Relative Humidity" & Chr$(37)

End With
```

```
'choose weather or season
If lstDir.ListIndex = -1 Then
   MsgBox ("Please select a direction. "), , "Error"
   complete = 1
   Exit Sub

ElseIf lstWeather.ListIndex = -1 Then
   MsgBox ("Please select a month. "), , "Error"
   complete = 1
   Exit Sub

ElseIf lstWeather.Text = "January" Then
j = 10
ElseIf lstWeather.Text = "February" Then
j = 178
ElseIf lstWeather.Text = "March" Then
j = 346
ElseIf lstWeather.Text = "April" Then
j = 514
ElseIf lstWeather.Text = "May" Then
j = 682
ElseIf lstWeather.Text = "June" Then
j = 850
ElseIf lstWeather.Text = "July" Then
j = 1018
ElseIf lstWeather.Text = "August" Then
j = 1186
ElseIf lstWeather.Text = "September" Then
j = 1354
ElseIf lstWeather.Text = "October" Then
j = 1522
ElseIf lstWeather.Text = "November" Then
j = 1690
ElseIf lstWeather.Text = "December" Then
j = 1858
Else
   MsgBox ("please make another weather seletion"), , "Error"
   Exit Sub
End If

'decide direction
If lstDir.ListIndex = -1 Then
   MsgBox ("Please select a direction"), , "Error"
   Exit Sub
ElseIf lstDir.Text = "North" Then
   a = "G"
   b = "H"
   c = "I"
ElseIf lstDir.Text = "East" Then
   a = "K"
   b = "L"
   c = "M"
ElseIf lstDir.Text = "South" Then
   a = "O"
   b = "P"
```

```
  c = "Q"
ElseIf lstDir.Text = "West" Then
  a = "S"
  b = "T"
  c = "U"
End If

Dim arrweather(1 To 168, 1 To 4)


For i = 1 To 168
arrweather(i, 1) = wbkObj.Worksheets(2).Range("E" & i + j).Value 'Labels
arrweather(i, 2) = wbkObj.Worksheets(2).Range(a & i + j).Value 'Series 1
arrweather(i, 3) = wbkObj.Worksheets(2).Range(b & i + j).Value 'Series 2
arrweather(i, 4) = wbkObj.Worksheets(2).Range(c & i + j).Value 'Series 3
Next i
MSChart1.ChartData = arrweather
MSChart1.Visible = True
complete = 5

FrmMain.AutoRedraw = True
End Sub

Private Sub cmdClear_Click()

Call ClearAll

End Sub

Private Sub cmdlight_Click(Index As Integer)
Image2.Picture = LoadPicture("C:\Test\line.jpg")
Image1.Picture = _
  LoadPicture("C:\Test\Summer.jpg")


End Sub

Private Sub cmdPrint_Click()
MsgBox ("Printer function is not available."), , "Printer"
End Sub

Private Sub cmdQuit_Click()
  End
End Sub
```

```
 Private Sub cmdSubmit_Click()
 On Error GoTo Label1


  Dim xlApp As Application
  Dim xlWorkbook As Workbook
  Dim xlWorkbooks As Workbooks
  Dim xlSheets As Sheets
  Dim xlsheet As Worksheet

  Dim xlOldApp As Application
  Dim xlOldWorkbook As Workbook
  Dim xlOldWorkbooks As Workbooks
  Dim xlOldSheets As Sheets
  Dim xlOldSheet As Worksheet


 'turn off the screen
 FrmMain.AutoRedraw = False

 'define filename and continue or stop
 If (FrmMain.Option1(0).Value = True) Then
     filename = "ac"
  Else
     filename = "nv"
  End If
  If (FrmMain.Option2(0).Value = True) Then
     filename = filename & "g"
  Else
     filename = filename & "t"
  End If

  If FrmMain.cmbFacade.ListIndex = -1 Then
        complete = 1
        MsgBox ("Please select Facade Type"), , "Error"
        Call ClearAll
        Exit Sub

 ElseIf FrmMain.cmbFacade.ListIndex >= 0 Then

     If FrmMain.cmbFacade.Text = "Lightweight Cladding" Then
        filename = filename & "cl"
        ElseIf FrmMain.cmbFacade.Text = "Heavyweight Cladding" Then
        filename = filename & "rs"
        ElseIf FrmMain.cmbFacade.Text = "Double Skinned Facade" Then
        filename = filename & "ds"
        ElseIf FrmMain.cmbFacade.Text = "Masonry" Then
        filename = filename & "br"
        ElseIf FrmMain.cmbFacade.Text = "Curtain Walling" Then
        filename = filename & "cw"
    End If
End If


If FrmMain.cmbOptions.ListIndex = -1 Then
      MsgBox ("Please select Facade Option"), , "Error"
```

```
        complete = 1
        Exit Sub

ElseIf FrmMain.cmbOptions.Text = "None" Then
        MsgBox ("Please Select Facade Option"), , "Error"
        Exit Sub

ElseIf FrmMain.cmbOptions.Text = "High Quality" Then
        filename = filename & "2"
ElseIf FrmMain.cmbOptions.Text = "Standard Quality" Then
        filename = filename & "1"
End If

    If FrmMain.lstShading.ListIndex = -1 Then
        MsgBox ("Please select Shading type"), , "Error"
        complete = 1
        Exit Sub
    ElseIf FrmMain.lstShading.Text = "None" Then
        filename = filename & "0"
    ElseIf FrmMain.lstShading.Text = "Overhang" Then
        filename = filename & "1"
    ElseIf FrmMain.lstShading.Text = "Metal Louvres" Then
        filename = filename & "3"
    ElseIf FrmMain.lstShading.Text = "Glass Louvres" Then
        filename = filename & "2"
    ElseIf FrmMain.lstShading.Text = "Vertical Louvres" Then
        filename = filename & "4"
    End If
     complete = 5

If lstShading.Text = "None" Then

  lblcase.Caption = cmbOptions.Text & " " & cmbFacade.Text & " with no shading."
Else
    lblcase.Caption = cmbOptions.Text & " " & cmbFacade.Text & " with " & lstShading.Text & "."
End If


'Was call setxls sucessful?
 If complete = 1 Then
 Exit Sub
 End If

'Do things to excel

 Set xlApp = CreateObject("Excel.Application")
 xlApp.Visible = False
 xlApp.DisplayAlerts = False
 Set xlWorkbooks = xlApp.Workbooks
 Set xlWorkbook = xlWorkbooks.Add()
 Set xlSheets = xlWorkbook.Worksheets
 Set xlsheet = xlSheets(1)

 Set xlOldApp = xlApp
 Set xlOldWorkbook = xlWorkbooks.Open("D:\Oneil\" & filename & ".xls")
 Set xlOldSheets = xlOldWorkbook.Worksheets
```

```
 xlWorkbook.Close (False)
 xlApp.Quit


 Set wbkObj = GetObject("D:\Oneil\" & filename & ".xls")

 Call fill

 'turn on the tabs
 SSTab1.TabEnabled(1) = True
 SSTab1.TabEnabled(2) = True
 SSTab1.TabEnabled(3) = True
 SSTab1.TabEnabled(4) = True
 'set the buttons
 cmdPrint.Enabled = True
 cmdClear.Enabled = True
 cmdSubmit.Enabled = False
 'turn on screen
 FrmMain.AutoRedraw = True
 complete = 1

 Label1:
    If Err.Number = 1004 Then
    Call sel_error
    Exit Sub
    End If
 'fill the boxes on the screen
 End Sub

 Private Sub fill()
 For i = 0 To 3
    lbln(i).Alignment = 1
    lbln(i).BackColor = &H80000005
    e(i) = wbkObj.Worksheets(1).Range("G" & i + 11).Value
    e(i) = Format$(e(i), "0.0")
    lbln(i).Caption = e(i)
 Next i
 For i = 4 To 9
    lbln(i).Alignment = 1
    lbln(i).BackColor = &H80000005
    e(i) = wbkObj.Worksheets(1).Range("G" & i + 11).Value
    If i = 7 Then
    e(i) = Format$(e(i), "0.0")
    Else
    e(i) = Format$(e(i), "0")
    End If

    lbln(i).Caption = e(i)
Next i

'fill in lble
For i = 0 To 3
   lble(i).Alignment = 1
   lble(i).BackColor = &H80000005
   e(i) = wbkObj.Worksheets(1).Range("O" & i + 11).Value
   e(i) = Format$(e(i), "0.0")
```

```
  lble(i).Caption = e(i)
Next i
For i = 4 To 9
  lble(i).Alignment = 1
  lble(i).BackColor = &H80000005
  e(i) = wbkObj.Worksheets(1).Range("O" & i + 11).Value
  If i = 7 Then
  e(i) = Format$(e(i), "0.0")
  Else
  e(i) = Format$(e(i), "0")
  End If
  lble(i).Caption = e(i)
Next i

'fill in lbls
For i = 0 To 3
  lbls(i).Alignment = 1
  lbls(i).BackColor = &H80000005
  e(i) = wbkObj.Worksheets(1).Range("G" & i + 28).Value
  e(i) = Format$(e(i), "0.0")
  lbls(i).Caption = e(i)
Next i
For i = 4 To 9
  lbls(i).Alignment = 1
  lbls(i).BackColor = &H80000005
  e(i) = wbkObj.Worksheets(1).Range("G" & i + 28).Value
  If i = 7 Then
  e(i) = Format$(e(i), "0.0")
  Else
  e(i) = Format$(e(i), "0")
  End If
  lbls(i).Caption = e(i)
Next i

'fill in lblw
For i = 0 To 3
  lblw(i).Alignment = 1
  lblw(i).BackColor = &H80000005
  e(i) = wbkObj.Worksheets(1).Range("O" & i + 28).Value
  e(i) = Format$(e(i), "0.0")
  lblw(i).Caption = e(i)
Next i
For i = 4 To 9
  lblw(i).Alignment = 1
  lblw(i).BackColor = &H80000005
  e(i) = wbkObj.Worksheets(1).Range("O" & i + 28).Value
  If i = 7 Then
  e(i) = Format$(e(i), "0.0")
  Else
  e(i) = Format$(e(i), "0")
  End If
  lblw(i).Caption = e(i)
Next i

End Sub
```

```
Private Sub Form_Load()

Load frmSplash
frmSplash.Show
FrmMain.Hide


lstShading.AddItem "None", 0
lstShading.AddItem "Overhang", 1
lstShading.AddItem "Glass Louvres", 2
lstShading.AddItem "Metal Louvres", 3
lstShading.AddItem "Vertical Louvres", 4

lblTemp(0).Caption = "Cooling Energy Load / kWh/m" & Chr$(178)
lblTemp(1).Caption = "Heating Energy Load / kWh/m" & Chr$(178)
lblmin.Caption = "Minimum Comfort Temperature /" & Chr$(176) & "C"
lblmax.Caption = "Maximum Comfort Temperature /" & Chr$(176) & "C"
label3.Caption = "Hours below 18" & Chr$(176) & "C /" & Chr$(37)
Label4.Caption = "Hours above 28" & Chr$(176) & "C /" & Chr$(37)
Label5.Caption = "Hours below 25" & Chr$(176) & "C /" & Chr$(37)
Label6.Caption = "Average Daylight Factor /" & Chr$(37)
Label7.Caption = "Embodied Energy / MJ/m" & Chr$(178)
Label8.Caption = "Environmental Impact / Eco-Points"


cmbOptions.ToolTipText = "Sets the facade quality."
cmbFacade.ToolTipText = "Select the facade type."
lstShading.ToolTipText = "Select the shading option."
cmdEU.ToolTipText = "Show graph"
cmdEI.ToolTipText = "Show graph"
cmdTE.ToolTipText = "Show graph"
cmdlight(2).ToolTipText = "Show graph"

cmbOptions.AddItem "None"
cmbOptions.Text = "None"


cmbFacade.AddItem "Curtain Walling", 0
cmbFacade.AddItem "Lightweight Cladding", 1
cmbFacade.AddItem "Heavyweight Cladding", 2
cmbFacade.AddItem "Double Skinned Facade", 3

lstSeason.AddItem "Summer"
lstSeason.AddItem "Winter"

lstWeather.AddItem "January"
lstWeather.AddItem "February"
lstWeather.AddItem "March"
lstWeather.AddItem "April"
lstWeather.AddItem "May"
lstWeather.AddItem "June"
lstWeather.AddItem "July"
lstWeather.AddItem "August"
lstWeather.AddItem "September"
lstWeather.AddItem "October"
lstWeather.AddItem "November"
```

```
lstWeather.AddItem "December"

lstShading.AddItem "None", 0
lstShading.AddItem "Overhang", 1
lstShading.AddItem "Glass Louvres", 2
lstShading.AddItem "Metal Louvres", 3
lstShading.AddItem "Vertical Louvres", 4

lstDir.AddItem "North"
lstDir.AddItem "East"
lstDir.AddItem "South"
lstDir.AddItem "West"

LstDir2.AddItem "North", 0
LstDir2.AddItem "East", 1
LstDir2.AddItem "South", 2
LstDir2.AddItem "West", 3

SSTab1.TabEnabled(1) = False
SSTab1.TabEnabled(2) = False
SSTab1.TabEnabled(3) = False
SSTab1.TabEnabled(4) = False
SSTab1.TabEnabled(0) = True
cmdClear.Enabled = False
SSTab1.Tab = 0

MSChart1.Visible = False
MSChart2.Visible = False
MSChart3.Visible = False
MSChart4.Visible = False

cmbFacade.ListIndex = -1
lstShading.ListIndex = -1
cmbOptions.ListIndex = -1

lstSeason.Enabled = False
lblseason.Enabled = False
End Sub


Private Sub cmbFacade_Click()
cmbOptions.RemoveItem (0)
If cmbFacade.Text = "Double Skinned Facade" Then
   cmbOptions.Clear
   cmbOptions.AddItem "Internal Weatherseal"
   cmbOptions.AddItem "External Weatherseal"
Else
   cmbOptions.Clear
   cmbOptions.AddItem "High Quality"
   cmbOptions.AddItem "Standard Quality"
End If

End Sub
```

```
Private Sub Option1_Click(Index As Integer)

If Option1(1).Value = True Then
   cmbFacade.AddItem "Masonry", 0
   cmbOptions.Clear
   cmbOptions.AddItem "None"
ElseIf Option1(0).Value = True Then
   cmbFacade.RemoveItem 0
   cmbOptions.Clear
   cmbOptions.AddItem "None"
End If
   cmbFacade.ListIndex = -1
   lstShading.ListIndex = -1
   cmbOptions.ListIndex = -1
End Sub


Private Sub OptTE_Click(Index As Integer)
If OptTE(0).Value = True Then
   lstSeason.ListIndex = -1
   lblseason.Enabled = False
   lstSeason.Enabled = False
   LblMonth.Enabled = True
   lstWeather.Enabled = True
   lstDir.Enabled = True
   LblDir.Enabled = True

Else
   lstWeather.ListIndex = -1
   lstDir.ListIndex = -1
   LblMonth.Enabled = False
   lstWeather.Enabled = False
   lstDir.Enabled = False
   LblDir.Enabled = False
   lblseason.Enabled = True
   lstSeason.Enabled = True
End If
End Sub

Option Explicit

Private Sub Form_KeyPress(KeyAscii As Integer)
   Unload Me
   FrmMain.Show
End Sub

Private Sub Frame1_Click()
   Unload Me
   FrmMain.Show
End Sub

Private Sub TmrSplash_Timer()
   Unload Me
   FrmMain.Show
End Sub
```